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High-redshift Lyman-alpha emitters in blank and lensing fields

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High-redshift Lyman α emitters in blank and lensing fields

PhD thesis

to obtain the degree of PhD at the
University of Groningen
on the authority of the
Rector Magnificus, Prof. C. Wijmenga,
and in accordance with
the decision by the College of Deans.

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1. INTRODUCTION

The question of where we come from has been at the forefront of human consciousness since the beginning of recorded history. This question has been greatly expanded in the past century with the realization that our star and galaxy are but a minuscule fraction of what constitutes the Universe. It has thus become of interest to know where all this matter and the Universe itself come from. This question is, however, not one easily approached, but we can nonetheless investigate the origin and history of a single or groups of objects in our reality. Studying the birth and evolution of galaxies and their location in space and time gives us a picture of what happened to the Universe since its birth.

While many new studies on galactic archaeology, especially using dwarf galaxies, are uncovering interesting traces of the past history of low redshift objects in the nearby Universe (Simon 2019, and references therein), being able to glimpse directly at the star formation processes as they are happening at high redshift constitutes a more secure and direct approach to characterizing the history of our Universe. Especially now that the instrumental limitations are being pushed further and further with upcoming new and more powerful instruments and telescopes.

In the last decade, studies of high redshift galaxies have shown that the global cosmic star formation rate density has an increasing trend with decreasing redshift for $z \gtrsim 2$, reaching a peak at $z \sim 2$ and then decreasing again until $z = 0$ (Hopkins & Beacom 2006; Behroozi et al. 2013; Madau & Dickinson 2014, see also Fig. 1.1). The star formation history of a galaxy is essential to understand its evolution. The amount and the type of stars formed during its lifetime determine not only the stellar mass and dynamics of the galaxy, but also the abundances of the chemical elements present in it. Furthermore, other studies have shown that the dust content of a galaxy at high redshift is greatly enhanced with respect to nearby galaxies (Hughes et al. 1998; Adelberger & Steidel 2000; Caputi et al. 2007; Gruppioni et al. 2010; Magnelli et al. 2011), thus modifying the light we can observe. The presence of dust is normally linked to star formation activity as attested by

Figure 1.1: Plots showing the star formation density and its evolution through redshift. Plot **a** focuses on data obtained through UV studies, plot **b** on IR studies, and finally plot **c** combines both previous plots. Picture taken from Madau & Dickinson (2014).

Gould & Salpeter (1963); Hollenbach & Salpeter (1971) and Gavilan et al. (2012). Finally, the number density of starburst galaxies with respect to that of main sequence galaxies is different from what we observe at $z = 0$, with starburst galaxies being more frequent at high redshift (Caputi et al. 2017; Bisigello et al. 2018).

In this thesis, I aimed to study and characterize high redshift Lyman α line emission ($\text{Ly}\alpha$) and its relation to other galactic properties, such as star formation rate (SFR), stellar mass and age. I started by comparing high redshift $\text{Ly}\alpha$ emitters to their non-emitting counterparts in the COSMOS field, by using the physical properties derived through spectral energy distribution (SED) fitting using extensive photometric data. I further studied the physical state of $\text{Ly}\alpha$ emitting galaxies by presenting the fit of “shell-model” spectra generated through a radiative transfer code on a new set of emitters detected both in blank and cluster lensed fields. Finally, I studied the emitter population of the deepest of our cluster data and made use of SED fitting to further characterize our emitting population.

1.1 HIGH REDSHIFT GALAXIES AND THEIR IMPORTANCE

Star formation in a galaxy can be detected in many different ways. For galaxies further away from our immediate vicinity, we can study their rest-frame ultraviolet (UV), infrared (IR), or radio emission to infer their SFR. Most importantly, though, the presence of emission lines tightly linked to star formation, identified either through spectroscopy or narrow-band imaging, is optimally capable of characterizing the current state of star formation in a galaxy.

Studies in the rest-frame UV are most effective for objects at $z > 1$ since the light has been redshifted into the optical, and is therefore observable from the ground. The downside of these studies is that even a slight presence of dust in and around the galaxy is able to dramatically reduce the amount of UV photons that are able to escape it. Without knowledge of the dust content of the considered objects, it is thus impossible to reconstruct the star formation rate of the galaxy.

A way of obtaining information on the dust cover of a galaxy, is to use observations in the IR. Since dust emits thermal radiation when it is excited by UV photons, the light that is missing in the UV can be reconstructed by translating the IR dust emission into UV luminosity. This conversion is not entirely straightforward, unfortunately, as part of the dust emission has been found to originate from ambient star light in local Galactic starforming regions (Lonsdale Persson & Helou 1987; Sodroski et al. 1997). This has been found to be valid also at higher redshifts (Salim et al. 2009).

Another way of studying the SFR of galaxies is to study their radio emission. This approach has as its main problem, though, that of active galactic nuclei (AGNs) being very strong radio emitters, to the point of covering up the emission coming from their galaxy's star formation if they are active. Since I do not deal with radio emission in this work, I leave the reader with the review by Madau & Dickinson (2014) if they would like to delve into this topic further.

Finally, emission lines of specific elements can also attest to ongoing star formation. Out of all of these tracers, the $H\alpha$ line is probably the most effective, as it is not influenced by other properties of the galaxy, i. e. such as [OII] at $3727 \text{ \AA}$ is by metallicity and interstellar medium (ISM) conditions, and it also is not resonantly scattered by neutral hydrogen such as the $Ly\alpha$ line. The downside of using $H\alpha$ is that the line leaves the optical for galaxies at $z > 0.5$ and thus needs to be observed in the IR if we want to probe greater distances. With the advent of the *James Webb* Space Telescope (JWST), however, measuring $H\alpha$ at high redshift is going to become much easier, as the instruments on the upcoming telescope are

going to be able to probe the light spectrum of a source down to $24\ \mu\text{m}$. This will allow us to measure $\text{H}\alpha$ down to the epoch of re-ionization.

Most studies focusing on the star formation density of a sample of high redshift galaxies ($z > 1$) have been performed either in the Great Observatories Origins Deep Survey (GOODS), the *Hubble* Ultradeep Field (HUDF) or the COSMOS field (Scoville et al. 2007). These regions in the sky offer a thorough catalog of photometric data that makes analyzing galaxies at different wavelengths particularly effective. Especially the use of *Herschel* and *Spitzer* (Werner et al. 2004) data allowed to accurately measure the redder parts of the spectrum of these galaxies and constrain their dust emission. A later addition to this wealth of data was the CANDELS survey that both expanded the amount of available observations and also allowed to reduce the effect of cosmic variance. A more in-depth description of what I just discussed can be found in Madau & Dickinson (2014).

As we discussed above, there are not many homogeneous surveys over a large area of the sky for high redshift studies. Surveys are in general either deep, to observe also fainter, less massive galaxies, or cover a large area, but are shallower. This is because large and deep high redshift surveys require a large amount of telescope time and only recently there have been telescopes dedicated to covering this difficult combination of parameter space. Having both deep data and a wide area at the same time is thus not common. The *Spitzer* Matching Survey of the UltraVISTA Ultra-deep Stripes (SMUVS) (Ashby et al. 2018) is the largest quasi-contiguous *Spitzer* field to investigate high redshift sources spanning over more than three orders of magnitude in stellar mass. SMUVS combines observations in the $3.6\mu\text{m}$ and $4.5\mu\text{m}$ *Spitzer* bands taken in the COSMOS field such that the area covered overlaps the three UltraVISTA ultra-deep stripes (McCracken et al. 2012) with the deepest optical coverage of the Subaru telescope (Taniguchi et al. 2007). I make use of this survey in Chapter 2 to define part of my galaxy sample.

Although in this section I mostly focused on photometric studies, this thesis is devoted to the study of the Lyman α emission line in star-forming galaxies. Therefore, the rest of the Introduction will almost completely deal with spectroscopic analysis, particularly related to the Ly α line.

1.2 LYMAN α EMISSION IN THE DISTANT UNIVERSE

Hydrogen is the most common element in the Universe and as such is an important source of information on the evolution of many aspects of our reality. If an astrophysical process is currently on-going, there is a

high chance that hydrogen is somehow involved in shaping the properties of the light emitted, whether in emission itself or by absorbing specific wavelengths. Hydrogen is also the element emitting one of the strongest state transition lines in the Universe: the Ly α line. One of the key properties of this line emission is that it is subject to resonant scattering if it encounters neutral hydrogen and that dust is capable of attenuating the line by absorbing it in the ultraviolet (UV, at its native 1216 Å wavelength) and re-emitting it as thermal radiation in the infrared (IR).

Nevertheless, the intensity of the Ly α line is often enough for a certain fraction of its photons to break through the portion of the Universe capable of extinguishing it and reach the detectors on our ground-based or space telescopes as optical or near-infrared (NIR) radiation, depending on the redshift of the emitting galaxy. For this reason, Ly α is often used to probe the high- z Universe for new objects.

The historical origin of the Ly α analysis used in conjunction with high- z galaxies can be found in Partridge & Peebles (1967). In that work, the authors theorized that Ly α emission would be an indicator of early galaxy evolution. While their predictions turned out to be an over-estimation of what we are capable of observing today, two of the main aspects of Ly α emission were introduced through their work: its impact on cosmic re-ionization and early galaxy formation.

It took until the mid-90s, however, for Ly α emitting sources to be detected. The first such systems were found around the QSO BR2237-0607 (Hu & McMahon 1996) through narrow band photometry in combination with spectroscopy, around the radio galaxy 53W002 (Pascarelle et al. 1996) and in blank fields (Cowie & Hu 1998). Subsequently, a number of deep observation programs have been launched to enlarge our sample of Ly α emitters, among which we can count the Multi Unit Spectroscopic Explorer (MUSE) Ultra Deep Field Survey by Bacon et al. (2017).

1.2.1 Origin and modeling of the Ly α line

Ly α photons originate from the recombination of ionized hydrogen atoms. There are five major ways for an HI atom to be excited and enter its ionized state. If the atom is located in the central regions of the galaxy and is part of the ISM the two main mechanisms to ionize it are either young massive stars or an AGN. If the excited atom is part of the circumgalactic medium (CGM) then the origin of the excitation can either be shock heating through outflows, excitation through the interaction of cold accretion inflows, or fluorescence caused by the UV radiation of a powerful background source.

Figure 1.2: Plots showing examples of different $\text{Ly}\alpha$ lines and attempts at fitting a model to the data. The blue line with errorbars represents the observed spectrum, the red line shows the “shell-model” best fit (with the intrinsic emission as the dashed line). Finally, the green line shows the fit with a “Gaussian-minus-Gaussian” approach. The numbers in the panels show the best fit χ^2 for the corresponding color. Picture taken from Gronke (2017).

Regardless of the actual origin of the $\text{Ly}\alpha$ photon, once it starts to travel through space on its way to leave its host galaxy, it will be subjected to resonant scattering due to its easy interaction with other neutral hydrogen, which will absorb it, become ionized, and re-emit the $\text{Ly}\alpha$ photon when the next recombination event happens. In this way, the path of these photons towards the exterior of the galaxy is going to be changed many times and result in a diffused light profile compared to the rest of the light emission of the host galaxy. Eventually, the $\text{Ly}\alpha$ photons will either reach the outskirts of their host or be redshifted out of resonance, so that they can escape and reach us.

In combination with its interactions with hydrogen, the line is also located in the UV part of the light spectrum and is thus absorbed by dust particles present in the ISM and CGM and re-emitted as thermal radiation in the IR. This interaction is different than the resonant scattering because it actively removes photons from the $\text{Ly}\alpha$ frequency instead of simply spreading the light on a larger area. For this reason, we are unable to detect the entirety of the radiation emitted, be it because part of the light profile is too faint for our current instruments or because the dust has extinguished part of the radiation.

The complexity of these interactions make it hard to reconstruct the original $\text{Ly}\alpha$ emission through simple means. Fortunately, it is possible to

use radiative transfer simulations to mimic the transport of Ly α photons through their host galaxy and its surrounding medium. Such simulations make use of Monte Carlo chains to propagate a certain amount of Ly α , and in some cases UV photons, through a spherically symmetric expanding shell of gas and dust. This allows for a model with a relatively small number of parameters to reproduce the emission we observe through our telescopes, namely as a combination of the initial line emission and the expansion velocity of the shell, the neutral hydrogen column density around the host galaxy, the temperature of the surrounding gas and the optical depth of the dust (Verhamme et al. 2008; Gronke 2017; Verhamme et al. 2018; Kakiichi & Gronke 2019). Figure 1.2 illustrates the aforementioned model fitting and some of the possible emission profile shapes the Ly α line can show.

While these models are still being refined and constitute a simplified version of the actual conditions in and around the observed galaxies, they have been an important tool to provide a venue of interpretation for our observations, as described below. Furthermore, these models are able to identify the cause for specific features in the profile shape, such as a double-peak emission or an extended asymmetric red tail, by using the physical state of the expanding shell to tweak the photon propagation so that the initial Gaussian emission is scattered and attenuated into the final shape we observe.

1.2.2 Observations of the Ly α line

Currently the method that has led to the discovery of most of the known Ly α emitters, subsequently verified through spectroscopy, is narrow band imaging. This method has yielded a total of $> 20,000$ objects against the $> 1,000$ spectroscopically discovered sources (Drake et al. 2017; Sobral et al. 2018b; Shibuya et al. 2019). Nonetheless, blind spectroscopy deserves still to be mentioned as one of the more effective methods to detect Ly α emission and one instrument that shines particularly in this regard is the aforementioned MUSE instrument mounted on the Very Large Telescope (VLT).

The advantage that spectroscopy has over imaging is that, while it might cover a smaller area of the sky at once, it is able to provide more information on the individual objects. Specifically, it shows not only the accurate intensity of the emission line, but also its emission profile shape. As I have discussed above, the visual shape of the light profile that reaches us is tightly linked to the emission, scattering and attenuation of the Ly α photons. So while imaging might be able to detect more Ly α candidates at

once and on a larger area, it is spectroscopy that allows us to get a clearer picture of the actual process behind the $\text{Ly}\alpha$ emission.

Finally, since the $\text{Ly}\alpha$ is linked to star formation, using it to derive a lower limit for the SFR of the host galaxy implies that we first convert the $\text{Ly}\alpha$ luminosity into an $\text{H}\alpha$ luminosity and then into an SFR following the empirical calibration relation of Kennicutt (1998). This results in a lower limit, because as I stated above, the light reaching us in the form of $\text{Ly}\alpha$ photons has been attenuated by gas and dust. The only way we have of accurately recover the SFR of the galaxy using hydrogen emission lines is if we have the luminosity of one or more Balmer lines available. A useful review on the topic of $\text{Ly}\alpha$ modeling and observations that deserves mention is Ouchi et al. (2020).

As stated in the beginning of this introduction, the intensity of the $\text{Ly}\alpha$ line makes it particularly adequate to probe for distant and faint objects. This naturally leads us towards the next topic I need to discuss in this section of the thesis: using lensing clusters as gravitational telescopes to detect faint galaxies.

1.3 LENSING CLUSTERS AS PROBES OF HIGH-Z GALAXIES

Galaxy clusters concentrate enough mass in one single location of space to give rise to a gravitational lens, which can effectively be considered one of “Nature’s Telescopes”. The total mass of the cluster and its distribution bend space-time in a way that photons originating from certain positions behind the cluster get concentrated towards our line of sight, actively magnifying the light coming from these distant objects. Some clusters reach magnification factors of 40x (Seitz et al. 1998) which corresponds to a 4 magnitude increase in brightness, while most others have magnifications of the order of 4x (Richard et al. 2011) which instead correspond to 1.5 magnitudes. Magnification is not uniform in the region of the cluster and the places where it peaks are close to the critical lines, that identify the region where magnification is theoretically infinite (see Fig. 1.3). Such regions of extreme magnification have been targeted in order to discover new and very faint objects (Yee et al. 1996; Franx et al. 1997; Ellis et al. 2001; Hu et al. 2002; Kneib et al. 2004; Richard et al. 2011; Atek et al. 2015, 2018; Bouwens et al. 2017).

There are in substance two ways of using a lensing cluster to detect faint sources: one is to perform a deep mapping of the area and to aim for completeness in the detected sample, the other is to perform a shallow

Figure 1.3: Picture showing the cluster Abell 1689. The red contours is the critical line for $z = 7$, while the yellow line delimits the region for which the lensing magnification is larger than a factor of 10. Picture taken from Kneib & Natarajan (2011).

mapping of the cluster to try and detect highly magnified sources (Kneib & Natarajan 2011). In this work I make use of a hybrid of these two approaches as I will present both shallow and deep cluster data in Chapter 3 and one very deep MUSE pointing in Chapter 4.

The magnification provided by lensing clusters can further enhance the already bright $\text{Ly}\alpha$ emission of high redshift sources. This allows us to detect lines down to very faint luminosities and in combination with the MUSE instrument mounted on the VLT telescope we can obtain this low luminosity sample serendipitously (de La Vieuville et al. 2019). In recent years, many studies using MUSE, $\text{Ly}\alpha$ emission and lensing clusters have pushed our knowledge of the first billion years of the star formation in our Universe (Caminha et al. 2016; Patrício et al. 2016; Herenz et al. 2017; Hernán-Caballero et al. 2017; Smit et al. 2017; Vanzella et al. 2017a,b, 2019; Richard et al. 2021). The downside of lensing is that the image we detect is distorted and often projected into multiple images. To solve this problem, theoretical lens models based on the mass distribution detected in the cluster allow us to reconstruct the natural luminosity and morphology of the lensed sources (Grillo et al. 2016; Lagattuta et al. 2017; Caminha et al. 2017a,b, 2019; Mahler et al. 2018; Jauzac et al. 2019).

1.4 THIS THESIS

In this work, I analyzed $\text{Ly}\alpha$ emitting galaxies at high redshift ($3 < z < 6.7$) to study the relation between this line emission and the physical properties of the host galaxy and its surrounding medium. To start with, in Chapter 2 I analyzed a sample of $\text{Ly}\alpha$ emitters detected in the COSMOS field through shallow MUSE pointings on a wide area (20.79 arcmin^2). I compared this serendipitously detected sample to a sample of galaxies that did not show $\text{Ly}\alpha$ emission, that were detected in the same area covered by MUSE, and that were located at similar redshifts. To construct my non-emitter sample I made use of the SMUVS survey catalog, which contained both non-emitter sources and also part of my emitter population. I measured the $\text{Ly}\alpha$ flux and luminosity for my emitter sources and assigned a profile shape type to my sample. For the sources present in SMUVS I compared their SED physical properties between emitters and non-emitters and also compared the SFR derived from the $\text{Ly}\alpha$ line as a lower limit to the average SFR needed for the galaxy to build up its stellar mass during its entire lifetime. I thus tested if the star formation event can be considered unique or if the star formation had to start up again after the first stellar population had formed.

In Chapter 3, I deepened my analysis of the $\text{Ly}\alpha$ emission of high redshift galaxies by making use of a quantitative method to classify the $\text{Ly}\alpha$ profile with the fitting of “shell-models” generated through the `tlac` radiative transfer code (Gronke & Dijkstra 2014). This allowed me to assign physical properties to each profile and test if a specific profile shape or family has any preferences when it comes to the initial emission prior to scattering and/or the state of the expanding gas and dust shell. I also enlarged my sample by using deeper MUSE data in the field and by also integrating lensing clusters in my catalogs to further push the limit in my detections.

In Chapter 4 I took advantage of one of the clusters that I studied in Chapter 3, MACS J0416, and the incredibly deep MUSE data available for it to further characterize my emitter sample. Being part of the *Hubble* Frontier Fields (HFF), MACS J0416 also has HST coverage and allowed me thus to carry out SED fitting in my analysis to derive physical properties of my objects that are disjointed from the $\text{Ly}\alpha$ emission. I used this information both to check the distribution of physical properties in this exceptionally faint sample, and to test for correlation between the physical properties obtained for the $\text{Ly}\alpha$ emission and the stellar mass and star formation rate of my objects. I also took a closer look at the physical properties of the LyC leakage candidates present in this region of the sky.

Finally, in Chapter 5 I summarize the conclusions of our single works and comment on the general picture emerging, that with our current observational capabilities, the population of $\text{Ly}\alpha$ emitters did not appear to be statistically different from each other and the non-emitting population. The few differences I found are interesting but could not be justified physically because of the limited information that is currently available. The use of future, more powerful facilities will potentially allow us to further characterize this population and eventually clarify their properties and physical processes.

1. INTRODUCTION

2. BRIGHT LYMAN- α EMITTERS AMONG *Spitzer* SMUVS GALAXIES IN THE MUSE/COSMOS FIELD

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2020, *Astronomy & Astrophysics*, 633, A159

We search for the presence of bright Ly α emitters among *Spitzer* SMUVS galaxies at $z > 2.9$ making use of homogeneous MUSE spectroscopic data. Although these data only cover a small region of COSMOS, MUSE has the unique advantage of providing spectral information over the entire field, without the need of target pre-selection. This results in an unbiased detection of all the brightest Ly α emitters among the SMUVS sources, which by design are stellar-mass selected galaxies. Within the studied area, $\sim 14\%$ of the SMUVS galaxies at $z > 2.9$ have Ly α fluxes $F_\lambda \gtrsim 7 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$. These Ly α emitters are characterized by three types of emission, 47% show a single-line profile, 19% present a double peak or a blue bump, and 31% show a red tail. One object (3%) shows both a blue bump and a red tail. We also investigate the spectral energy distribution (SED) properties of the SMUVS galaxies that are MUSE detected and those that are not. After stellar mass matching the two populations, we find that the MUSE detected galaxies have generally lower extinction than SMUVS-only objects, while there is no clear intrinsic difference in the mass and age distributions of the two samples. For the MUSE-detected SMUVS galaxies, we compare the instantaneous star formation rate (SFR) lower limit obtained from the Ly α line with its past average derived from SED fitting, and find evidence for rejuvenation in some of our oldest objects. In addition, we study the spectra of those Ly α emitters that are not detected in SMUVS in the same field. We find that of the emission line profiles shown 67% have a single line, 3% a blue bump, and 20% a red tail. The difference in profile distribution could be ascribed to the fainter Ly α luminosities of the MUSE sources not detected in SMUVS and an intrinsically different mass distribution. Finally, we search for the presence of galaxy

associations using the spectral redshifts. The integral coverage of MUSE reveals that these associations are 20 times more likely than what is derived from all the other existing spectral data in COSMOS, which is biased by target pre-selection.

2.1 INTRODUCTION

The Lyman- α ($\text{Ly}\alpha$) line contains important information about some of the main physical processes occurring in galaxies. In particular, bright $\text{Ly}\alpha$ emitters are tracers of the most prominent unobscured star formation activity at different cosmic times. The interpretation of the $\text{Ly}\alpha$ line is not trivial, however, because of its resonant nature; it is easily scattered by the interstellar medium (ISM) on its way out of the galaxy. Furthermore, $\text{Ly}\alpha$ photons are absorbed by dust and re-emitted at longer wavelengths, thus subtracting them from the line intensity. The kinematics of the gas also needs to be taken into account. All these processes give rise to different line profile shapes depending on the conditions surrounding the emitter galaxy (Shapley et al. 2003; Karman et al. 2014; Martin et al. 2015; Dijkstra 2017; Hernán-Caballero et al. 2017; Karman et al. 2017; Bridge et al. 2018; Erb et al. 2018; Gurung-Lopez et al. 2018; Nakajima et al. 2018; Orlitová et al. 2018; Sobral et al. 2018a; Vanzella et al. 2018; Kimm et al. 2019a; Marchi et al. 2019; Remolina-Gutiérrez & Forero-Romero 2019; Smith et al. 2019).

It is possible to recover the original $\text{Ly}\alpha$ flux if information on the $\text{H}\alpha$ line is available. There is no canonical conversion factor between $\text{Ly}\alpha$ and $\text{H}\alpha$ because secondary effects influence the conversion, but assuming case B recombination the values can reasonably range from ≈ 8 (Dijkstra 2017) to ~ 8.7 (Hu et al. 1998). When information on the $\text{H}\alpha$ line is not present, we can rely on radiative transfer models exclusively treating the $\text{Ly}\alpha$ line to try and recover the original emission from line shape fitting. These models need to take into account the composition of the circumgalactic medium, the presence of dust, how dense the neutral hydrogen is, as well as the gas dynamics and the time evolution of the medium along with the star formation event. Models reproducing the shape of the $\text{Ly}\alpha$ emission go from the early approach of Tenorio-Tagle et al. (1999) and Mas-Hesse et al. (2003) to the more recent models by Verhamme et al. (2008, 2018), Gronke (2017), and Kakiichi & Gronke (2019), among others. Finally, selecting objects using the $\text{Ly}\alpha$ line is a way to ensure that the more active star-forming non-dusty galaxies are selected (Zhang et al. 2019).

The use of *Spitzer* (Werner et al. 2004) data in the 3.6/4.5 μm bands allows us to access the red flat part of the spectrum of high-redshift galaxies. This results in a stellar mass selection, as the more luminous high- z galaxies at those wavelengths are typically the most massive. These objects are interesting because they represent possible progenitors of today's most massive galaxies and because they possibly played an integral role in the peak of star formation history around $z \sim 2$ (Caputi et al. 2011; Deshmukh et al. 2018; Martinache et al. 2018).

By combining the more massive galaxies selected by *Spitzer* and the most prominent Ly α emitters, we probe a very specific part of the galaxy evolution picture. We not only select the most massive objects at early times, but we also ensure that they are intensely star-forming and contain relatively little dust by detecting their Ly α emission.

Previous studies combining Ly α information with photometric SED fitting have been able to constrain stellar mass, age, star formation rate (SFR), and E(B-V) of Ly α emitters among other properties. The general result of these studies is that Ly α emitters are young, prominently star-forming, mostly unobscured intermediate-mass galaxies. Some of these studies also find evidence of more massive objects being present among the Ly α population. Moreover, the age distribution of the Ly α emitters presents in some cases an age bimodality, for which a significant fraction of the galaxies studied is not young, but has ages around 1 Gyr (Lai et al. 2008; Finkelstein et al. 2009; Ono et al. 2010; Pentericci et al. 2009, 2010; Yuma et al. 2010; Guaita et al. 2011; Acquaviva et al. 2012; Mallery et al. 2012; Curtis-Lake et al. 2013; McLinden et al. 2014; De Barros et al. 2017; Hao et al. 2018; Marchi et al. 2019).

Among the best studied blank areas of the sky is the COSMOS field (Scoville et al. 2007), for which a wide range of homogeneous and deep data sets are available. One of the surveys spanning part of the field is the *Spitzer Matching Survey of the UltraVISTA ultra-deep Stripes* (SMUVS, Ashby et al. 2018). The SMUVS survey combines *Spitzer* 3.6 and 4.5 μm data with 26 complementary photometric bands to infer the redshift and physical properties of its galaxies. Most importantly, it uses the *Spitzer* InfraRed Array Camera (IRAC) data (Fazio et al. 2004) to gain access to the flat part of the continuum of high-redshift objects. The SMUVS survey has already produced a number of studies of galaxy properties at redshift $z > 2$ (Caputi et al. 2017; Cowley et al. 2018, 2019; Deshmukh et al. 2018).

The Multi Unit Spectroscopic Explorer spectrograph (MUSE, Bacon et al. 2010) provides a powerful tool to expand the existing analysis of any part of the sky. Being an integral field unit (IFU) spectrograph, it allows to take the spectra of a $\sim 1' \times 1'$ portion of the sky with no source pre-selection. Furthermore, new sources can be discovered serendipitously and biases in the galaxy sample, inherent to slit spectroscopy, can be avoided.

As we aim to combine MUSE and SMUVS, and given the wavelength range covered by MUSE, the spectral feature available for us to study in objects above $z \sim 3$ is the Ly α emission. This line emission is visible in the MUSE spectral range for objects at redshifts $2.9 \lesssim z \lesssim 6.6$.

The scope of this paper is to analyze the physical properties of the more prominent Ly α emitters detected in MUSE. We thus use homogeneous

MUSE observations in subregions of the COSMOS field of view to spectroscopically confirm SMUVS sources in an area of $\approx 20.79 \text{ arcmin}^2$. We give special attention to sources in the redshift range $2.9 \leq z \leq 6.6$, where we can obtain secure confirmation from the $\text{Ly}\alpha$ line with MUSE, and study its physical properties using the rich broadband photometry from SMUVS, also comparing with the sample of non- $\text{Ly}\alpha$ emitters at the same redshift range. Furthermore, we also list new sources detected by a blind search performed in the MUSE pointings and test our spectroscopic sample for possible physical associations.

In Section 2.2 we describe the data we used, in Section 2.3 we outline our results, and in Section 2.4 we discuss our results and draw our conclusion. Throughout this paper we adopt a flat Λ CDM cosmology with $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.286$, and $\Omega_\Lambda = 0.714$.

2.2 DATA

The COSMOS field is one of the most observed regions of the sky with numerous ancillary data sets obtained from ground- and space-based observatories. In this section we describe only the data sets that we used for our sample selection.

2.2.1 SMUVS sources

We used the version of the SMUVS catalog (Ashby et al. 2018) presented in Deshmukh et al. (2018) to select part of our sources. We focused on the area of the MUSE/COSMOS GTO field. SMUVS is a *Spitzer Space Telescope* Exploration Science Program that combines observations in the IRAC (Fazio et al. 2004) $3.6\mu\text{m}$ and the $4.5\mu\text{m}$ bands, taken over $\sim 0.66 \text{ deg}^2$ of the COSMOS field. The area observed by SMUVS overlaps with the three UltraVISTA ultra-deep stripes (McCracken et al. 2012) and with the COSMOS deepest optical coverage of the Subaru telescope (Taniguchi et al. 2007).

The SMUVS source detection is a double-selection in the HK_s average stack maps constructed using data from the UltraVISTA third data release and in the $3.6/4.5 \mu\text{m}$ IRAC bands. As described in Deshmukh et al. (2018), SExtractor (Bertin & Arnouts 1996) is applied on the HK_s UltraVISTA maps to select sources that will then be used as priors to perform a point spread function (PSF) fitting on the IRAC images to finalize the selection. The SMUVS catalog includes multi-wavelength photometric data available for COSMOS in 26 bands, from the U through the UltraVISTA K_s band. All

this photometric data, along with the IRAC photometry, has been used to perform the spectral energy distribution (SED) fitting and derive physical properties for about 300,000 galaxies (Deshmukh et al. 2018). In this paper we consider the $\sim 3,000$ SMUVS sources that lie on the 20.79 arcmin^2 area of the MUSE COSMOS/GTO program.

2.2.2 MUSE spectroscopy

In this work we analyze archival data from MUSE (Bacon et al. 2010) in the COSMOS field (Scoville et al. 2007), over an area of 20.79 arcmin^2 embedded in the SMUVS footprint (Ashby et al. 2018). MUSE is one of the latest spectrographs mounted on the Very Large Telescope and offers integral field spectroscopy over an entire 1 arcmin^2 field of view, providing a spectrum for each $0.2 \times 0.2 \text{ arcsec}^2$ pixel element. Therefore, the observations do not require pre-selection of targets, and thanks to its small pixel size, the source separation is limited only by observational conditions. MUSE covers the wavelength range $4750\text{--}9350 \text{ \AA}$ with a spectral bin of $1.25 \text{ \AA/pixel}$, resulting in an average resolving power $R \approx 3000$ at $\lambda \sim 7500 \text{ \AA}$ and an almost constant resolution of $\Delta\lambda \approx 2.4 \text{ \AA}$.

We made use of a homogeneous data set obtained by the MUSE consortium under the Guaranteed Time Programme IDs 095.A-0240, 096.A-0090, 097.A-0160, and 098.A-0017 (P.I.: L. Wisotzki) as part of the MUSE-Wide survey (Herenz et al. 2017; Diener et al. 2017; Urrutia et al. 2019). The observations consist of 23 different MUSE pointings with one hour of exposure time, of which 21 form a contiguous area in a 3×7 mosaic, and the remaining two are located in a region $\approx 5 \text{ arcmin}$ apart. The data acquisition was carried out under fair observational conditions with a median seeing of 1.10 arcsec , from the DIMM station measurements, and $\approx 17\%$ of the exposures have seeing higher than 1.5 arcsec . The field of view was chosen in order to overlap with deep HST imaging from the CANDELS/COSMOS survey (Grogin et al. 2011; Koekemoer et al. 2011), maximizing the amount of photometric information we have on our objects. Additional MUSE pointings from different GO and GTO programs overlapping with the SMUVS field are publicly available. However, we do not consider them here as our aim was to work with a data set of homogeneous depth for the sake of clarity in our results and conclusions.

We retrieved the MUSE raw exposures and calibration files from the ESO archive and used the standard reduction pipeline version 2.0.3 (Weilbacher et al. 2006, 2012, 2014) in combination with the MUSE Python Data Analysis Framework (MPDAF version 2.3, Bacon et al. 2016; Piqueras et al.

Figure 2.1: Histogram of the V-band magnitudes assigned by SMUVS to our MUSE detected sources. The peak of the distribution shows the magnitude after which the number counts of MUSE drop significantly.

2017) and the Zurich Atmosphere Purge (ZAP version 2.1, Soto et al. 2016) to create the final data cubes.

Finally, we corrected the WCS coordinates by using SExtractor to identify the centroids of the brighter objects in the MUSE white images and the CANDELS HST F160W image. We verified that MUSE shows an average offset with respect to HST of $0.141''$ with standard deviation $0.110''$, while the offset with the reported SMUVS coordinates is $0.196 \pm 0.123''$. We corrected the MUSE coordinates taking the HST centroids as reference and note that the offsets between the different catalogs are always smaller than the MUSE pixel scale (0.2 arcsec).

2.3 RESULTS

2.3.1 SMUVS sources in the MUSE/COSMOS GTO fields

We searched for detections of the SMUVS sources in the 20.79 arcmin^2 covered by the MUSE datacubes, and measure their redshifts from emission

Figure 2.2: *Upper panel:* Redshift distribution of our sample of SMUVS/MUSE sources with spectral $QF \geq 2$ in blue. These objects constitute $\sim 66.5\%$ of the 1038 SMUVS objects identified with MUSE, and $\sim 23\%$ of all the SMUVS objects in the COSMOS/MUSE GTO field. The distribution of all the SMUVS redshifts in our MUSE fields is drawn in red and renormalized to the number of MUSE sources detected with $QF \geq 2$. *Lower panel:* Distribution of spectral QF for the 1038 MUSE detected sources. The dashed line indicates the boundary between a secure and an uncertain redshift measurement. Quality flag 0 was assigned to all galactic stars, independently of their actual spectral quality.

Table 2.1: SMUVS high-redshift ($z \geq 2$) sources identified in the COSMOS/MUSE GTO field. The SMUVS ID, position on the sky, measured spectroscopic redshift, and quality flags are listed.

Obj. ID	RA	Dec	z_{spec}	QF
73023	150.1778406	2.1941108	3.8686	2
73055	150.1044581	2.1943565	3.7710	9
73162	150.1868076	2.1950781	4.4239	9
73174	150.1807239	2.1949942	3.3375	3
73452	150.0935903	2.1970951	3.0377	3
73503	150.1657897	2.1971041	3.2774	9
73761 ¹	150.0973771	2.1988546	3.0747	3
73993	150.1835347	2.2011801	3.2854	9
74055	150.1698170	2.2012076	3.1317	9
74237	150.1139483	2.2015449	3.4416	9
74717	150.1050908	2.2068064	3.6090	9
74990	150.0925832	2.2078347	3.5265	3
75041	150.1815360	2.2085007	4.4443	3
75190	150.1038713	2.2103898	3.2407	9
75249	150.1209257	2.2102457	3.2212	9
75267	150.1876116	2.2097678	2.4796	2
75288	150.1393225	2.2109674	5.2944	3
75461	150.1469868	2.2122848	3.4608	3
75570	150.1181685	2.2128694	3.0031	9
75825	150.1249549	2.2145933	5.9886	3
76037	150.1601037	2.2163066	3.0060	3
76038	150.0944809	2.2157858	3.3990	9
76101	150.1703151	2.2160544	3.5259	3
76321	150.1410657	2.2179212	3.9089	3
76802	150.1064151	2.2215919	6.3044	9
76829	150.1926599	2.2198279	3.0900	3
76877	150.1659591	2.2216971	3.0913	3
77599	150.1563335	2.2255982	3.1819	3
77637	150.1334882	2.2276703	4.1650	3
78106	150.1175785	2.2315227	2.9722	3
78164	150.1058933	2.2303365	3.0097	3
78359	150.1800388	2.2312780	2.1458	3
78448	150.1866714	2.2319585	2.1723	2
78588	150.1167228	2.2351184	3.8206	9
78635	150.0881948	2.2344639	3.4881	3
78718	150.1097010	2.2362429	3.7711	3
90896	150.1160814	2.3273753	3.2644	9
91354	150.1226590	2.3311551	3.0957	9
91380	150.1274174	2.3309118	4.4672	9

¹ $z_{MOSFIRE} = 3.0768$ (Kriek et al. 2015).

and/or absorption lines in their spectra. We consider a SMUVS counterpart detected in MUSE when the MUSE emission arises within $1''$ from the SMUVS source centroid. Furthermore, we use HST images from CANDELS to verify possible contamination from nearby sources. We find that the MUSE emission can always be univocally assigned to one source, and we discuss the implications of source contamination on the photometry of our sample in more detail in Sect. 2.3.3.

As explained above, the advantage of analyzing the MUSE data with respect to any other spectroscopic data set in COSMOS is that MUSE does not require a source pre-selection, and thus the identification completeness is solely governed by the spectroscopic depth. Figure 2.1 shows that if we translate the depth to a V-band magnitude, the number counts in the MUSE pointings start to drop significantly after a magnitude of ~ 24.75 . We consider this limiting magnitude to compare the depth of the MUSE pointings to the depth of the SMUVS survey.

Out of 2997 SMUVS objects present in the area covered by MUSE, we managed to successfully identify 1038 objects spectroscopically. All redshifts have been measured and agreed upon by two independent observers, following the work philosophy adopted in, for example, the zCOSMOS spectroscopic survey (Lilly et al. 2007).

Also similarly to zCOSMOS, we classify the quality of our spectra by applying the following quality flags (QFs):

- -99: non-detection;
- 0: galactic stars, independently of the spectral quality;
- 1: redshift measurement is only tentative;
- 2: relatively secure redshift measurement, with the spectrum showing faint line(s) and/or a continuum, for which the redshift is likely to be correct;
- 3: very secure redshift measurement, typically based on more than one emission line and/or a clear continuum with absorption lines;
- 4: text-book spectrum with emission and absorption lines, and a very clear continuum;
- 9: redshift based on a single but clearly detected emission line, for which we are unsure about its identification. In these cases, a few alternative spectroscopic redshift values are possible for the source.

The MUSE detection rate for the whole SMUVS sample is $\sim 35\%$ ($=1038/2997$), considering all detections regardless of their QF. Among these objects, a total of 691 have a spectroscopic redshift measurement with $\text{QF} \geq 2$, i.e., $\sim 23\%$ of all the SMUVS sample in the COSMOS/MUSE GTO field, with the following distribution: 49 galaxies have $\text{QF}=2$; 486 have $\text{QF}=3$; 25 have $\text{QF}=4$; and 131 are classified with $\text{QF}=9$, as shown in

the lower panel of Fig. 2.2. Furthermore, we also detected 41 stars ($QF=0$) and 306 galaxies for which the MUSE data quality is not good enough to constrain the redshift of the object with a high enough confidence level ($QF=1$). The remaining 1959 SMUVS objects are non-detections in MUSE.

The upper panel of Fig. 2.2 shows the redshift distribution of our SMUVS/MUSE sources in blue and the z_{phot} distribution of all the SMUVS sources in the COSMOS/GTO field in red. The SMUVS histogram has been renormalized to match the SMUVS/MUSE sample numbers. As is evident, most of the SMUVS/MUSE detections are located at low redshifts with two overdensities at $z \sim 0.7$ and $z \sim 0.9$, which belong to previously identified large-scale structures in the COSMOS field (Le Fèvre et al. 2005; Kovač et al. 2010). Since the MUSE data is shallow, it is natural that we only see the brighter sources at higher redshifts. We can also see that the MUSE detections clearly identify the overdensities, and favor redshifts where strong emission lines are present in the MUSE wavelength range (i.e., [OII] between ~ 0.2 and ~ 1.4 and $\text{Ly}\alpha$ above $z = 2.9$). This is in contrast with the photometric redshift distribution, whose intrinsic dispersion smooths out the peaks, making it less suitable to identify preferential redshifts.

Among the SMUVS sources with MUSE $QF \geq 2$ there are 39 with spectroscopic redshift $z_{\text{spec}} \geq 2$. These include three sources in the redshift range $2 \leq z < 3$ and 36 with redshifts $z \geq 3$. The $2 \leq z < 3$ sources consist of two bright galaxies with absorption lines and one AGN with broad CIV and [CIII] emission; the $z \geq 3$ sources are prominent $\text{Ly}\alpha$ emitters. If we compare the blue and red histograms in Fig. 2.2, we can see that the MUSE incidence is comparable to SMUVS until $z > 4$. For the higher redshift, it is the SMUVS relative incidence that is more pronounced.

At $1.5 \lesssim z \lesssim 3$ the number of identified SMUVS/MUSE objects is drastically lower than at higher redshifts. This is known as the “redshift desert,” where no strong nebular emission line falls into the wavelength range covered by MUSE, and thus makes detection particularly difficult. This is clearly illustrated if we look at the number of sources identified in SMUVS in the same redshift range (see red histogram in Fig. 2.2).

Table 2.1 shows the results of our redshift measurements for our high-redshift ($z_{\text{spec}} \geq 2$) sample. We list the SMUVS ID and position of the objects, as well as the spectroscopic redshifts measured and the quality flag assigned to their spectra. There are three sources with $QF = 2$, additional 20 sources with $QF = 3$, and 16 sources with $QF = 9$. For some of the latter, the ambiguity in the single emission line identification could be solved via the available photometric redshifts of these sources (Deshmukh et al. 2018), as will be discussed in Sect. 2.3.3. We also note that one of our objects (no. 73761) has a previous spectroscopic redshift identification obtained

with MOSFIRE on the Keck Telescope (Kriek et al. 2015), and that our own redshift is in good agreement with this previous value ($z_{\text{MOSFIRE}} = 3.0768$). All the remaining spectroscopic redshifts listed here are new (i.e. they are not present in the existing spectroscopic catalogs for the COSMOS field).

2.3.2 MUSE spectra

We focused our attention on the spectra of the 39 galaxies that have $z_{\text{spec}} \geq 2.0$. We separated the Ly α emitters from absorption line galaxies and AGNs, ending up with 36 sources at $z \gtrsim 3$ and 3 sources at redshift $2 \leq z \leq 3$, as described above.

2.3.2.1 Lyman- α emitters

We extracted the spectra of our Ly α emitters by identifying the extended area of the line emission. This area is defined by the pixels that have a signal-to-noise ratio higher than three. In order to account for the instrument PSF, we also required a minimum area of 50 pixels. We then added the flux from the single pixels in the area of emission. Finally, we fitted one or two Gaussians to the obtained spectrum and measured the observed flux of the line.

Table 2.2 contains our line flux measurements, along with the luminosity of the Ly α line derived using the flux and the redshift measured for our objects. We measured the line flux by fitting our data with a number of Gaussians depending on the line profile shown in the spectrum. We then integrated the Gaussians in the wavelength interval containing the line to get the value of the flux reported in Table 2.2. The mean signal-to-noise ratio of our lines is ~ 9.3 , with values spanning from 2.5 to 30. The luminosities we measured are on the order of $10^{42} - 10^{43} \text{ erg s}^{-1}$, in line with the values published for MUSE-Wide data in other fields (Herenz et al. 2017, 2019).

Finally, we note that three different line profiles can be identified in our sample: a single-line profile, where the emission appears mostly symmetric; a blue bump profile, where in addition to the main more intense line a secondary peak in the blue is visible; and a red tail profile, where the emission is either asymmetric with an extended tail in the red part of the spectrum or presents a secondary peak in the red. Figure 2.7 shows the zoomed-in region of the spectra in the Ly α wavelength range. The plots in the figure also show that we cannot detect a continuum level in our data, thus we are not able to recognize P Cygni profiles, even if they are commonly observed for low-redshift objects. For the three profiles that we

Table 2.2: Measured Ly α fluxes and luminosities for our SMUVS/MUSE sources. The ID, center of the main and the secondary peak, the measured flux from the fit, and the Ly α luminosity are reported.

SMUVS ID no.	Line Center (Main) [Å]	Line Center (Sec.) [Å]	F _{fit} [10 ⁻¹⁸ erg s ⁻¹ cm ⁻²]	L _{fit} [10 ⁴² erg s ⁻¹]
73023	5917.9 ± 0.6	5920.4 ± 1.6	34.98 ± 4.98	5.18 ± 0.74
73055	5799.2 ± 0.5	-	13.42 ± 2.03	1.87 ± 0.28
73162	6594.1 ± 0.2	-	7.27 ± 0.85	1.48 ± 0.17
73174	5272.9 ± 0.2	-	37.46 ± 2.67	3.89 ± 0.28
73452	4909.5 ± 0.2	-	49.81 ± 3.57	4.13 ± 0.30
73503	5201.2 ± 0.6	5192.7 ± 0.8	46.32 ± 5.21	4.61 ± 0.52
73761	4958.2 ± 0.2	4950.0 ± 0.2	240.86 ± 8.01	20.56 ± 0.68
73993	5210.7 ± 0.6	-	13.76 ± 2.33	1.38 ± 0.23
74055	5024.1 ± 0.6	-	16.10 ± 3.02	1.44 ± 0.27
74237	5399.2 ± 0.4	5405.9 ± 0.6	32.37 ± 3.42	3.62 ± 0.38
74717	5604.2 ± 0.4	-	18.93 ± 2.78	2.37 ± 0.35
74990	5508.9 ± 0.2	-	46.55 ± 3.94	5.52 ± 0.47
75041	6618.6 ± 0.3	6610.5 ± 0.8, 6623.4 ± 3.9	17.11 ± 3.32	3.52 ± 0.68
75190	5156.4 ± 0.5	5145.2 ± 0.8	37.35 ± 5.16	3.61 ± 0.50
75249	5131.0 ± 1.0	-	17.94 ± 3.65	1.71 ± 0.35
75288	7652.2 ± 0.9	7656.8 ± 2.0	22.52 ± 4.55	7.00 ± 1.42
75461	5422.0 ± 0.3	5423.5 ± 1.1	21.55 ± 3.29	2.44 ± 0.37
75570	4866.6 ± 0.2	-	68.61 ± 4.62	5.53 ± 0.37
75825	8495.8 ± 0.2	8500.2 ± 0.3	43.01 ± 3.23	17.82 ± 1.34
76037	4868.8 ± 0.5	4873.1 ± 3.9	26.42 ± 10.52	2.13 ± 0.85
76038	5347.7 ± 0.8	-	16.98 ± 2.96	1.85 ± 0.32
76101	5501.9 ± 0.3	-	11.91 ± 1.58	1.41 ± 0.19
76321	5967.2 ± 0.2	5971.0 ± 2.4	50.53 ± 8.81	7.67 ± 1.34
76802	8879.8 ± 0.3	-	24.76 ± 3.13	11.56 ± 1.46
76829	4968.7 ± 0.5	4975.9 ± 0.9	32.19 ± 4.05	2.78 ± 0.35
76877	4973.4 ± 0.3	-	35.59 ± 3.44	3.08 ± 0.30
77599	5083.7 ± 0.2	-	64.82 ± 6.18	6.01 ± 0.57
77637	6278.8 ± 0.3	6284.5 ± 2.1	26.72 ± 3.46	4.71 ± 0.61
78106	4829.3 ± 0.2	-	48.94 ± 4.58	3.85 ± 0.36
78164	4875.8 ± 0.3	4883.2 ± 0.7	59.26 ± 6.23	4.80 ± 0.50
78588	5861.3 ± 0.7	5864.3 ± 1.2	39.44 ± 8.04	5.66 ± 1.15
78635	5456.2 ± 0.2	-	70.35 ± 4.68	8.13 ± 0.54
78718	5800.5 ± 0.2	-	121.65 ± 7.48	16.94 ± 1.04
90896	5185.3 ± 0.7	-	24.07 ± 3.85	2.37 ± 0.38
91354	4979.2 ± 0.2	4972.6 ± 0.4	40.92 ± 3.37	3.55 ± 0.29
91380	6646.6 ± 0.5	-	38.46 ± 4.09	8.02 ± 0.85

recognize, we report the following statistics. Out of 36 objects, 17 show a single-line profile ($\sim 47\%$), 7 show a blue bump ($\sim 19\%$), 11 show a red tail ($\sim 31\%$), and 1 shows both a blue bump and a red tail ($\sim 3\%$).

The different profiles are caused by the condition and state of the medium in and around the galaxy. For example, a narrow single line can be caused by a reduced amount of scattering for the Ly α photons due to a low hydrogen column density. The blue bump can be caused either by re-emission by the medium of blueshifted Ly α photons or by a strong absorption at the resonant wavelength, leaving only the red tail and a fraction of the original emission. Finally, the red tail can give us information on the offset velocity of the medium, its optical depth, and the hydrogen column density. Radiative transfer models like the ones by Verhamme et al. (2008) or the more recent ones by Gronke (2017) can help disentangle the state of the gas and dust around the emitting galaxy. Applying such models is, however, outside of the scope of this paper, mainly due to the high noise in our spectra, and is left for follow-up studies.

2.3.2.2 SMUVS/MUSE sources at $2 \leq z \leq 3$

In addition to the 36 Ly α emitters, we identified 3 other high-redshift objects in the range $2 \leq z \leq 3$. Object 75267 is an absorption line galaxy at redshift $z = 2.4796$, classified as a QF = 2 spectrum. We report seeing the CIV doublet in absorption. Object 78359 is classified as a QF = 3 AGN at redshift $z = 2.1458$ with broad-line emission of both [CIII] and CIV indicating the AGN activity. And finally, object 78448 is a galaxy at redshift $z = 2.1723$ with QF = 2 emitting CIII and with possible FeII absorptions.

2.3.3 Physical properties of the SMUVS MUSE galaxies inferred from broadband photometry

We investigate the distribution of properties derived from SED fitting for our sample. Since the physical properties of each object are derived from SMUVS photometry by fitting its SED, we first need to check whether the redshift measured with MUSE matches the photometric redshifts originally derived by Deshmukh et al. (2018).

Out of the 691 SMUVS/MUSE sources for which we measured spectroscopic redshifts with high confidence, we find that 624 sources have a redshift compatible with the photometric value, while 62 are outliers. To define outliers we follow the same definition used by Deshmukh et al.

(2018), i.e.,

$$\sigma_z = \frac{|z_{\text{spec}} - z_{\text{phot}}|}{(1 + z_{\text{spec}})} > 0.15, \quad (2.1)$$

where z_{spec} is our spectroscopic redshift, while z_{phot} is the photometric redshift of the SMUVS catalog.

Here we find a percentage of outliers of $\sim 10\%$, which is somewhat larger than was found in Deshmukh et al. (2018) when comparing all their photometric redshifts with the available COSMOS spectroscopic redshifts, over the whole SMUVS/COSMOS area (the outlier fraction there was 5.5%). This difference is perhaps not surprising, given that there is no source pre-selection in MUSE, while spectra taken with all other spectrographs are preferentially available for bright sources (for which the photometry has a higher signal-to-noise ratio, and thus the photometric analysis is more likely to yield good redshifts). In any case, it is reassuring that the percentage of redshift outliers that we obtain here is still reasonably low.

Before considering the SED fitting properties of our galaxies, we investigated the reason of the redshift discrepancies among the outliers. We focused on the $z \geq 2$ sources, which are the main interest here. Among the 39 high-redshift sources, we found 24 for which the photometric and spectroscopic redshifts are in good agreement. We analyzed the remaining 15 cases on an individual basis, in order to understand whether there is any problem in the spectroscopic and/or photometric analysis, or whether the SMUVS/MUSE sources matching is correct. For eight of the outliers we found that the photometry is contaminated by a brighter neighbor; for the other seven we found no apparent photometric contamination. The redshift discrepancy is produced by either the galaxy being fainter than the limiting magnitude of the survey (four cases) or the SMUVS detection actually being two unresolved, separate sources (three cases). In the first situation the photometry of the source is likely unreliable in some bands and in the second case both sources influence the values measured in the photometry, but only one of them emits Ly α and is detected in MUSE. In both cases the photometric fit results in lower z_{phot} in comparison to the z_{spec} .

As the next step, we redid the SED fitting of our high-redshift galaxies with uncontaminated photometry, fixing their redshifts to the MUSE-based spectroscopic value. We used the code LePhare¹ (Arnouts et al. 1999; Ilbert et al. 2006), with the same template family and parameter values as in Deshmukh et al. (2018), and considered the same SMUVS 28-band input

¹<http://www.cfht.hawaii.edu/~arnouts/lephare.html>

Table 2.3: Table showing the results of all the KS tests performed in this work.

Test performed on	p-values for		
	SMUVS/... MUSE vs notMUSE original	mass matched	SMUVS/MUSE vs MUSE/NS
Age	0.43	3.5×10^{-2}	-
Extinction	0.61	2.3×10^{-6}	-
Stellar Mass	0.08	0.997	-
Redshift	0.12	-	0.02
$L_{\text{Ly}\alpha}$	-	-	1.5×10^{-3}
$F_{\text{Ly}\alpha}$	-	-	4×10^{-6}

catalog. We then reran LePhare with fixed redshifts also on the sources that did not show a severe contamination, and found that six of them could be recovered. We thus obtained a final sample of 30 sources (instead of the previous 24) with physical properties derived from photometry, 28 of which are MUSE Ly α emitters.

We see that the SMUVS/MUSE sources have extinction values between $0.0 \leq E(B - V) \leq 0.3$, with $\sim 70\%$ having $E(B - V) \leq 0.1$, as we would expect from systems that show prominent Ly α lines. Nonetheless, there are still sources that have higher extinctions ($0.2 \leq E(B-V) \leq 0.3$), hinting at an even higher unattenuated Ly α luminosity in those cases. The stellar mass range covered by our sources is from $\sim 1.5 \times 10^8 M_\odot$ to $\sim 7 \times 10^{11} M_\odot$, with a mean value of $\sim 10^9 M_\odot$. Finally, we see that our objects have ages ranging from 10 Myrs to 2 Gyrs.

In the next subsection we compare the distribution of the derived SED properties for the Ly α emitters and other SMUVS sources with $z \geq 2.9$ (see also Fig. 2.3).

2.3.4 Comparison of SED properties for SMUVS galaxies with and without MUSE identification

We compare the derived SED properties of the SMUVS $z > 2.9$ sources identified with MUSE (i.e., those with a spectroscopic redshift measurement with $\text{QF} \geq 2$) with those of the SMUVS $z \gtrsim 2.9$ galaxies that are not MUSE-detected, in the same field. Our aim is to investigate whether there are significant differences in these properties, in particular to understand whether the most prominent Ly α emitters at $z > 3$ are characterized by

2.3.4. Comparison of SED properties for SMUVS galaxies with and without MUSE identification

Figure 2.3: Histogram of the three main properties (age, extinction, and stellar mass) derived from the SMUVS photometry and the redshifts measured by MUSE. We compare our sample of 28 $\text{Ly}\alpha$ emitters to the SMUVS sample of complementary high- z objects (218 galaxies).

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Figure 2.4: Redshift cut and new stellar mass distribution due to the cut as they were before the mass matching in the upper panels. The mass matched histograms of the extinction $E(B-V)$ and the age derived from the SMUVS photometry for 23 SMUVS/MUSE and 146 SMUVS/notMUSE sources in the redshift range $3 \leq z \leq 4$ are shown in the lower panels.

2.3.4. Comparison of SED properties for SMUVS galaxies with and without MUSE identification

special values in their physical properties (stellar mass, star formation histories, dust extinction, etc.).

Prior to comparing the SED properties of our objects, we tested whether SMUVS/MUSE and SMUVS/notMUSE galaxies come from the same parent absolute-magnitude distribution. The sample of galaxies we consider is 218 SMUVS galaxies with redshift $2.9 \lesssim z_{phot} \lesssim 7$ and the 28 MUSE Ly α emitters for which our spectroscopic redshifts and the SMUVS photometric redshift estimates are in good agreement (as defined in Section 2.3.3). The comparison is performed on all 28 photometric bands available to SMUVS separately. We performed a Kolmogorov-Smirnov (KS) test on the statistics of the absolute magnitudes derived with LePhare for our two samples. The results of these tests are that the D parameter assumes values $\lesssim 0.25$ over all the bands tested, and the p-value is always ≥ 0.08 . This indicates that our SMUVS high-redshift MUSE-detected and non-detected sources show no statistically significant difference.

To test whether the sample size can influence the outcome of the test, we reduced the SMUVS sample randomly 10,000 times to subsamples containing an average of 40 objects. The KS test is then performed on these smaller samples and the results are compared to the test on the whole SMUVS sample by means of their statistics. We conclude that sample size does not matter statistically in our case.

Figure 2.3 shows the distribution of the physical properties of our two samples derived from the SED fit. As can be expected, the redshift distribution of both samples is biased towards lower redshifts in the range $2.9 \leq z < 6.6$ covered by MUSE. The distribution of the stellar mass for our SMUVS/MUSE sample is between $8 < \log_{10}(M_*) < 11$, with a peak at $\sim 10^{9.5} M_\odot$. This sample is also mostly composed of galaxies with little dust content. Nevertheless, some of our objects have $E(B - V) > 0.25$ and are still visible as Ly α emitters. Unless the emission is seen through a gap in the dust distribution, this would make them extremely bright in Ly α to overcome such higher values of dust extinction and still be visible. Finally, the age distribution exhibits a bimodality, either classifying our galaxies as very young ($\lesssim 100$ Myr) or ~ 1 Gyr old. We comment further on this feature in the next subsection. Figure 2.3 confirms our previous analysis on the input photometric bands used in SMUVS: The distribution of the properties of the SMUVS/MUSE and SMUVS/notMUSE sample are not statistically different.

After we performed a KS test on the physical properties, we concluded that, compared to the SMUVS/notMUSE sample, the spectroscopically detected galaxies generally have lower dust extinction, about the same mass and age distributions, and fewer objects are detected in higher redshift

regimes ($4 \leq z \leq 6.6$), but we see no significant statistical difference in any of the properties. The individual results of our KS tests can be seen in Table 2.3.

To further test the distribution of the physical properties in both samples, we constructed Fig. 2.4. We restricted ourselves to analyzing galaxies in the redshift range $\sim (3, 4)$, to limit the effect of galaxy evolution with redshift and because most of the SMUVS/MUSE objects lie in that range. We then also stellar mass matched the SMUVS/notMUSE galaxies to SMUVS/MUSE. The redshift cut applies to all the panels, while the mass matching is shown only for the extinction and the ages. We can see how the age distribution appears very similar in the two samples and how the distribution of redshift and masses do not deviate much from what we saw in Fig. 2.3, before the redshift cut was applied. The interesting panel is the one showing the extinction. We can see now how applying a cut in redshift and stellar mass matching the SMUVS/notMUSE sample reveals a slight difference in the distribution. SMUVS/MUSE shows preferentially lower extinctions compared to SMUVS/notMUSE, which deviates from $E(B-V) > 0.2$ onward and drives the difference. Again, the results of a formal KS test can be seen in Table 2.3.

2.3.4.1 Further study of the age bimodality

We study the implications of an age bimodality in our MUSE-detected SMUVS sample by comparing the stellar mass–age and $E(B-V)$ –age relations of SMUVS/MUSE to the relations found in SMUVS/notMUSE (see Fig. 2.5). We can see, as is expected from the current view on galaxy evolution, that the younger objects tend to be less massive than the older objects and that they are in general more obscured than older objects. We associate these characteristics with the fact that the younger galaxies in our sample are currently experiencing their first star formation event. The older objects in contrast have already formed the bulk of their stars, and thus show older populations and have less dust in their surroundings.

We notice however that all SMUVS/MUSE objects are detected in $\text{Ly}\alpha$ emission and so we expect them to be actively star-forming. We argue that the star formation that we see in the older objects is not part of the first event, but a separated second episode of star formation. To test this, we generated the lower plots in Fig. 2.5. We compare the SFR obtained if we assume a continuous star formation throughout the lifetime of our objects and the lower limit of the SFR given by the $\text{Ly}\alpha$ emission we detect. The first value is obtained by dividing the stellar mass given by the SED fit with the age of the galaxy and represents the average of the SFR. The second

2.3.4. Comparison of SED properties for SMUVS galaxies with and without MUSE identification

Figure 2.5: *Upper panels:* Mass–age relation on the left and E(B-V)–age relation on the right for both our SMUVS detected samples. Here, SMUVS/MUSE is represented in red, while SMUVS/notMUSE is plotted in gray. We see that the older objects are generally more massive and that the younger objects experience generally more extinction than older objects. *Lower panels:* Test of the lower limit of the instantaneous SFR derived from our Ly α flux measurements against an average star formation rate obtained by dividing the stellar mass by the age of the galaxy obtained from the SED fit. We see on the left that the higher SFR is associated with intermediate-mass objects, and on the right that older objects have a higher SFR than what would be expected if they had continuously formed stars in one single episode. The gray line in the plots indicates where the ratio between SFRs is unity. The error bars shown in the plots are representative of the average errors on the galactic properties.

value is obtained by applying the conversion $L_{H\alpha} = L_{Ly\alpha} * \frac{1}{8.7}$, which gives us a lower limit for the luminosity in the $H\alpha$ line and for which we chose to use the $Ly\alpha$ - $H\alpha$ conversion factor by Hu et al. (1998). We then use the Kennicutt (1998) equation to obtain the SFR from the $H\alpha$ luminosity to obtain the lower limit of the instantaneous SFR.

By comparing these two values we can qualitatively say whether a galaxy is consistent with a monotonically declining star formation history ($SFR_{\text{instant}}/SFR_{\text{average}} \leq 1$) or if a second star formation episode is needed to explain the SFR ($SFR_{\text{instant}}/SFR_{\text{average}} > 1$). We see that galaxies that are experiencing a second event are intermediate-mass objects ($9 \lesssim \log_{10}(M_*) \leq 10$) and are exclusively old. We argue that the main component of the stellar population has formed in early times with the first star formation event and is what the SMUVS photometry detects, while the new stars being formed are detected by MUSE. We conclude that these objects are probably experiencing a rejuvenation event, and that their star formation restarted after the stellar bulk was formed, about 1 Gyr before the time we observe them.

2.3.5 Additional MUSE high-redshift sources not present in SMUVS

Additionally to the $Ly\alpha$ emitters in the SMUVS/MUSE sample, we also performed a blind search in the MUSE cubes and found 66 other sources presenting a secure or possible $Ly\alpha$ emission ($QF = 2, 3$, and 9). These new sources (hereafter MUSE/NS) have been identified by visually inspecting the MUSE data cubes, and do not have a previous spectroscopic confirmation. We also verified that, in the specific framework of our analysis, performing an automated search in our cubes (i.e., by using the software LSDCat, Herenz & Wisotzki 2017) rather than a visual one would not add new sources to our secure detections ($QF > 1$). Since the MUSE/NS sample is not present in the SMUVS catalog, we have information on the redshift and measurements of the $Ly\alpha$ flux and luminosity, but no estimate of the physical properties of these objects from SED fitting. The MUSE/NS sources and all their related quantities are listed in Table 2.5.

To test whether these objects belong to a different population from the galaxies selected in SMUVS, we verified that none of these new sources was situated in masked areas of the survey. In fact, 61 of them were never selected for the catalog to begin with and 5 have a SMUVS neighbor within $1''$, but are clearly different objects. Since the SMUVS galaxies were detected based on a prior selection in the UltraVISTA HK_s stacks, we

Figure 2.6: *Upper panel:* Comparison in redshift distribution between the SMUVS sources (red) and the sources identified in the Blind search (blue). *Left panel:* $\text{Ly}\alpha$ luminosity plotted as a function of redshift for our sources. The green circles identify the blue bump objects. *Right panel:* Histogram of the measured luminosities for both our samples. The blind search objects show slightly fainter luminosities compared to the SMUVS sources.

conclude that these MUSE/NS sources are faint in the HK_S stacks and/or in the images from the *Spitzer* $3.6\mu\text{m}$ and $4.5\mu\text{m}$ bands.

Given that the UltraVISTA images are deep, we can safely assume that the reason these objects are undetected is that they are below the mass limit of the survey. Even without having performed an SED fit, we can state that the MUSE/NS sample will likely have a very different mass distribution compared to the SMUVS/MUSE sample. This is likely the source of the discrepancies we find between the two populations. We put an upper limit on their stellar mass by citing the 50% completeness limit reported in Table 1 of Deshmukh et al. (2018). For galaxies in $3.0 \leq z \leq 4.0$ the upper limit mass is $\log_{10}(M_*/M_\odot) = 9.0$, for the range $4.0 < z \leq 5.0$ it is 9.2, and finally for galaxies with $5.0 < z \leq 6.0$ it is 9.4.

We measured the $\text{Ly}\alpha$ emission and luminosity for the MUSE/NS sample in the same way as we did for the SMUVS/MUSE sources. The first difference we noticed is that the number of blue bump profiles is strongly reduced compared to the SMUVS/MUSE sample (2/66 against 7/36, or $\sim 3\%$ against $\sim 19\%$). Furthermore, the single-line profile appears in 44 spectra, constituting $\sim 67\%$ of the sample, which makes it more prominent than in the SMUVS/MUSE sample, where it was observed $\sim 47\%$ of the time. Finally, the red tail profile appears in 20 of our galaxies and is about as frequent as in the SMUVS/MUSE sample (MUSE/NS $\sim 30\%$, SMUVS/MUSE $\sim 31\%$). If we compare SMUVS/MUSE to MUSE/NS, both in line flux and luminosity using a KS test, we see that their distributions are different and that MUSE/NS are the fainter objects. This confirms the fact that blue bump profiles are harder to detect, and thus the single-line profiles increase in number for the fainter sources. Further evidence for this interpretation is that the blue bump objects are found in the brighter objects located at $3 \leq z < 4$ of the SMUVS/MUSE (green circles in Fig. 2.6). The results of these KS tests can again be found in Table 2.3.

The right panel of Fig. 2.6 illustrates this trend by showing the distribution of $L_{\text{Ly}\alpha}$ for the two samples. We also plotted their distribution in redshift and how their luminosity evolves with it, in the upper and left panel of Fig. 2.6, respectively. We see in the central panel of Fig. 2.6 that for both samples the measured $\text{Ly}\alpha$ luminosity plotted against redshift increases with it, as can be expected given the detection limit on the line flux. More interestingly, the MUSE/NS sources seem to lie close enough in redshift space to the SMUVS/MUSE sources, suggesting they could belong to the same physical structure. To test if this is the case, we defined a Δz dependent on redshift, such that two objects with said distance in redshift lie 2 Mpc apart. We then expanded our check also to the position on the

Table 2.4: Table showing the position and redshift of the three secure associations identified via our method.

Association number	Obj-ID	RA	Dec	z
A1	NS67	150.1634469	2.210140164	3.8656
	NS92	150.1805399	2.235132627	3.8673
A2	76829	150.1926599	2.2198279	3.09
	76877	150.1659591	2.2216971	3.0913
A3	NS4	150.0902794	2.208985301	4.0681
	NS75	150.094679	2.230024846	4.0667

sky and defined a sphere of 2 Mpc radius as our criterion to check for associations.

We find that we can identify nine associations in the area covered by MUSE. If we restrict ourselves to only considering $QF = 3, 4$ objects, then the number of associations we find drops to three (see Table 2.4). We compared the number of associations we find with MUSE in our small area to the number of associations we could find in the part of the COSMOS field covered by SMUVS using spectroscopic confirmed objects currently known in the literature. We chose spectroscopic sources with $QF = 3, 4$ only and applied the same criteria used on the MUSE data to identify associations. We find 16 associations over the entirety of the SMUVS/COSMOS field. If we assume that the MUSE rate in our small area is indicative of what we could find if MUSE covered SMUVS/COSMOS entirely, then we would expect to find ~ 360 associations in this larger area. Unless cosmic variance is playing a big role in the area MUSE covered in our data, we estimate that MUSE has a $\sim 20\times$ higher chance of detecting objects that could be physically linked, confirming the usefulness of MUSE for unbiased source detection.

2.4 SUMMARY AND CONCLUSIONS

We made use of publicly available MUSE data in the COSMOS field to analyze a sample of 2997 photometrically selected galaxies from the SMUVS survey over an area of 20.79 arcmin^2 . We managed to detect and measure the redshift of 691 objects, of which 39 are located at $z \geq 2$. For these sources, we report two absorption line galaxies and one AGN in addition to 36 Lyman- α emitters. Of these 39 sources, all but 1 are new redshift measurements not previously present in the literature. Furthermore, we identify 66 additional Ly α emitters by performing a blind

search in the MUSE cubes. The values we measured for the Ly α flux and luminosity of our sources are in line with other works using MUSE pointings with similar depth and conditions (Herenz et al. 2017, 2019). We also detect three different line profiles in our combined Ly α sample, hinting at different medium conditions in and around our objects. A quantitative analysis of these features was, however, beyond the scope of this paper, whose goal was instead to investigate the differences in physical properties between the sources identified in the SMUVS catalog also detected in MUSE and those that could not be detected in MUSE.

The main result of our paper is to compare the physical properties of the SMUVS/MUSE and SMUVS/notMUSE sources. While there are some differences in the distribution of E(B-V), stellar mass, and age in the two samples, we find that their overall distribution does not vary substantially. We know that the SMUVS catalog is more sensitive to the brighter, more massive galaxies. MUSE instead has the only bias of being able to select objects that are at least bright enough in line emission to be detected. For $z > 2.9$ galaxies, this means they are bright Ly α emitters, intense star-forming objects with little dust attenuation/HI absorption. Not finding a significant difference in physical properties between our two samples, even after applying a redshift cut and mass matching them, could imply that the SMUVS selected Ly α emitters we observe in MUSE are similar to the general population in SMUVS. Although SMUVS is not the largest nor deepest survey in COSMOS, it is the Spitzer survey with the largest area for its depth (only shallower than CANDELS, which covers an area 12 times smaller in COSMOS). We can thus probe a sample of galaxies that is more complete in parameter space than ever before.

After mass matching our samples, we see that SMUVS/MUSE is less obscured than SMUVS/notMUSE. We also note how the age distribution of our Ly α emitters shows a bimodality. Both these results have been found in other studies where Ly α information has been combined with photometric SED fitting (Lai et al. 2008; Finkelstein et al. 2009; Pentericci et al. 2009). Furthermore, we deepened our study of the bimodality in the age of our sample by studying the SFR of our objects qualitatively. We find that the younger objects are most likely experiencing their first burst of star formation. The older objects in our sample show instead a lower limit to their instantaneous SFR, derived from their Ly α luminosity, that suggests they are undergoing a second burst of star formation, while the light of the galaxy is dominated by an older population of stars. This rejuvenation effect has also recently been observed in low-redshift objects by Angthopo et al. (2019) and Cooke et al. (2019).

We also compared the SMUVS/MUSE and MUSE/NS samples. Using MUSE data allowed us an unbiased detection of all the sources that are bright in $\text{Ly}\alpha$. We were able to perform a blind search in the MUSE cubes and enlarge our sample of $\text{Ly}\alpha$ emitters by a factor of ~ 3 . MUSE thus confirms its potential for systematic searches of a given area in the sky. This sensitivity to emission lines also allowed us to detect three secure and previously undiscovered physical galaxy associations.

What is puzzling, however, is that MUSE detects MUSE/NS objects at luminosities around $10^{42} \text{ erg s}^{-1}$ and below, but does not detect such lower luminosities for the SMUVS/MUSE sample (see right histogram in Fig. 2.6). We determined that the MUSE/NS sample lies most likely below the mass completeness limit of the SMUVS survey. We note, however, that the $\text{Ly}\alpha$ luminosities of the MUSE/NS sample have a significant overlap with the SMUVS/MUSE luminosities. Since the $\text{Ly}\alpha$ line intensity is linked to the ionizing radiation emitted and not the mass of the object, this overlap is not surprising. It does, however, point out that we cannot attribute the lack of lower luminosity SMUVS/MUSE objects to a simple scaling effect due to the mass-selection in SMUVS. At present we do not have a definitive solution for this issue.

The area of improvement in this study is the depth of the pointings. Longer exposure times could yield a higher detection rate for the SMUVS selected sources (to date about 2/3 could not be detected) and deep enough spectra to measure a continuum. This would allow us to more accurately investigate the line shapes (we could distinguish P Cygni profiles from single lines) and also measure equivalent widths for the brighter objects.

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²<http://www.astropy.org>

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Table 2.5: Blind search detected high-redshift ($z \geq 2.9$) Ly α emitting sources in the COSMOS/MUSE GTO field. As in Table 2.1, the ID, position on the sky, measured redshift, and quality flag are displayed. Also listed is the information on the Ly α flux and luminosity measurement. The labels on the line profile refer to the single peak (SP), blue bump (BB), or red tail (RT).

ObjID no.	RA	Dec	z_{spec}	QF	Line Center (Main) [Å]	Line Center (Sec.) [Å]	Line Profile [SP,BB,RT]	F_{fit} [10^{-18} erg s $^{-1}$ cm $^{-2}$]	L_{fit} [10^{42} erg s $^{-1}$]
N51	150.0956195	2.207896860	3.7137	2	5730.5 $\pm$ 0.3	-	SP	18.96 $\pm$ 1.83	2.55 $\pm$ 0.25
N52	150.0890289	2.202755060	4.0670	9	6160.0 $\pm$ 0.4	-	SP	13.39 $\pm$ 1.85	2.23 $\pm$ 0.31
N53	150.0902794	2.208985301	4.0681	3	6160.8 $\pm$ 0.3	6163.4 $\pm$ 0.9	RT	22.03 $\pm$ 2.25	3.67 $\pm$ 0.38
N54	150.1064723	2.205990995	3.1468	9	5042.2 $\pm$ 0.3	5035.3 $\pm$ 0.5	BB	14.57 $\pm$ 1.86	1.32 $\pm$ 0.17
N55	150.1263266	2.202361769	3.6407	3	5641.9 $\pm$ 0.4	5646.8 $\pm$ 2.1	RT	24.50 $\pm$ 5.05	3.13 $\pm$ 0.65
N56	150.1107880	2.196746174	4.9088	9	7182.3 $\pm$ 0.4	-	SP	15.64 $\pm$ 1.65	4.06 $\pm$ 0.43
N57	150.1271171	2.193819620	4.5575	3	6756.1 $\pm$ 0.3	6759.7 $\pm$ 0.9	RT	26.69 $\pm$ 2.32	5.82 $\pm$ 0.51
N58	150.1631312	2.200038868	3.1316	9	5022.0 $\pm$ 0.5	-	SP	13.49 $\pm$ 2.33	1.20 $\pm$ 0.21
N59	150.1611895	2.206540221	3.6455	9	5645.9 $\pm$ 0.3	5648.9 $\pm$ 1.1	RT	22.51 $\pm$ 3.12	2.89 $\pm$ 0.40
N60	150.1766375	2.200547905	3.1329	3	5024.4 $\pm$ 0.4	5026.9 $\pm$ 2.1	RT	37.82 $\pm$ 7.11	3.37 $\pm$ 0.63
N61	150.1804873	2.207906097	3.9656	2	6036.8 $\pm$ 0.2	-	SP	17.42 $\pm$ 1.30	2.74 $\pm$ 0.20
N62	150.1897355	2.204086497	4.0641	3	6156.4 $\pm$ 0.2	-	SP	23.91 $\pm$ 1.86	3.98 $\pm$ 0.31
N63	150.1819584	2.196144730	4.3955	9	6559.7 $\pm$ 0.4	6563.7 $\pm$ 3.8	RT	7.04 $\pm$ 3.56	1.41 $\pm$ 0.71
N64	150.1763508	2.194987214	4.4405	3	6612.7 $\pm$ 0.3	6615.4 $\pm$ 0.6	RT	12.50 $\pm$ 1.14	2.56 $\pm$ 0.23
N65	150.1871556	2.205024286	5.0682	2	7377.7 $\pm$ 0.3	-	SP	8.26 $\pm$ 1.17	2.32 $\pm$ 0.33
N66	150.1871556	2.205024286	5.0682	2	7377.7 $\pm$ 0.3	-	SP	8.26 $\pm$ 1.17	2.32 $\pm$ 0.33
N67	150.0900671	2.221593035	3.2476	3	5163.4 $\pm$ 0.5	-	SP	22.50 $\pm$ 2.82	2.19 $\pm$ 0.27
N68	150.0938165	2.212022447	3.3896	3	5336.1 $\pm$ 0.2	5338.3 $\pm$ 1.0	RT	36.35 $\pm$ 4.19	3.92 $\pm$ 0.45
N69	150.0967870	2.210240788	3.4315	9	5387.0 $\pm$ 1.2	5387.4 $\pm$ 0.3	RT	11.21 $\pm$ 2.80	1.24 $\pm$ 0.31
N70	150.0974611	2.210715291	3.7856	3	5818.2 $\pm$ 0.2	5823.5 $\pm$ 0.5	RT	42.11 $\pm$ 3.16	5.92 $\pm$ 0.44
N71	150.0859870	2.224398122	4.2863	3	6426.5 $\pm$ 0.2	-	SP	18.42 $\pm$ 1.40	3.48 $\pm$ 0.26
N72	150.0870797	2.216011780	4.9009	9	7172.5 $\pm$ 0.6	7177.7 $\pm$ 1.3	RT	8.61 $\pm$ 1.52	2.41 $\pm$ 0.43
N73	150.0868042	2.219972452	4.9027	9	7175.7 $\pm$ 0.4	-	SP	15.66 $\pm$ 1.53	4.06 $\pm$ 0.40
N74	150.0850979	2.213391448	5.0266	9	7324.7 $\pm$ 0.3	7327.8 $\pm$ 0.6	RT	18.20 $\pm$ 1.60	5.00 $\pm$ 0.44
N75	150.1027830	2.218819424	3.6257	9	5622.8 $\pm$ 0.2	-	SP	17.26 $\pm$ 2.44	2.19 $\pm$ 0.31
N76	150.1009535	2.213916903	3.8283	9	5870.8 $\pm$ 0.5	-	SP	22.61 $\pm$ 3.47	3.27 $\pm$ 0.50
N77	150.1045699	2.221037671	5.2998	2	7659.2 $\pm$ 0.3	7666.1 $\pm$ 2.8	RT	20.27 $\pm$ 3.15	6.31 $\pm$ 0.98
N78	150.1273378	2.214692674	3.0943	3	4977.4 $\pm$ 0.3	-	SP	33.23 $\pm$ 3.75	2.88 $\pm$ 0.33
N79	150.1282981	2.211522251	3.3210	9	5252.9 $\pm$ 0.4	-	SP	13.47 $\pm$ 2.13	1.38 $\pm$ 0.22
N80	150.1236488	2.221830819	4.2820	9	6420.5 $\pm$ 0.3	6425.5 $\pm$ 2.0	RT	10.05 $\pm$ 1.88	1.89 $\pm$ 0.35
N81	150.1311033	2.221893546	3.2790	9	5202.1 $\pm$ 0.2	-	SP	11.75 $\pm$ 1.37	1.17 $\pm$ 0.14
N82	150.1444920	2.210705671	4.1055	9	6206.9 $\pm$ 0.3	-	SP	10.56 $\pm$ 1.28	1.80 $\pm$ 0.22
N83	150.1331736	2.224723824	4.5402	9	6735.4 $\pm$ 0.3	6738.3 $\pm$ 0.9	RT	7.16 $\pm$ 1.42	1.55 $\pm$ 0.31
N84	150.1355132	2.212112631	5.4193	9	7804.4 $\pm$ 0.2	-	SP	6.95 $\pm$ 0.94	2.28 $\pm$ 0.31
N85	150.1442147	2.221428993	5.8863	9	8372.0 $\pm$ 0.3	-	SP	14.19 $\pm$ 1.30	5.65 $\pm$ 0.52
N86	150.1572317	2.209132493	3.8550	9	5901.6 $\pm$ 0.7	5902.4 $\pm$ 0.8	RT	18.30 $\pm$ 2.67	2.69 $\pm$ 0.39
N87	150.1720900	2.212290512	2.9695	3	4825.8 $\pm$ 0.2	-	SP	14.97 $\pm$ 1.80	1.17 $\pm$ 0.14
N88	150.1644704	2.214284122	3.0976	9	4981.4 $\pm$ 0.4	4985.1 $\pm$ 4.8	RT	14.44 $\pm$ 7.93	1.25 $\pm$ 0.69
N89	150.1617505	2.210353565	3.4902	9	5458.4 $\pm$ 0.5	-	SP	8.10 $\pm$ 1.59	0.94 $\pm$ 0.18
N90	150.1634469	2.210140164	3.8656	3	5914.6 $\pm$ 0.3	5919.6 $\pm$ 0.4	RT	16.96 $\pm$ 1.57	2.51 $\pm$ 0.23
N91	150.1674625	2.215432552	4.4342	9	6606.2 $\pm$ 0.8	-	SP	10.62 $\pm$ 1.67	2.17 $\pm$ 0.34
N92	150.1818099	2.215637886	5.2455	9	7592.6 $\pm$ 0.3	-	RT	25.86 $\pm$ 2.79	7.87 $\pm$ 0.85
N93	150.0847432	2.223357253	3.2413	3	5155.9 $\pm$ 0.2	5157.3 $\pm$ 1.1	RT	54.08 $\pm$ 4.63	5.24 $\pm$ 0.45
N94	150.0865742	2.227631189	3.4529	9	5413.2 $\pm$ 0.2	-	SP	14.23 $\pm$ 1.57	1.61 $\pm$ 0.18
N95	150.0946790	2.230024846	4.0667	3	6160.4 $\pm$ 0.3	-	SP	13.55 $\pm$ 1.50	2.26 $\pm$ 0.25
N96	150.0964429	2.229859080	5.7850	9	8249.5 $\pm$ 0.3	-	SP	8.59 $\pm$ 1.35	3.29 $\pm$ 0.52
N97	150.1131469	2.230677797	3.2805	9	5203.0 $\pm$ 0.5	-	SP	56.12 $\pm$ 6.08	5.60 $\pm$ 0.61
N98	...	...	...	...	...	...	...	...	...
N99	...	...	...	...	...	...	...	...	...
N100	...	...	...	...	...	...	...	...	...

2. BRIGHT LYMAN- α AMONG SMUVS GALAXIES

Figure 2.7: Zoomed-in image of the spectra of our MUSE/SMUVS Ly α emitters. The wavelength range is chosen so that the Ly α line is visible and centered in the plot. The fit is performed by extracting the spectrum from the MUSE data cube in the region where the Ly α emission is $\sim 3\sigma$ above the background or covers at least 50 pixels. The number of Gaussians used in the fit is determined after visual inspection of the shape of the spectrum and serves purely to measure the flux. All three line profiles are represented here.

2.4. SUMMARY AND CONCLUSIONS

Figure 2.8: Continuation of Fig. 2.7

2. BRIGHT LYMAN- α AMONG SMUVS GALAXIES

3. CONNECTING THE LYMAN- α PROFILE SHAPE TO THE PHYSICAL PROPERTIES OF $2.9 < z < 6.7$ STAR-FORMING GALAXIES

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We studied the shape of the Lyman- α ($\text{Ly}\alpha$) emission line in 144 $\text{Ly}\alpha$ emitters in the redshift range $2.9 \lesssim z \lesssim 6.6$, present in a small region of the COSMOS field and four CLASH lensing clusters covering a total area of $\sim 9 \text{ arcmin}^2$. All the data we analysed has been taken with the MUSE instrument, which provides an unbiased sample since no target pre-selection is required. The goal of this work is to investigate the existence of any relation between the $\text{Ly}\alpha$ emission-line profile type and the physical properties characterising the interstellar medium of the galaxies. For this purpose, we fitted our observed data using the “shell-model” spectra obtained with a radiative transfer code. We find that a symmetric single-peak $\text{Ly}\alpha$ emission tends to be associated with fainter sources surrounded by a low HI column density, while multi-peak profiles originate from a broader initial emission compared to the single-peak line. Multi-peak profile sources constitute 36% of our sample, which is in line with previous findings at high redshifts, as well as the high incidence of multi-peak $\text{Ly}\alpha$ line profiles among green-pea galaxies at low redshifts. Finally, $\sim 23\%$ of our sources exhibit low HI column densities ($\lesssim 10^{17} \text{ cm}^{-2}$), hinting at a possible LyC leakage.

3.1 INTRODUCTION

Many optical studies of the star formation processes occurring at high redshifts currently rely on the Lyman α ($\text{Ly}\alpha$) emission line. The presence of this line is a sign that a galaxy is undergoing a phase of prominent and (mostly) unobscured star formation activity. Dust and neutral hydrogen surrounding the galaxy can make studying this emission difficult, since the $\text{Ly}\alpha$ photons are easily scattered by the interstellar medium (ISM) and extinguished by dust when leaving their host. The kinematics of the gas also influence the intensity and line shape we can observe. Putting all these processes together we get an interesting, if a bit muddled, picture of what is happening in the universe at the first few billion years of cosmic time (Shapley et al. 2003; Dijkstra 2017; Hernán-Caballero et al. 2017; Karman et al. 2017; Vanzella et al. 2018; Marchi et al. 2019). A recent review on the state of the $\text{Ly}\alpha$ observations can be found in Ouchi et al. (2020).

Modeling the $\text{Ly}\alpha$ line profile is useful to investigate the physical conditions of the galaxy interstellar medium. Radiative transfer models allow us to replicate the conditions of the original emission and the surrounding shell of gas and dust. An early example are the models of Tenorio-Tagle et al. (1999) and Mas-Hesse et al. (2003) where the dynamical state of a simple shell of expanding gas is considered to justify the blue and red emission of the line. More recent models allow for specific quantities to be tested along with the expansion velocity of the shell, such as the hydrogen column density or the optical depth of the dust, thus giving a clearer picture of the medium surrounding the galaxy (Verhamme et al. 2008; Gronke 2017; Verhamme et al. 2018; Kakiichi & Gronke 2019).

It is important to analyze the shape of the profile not only because it gives information about the host galaxy and the medium surrounding it (Kulas et al. 2012; Yamada et al. 2012; Trainor et al. 2015; Leclercq et al. 2020), but also because it allows us to link studies of low and high- z $\text{Ly}\alpha$ emitters.

In recent years, it has been suggested that Green Pea galaxies (GPs) might be the low redshift analog of high redshift star forming galaxies (Henry et al. 2015; Yang et al. 2016; Kim et al. 2021). These studies found that the majority of GPs tend to have a multi-peak $\text{Ly}\alpha$ emission line, either with two comparable peaks or with a main and secondary peak (Henry et al. 2015; Yang et al. 2016, 2017). It is thus interesting to test whether a bigger sample of star-forming high redshift galaxies follows a similar trend in profile distribution.

We studied the profile shape of a significant high redshift sample of galaxies in Rosani et al. (2020, hereafter Rosani20) and found that the

majority of our profiles were single-peaks. We notice, however, that this classification was solely based on the visual inspection of the spectra. In the work we present here, instead, we complement our visual classification with the latest version of the shell-model fitting described in Gronke et al. (2015) in order to do a more quantitative analysis of the Ly α shape.

One instrument that has proven itself very effective in this field of study is the Multi Unit Spectroscopic Explorer spectrograph (MUSE, Bacon et al. 2010). MUSE is able to identify any source in its field of view (FOV) bright enough to be detected, without source pre-selection. As such, the instrument is uniquely qualified to study sources that are only detectable by line emission, such as objects at $2.9 \lesssim z \lesssim 6.6$ with a prominent Ly α line. This implies we can avoid potential biases stemming from a pre-selection process when compiling the source catalog.

Another powerful tool to study faint galaxies at high redshift is to make use of a lensing cluster as a magnifier of their emission (Bradley et al. 2014; Richard et al. 2014; Atek et al. 2014, 2015, 2018; Treu et al. 2015; Karman et al. 2015, 2017; Caminha et al. 2019; Erb et al. 2019). In combination with MUSE, lensing clusters have been shown to augment the number of detected objects by pushing the limit of detection towards lower luminosities and fluxes (de La Vieuville et al. 2019). Studies of lensed Ly α emitters have already yielded results on the luminosity distribution and the expected number density of these sources (Herenz et al. 2017; Richard et al. 2021), but a detailed statistical study of their emission profile shape has yet to be done. For this study we combine four CLASH-VLT (Postman et al. 2012; Rosati et al. 2014) lensing clusters: MACS J0329, J0416, J1206, and J1931 (Caminha et al. 2017b, 2019; Bergamini et al. 2021; Chen et al. 2021; Vanzella et al. 2021) with a MUSE pointing in the COSMOS field (Scoville et al. 2007) to gain access to a broader range of galaxy luminosities.

The scope of this paper is to analyze the incidence of specific Ly α profile shapes and we aim to investigate whether the Ly α line profile relates to other global galaxy properties. Furthermore, we also want to test whether a specific profile shape favors a configuration of physical properties both for the initial emission as for the model parameters.

In Section 3.2 we introduce the data we used, in Section 3.3 we describe our method and the models we used to fit our data, in Section 3.4 we outline our results and in Section 3.5 we summarize and draw our conclusions. Throughout this paper, we adopt a flat Λ CDM cosmology with $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.286$ and $\Omega_\Lambda = 0.714$.

3.2 DATA

In this paper we analyze publicly available MUSE (Bacon et al. 2010) observations to construct our data set. The pointings we are considering are targeting both a region of the COSMOS field (Scoville et al. 2007) and four lensing clusters in the Hubble Frontier Field (Koekemoer et al. 2014; Lotz et al. 2017) at different exposure times. Using MUSE allows us to capture all the information present in its 1 arcmin^2 FOV and so analyze a region of the sky without pre-selection. Furthermore, we chose different pointings on the sky with and without a lensing cluster to mitigate the influence of cosmic variance on our sample. The spatial resolution of our MUSE data is seeing limited and sampled with a pixel size of 0.2 arcsec , while the spectral coverage spans the interval $4750 - 9350 \text{ \AA}$ with a spectral bin of $1.25 \text{ \AA/pixel}$, translating into an average resolving power $R \approx 3000$ at $\lambda \sim 7500 \text{ \AA}$ and resolution of $\Delta\lambda \approx 2.4 \text{ \AA}$.

The exposures taken in the COSMOS field under the program ID 094.A-0487 (P.I.: M. Aravena) consist of 4 pointings arrayed in a square with overlaps on the edges located towards the center. Each pointing has an average exposure time of $\sim 5 \text{ h}$ with overheads. While the data was acquired under fair observational conditions, the passage of a satellite in ~ 2 out of 85 short exposures required us to remove the number of IFUs affected by the satellite, thus slightly lowering the depth of some areas. This field was chosen because VLA and ALMA observations reported a potential proto-cluster structure at $z \sim 5.3$.

The exposures related to our lensing cluster MACS J0416 have been taken in program IDs 0100.A-0763(A) (P.I.: E. Vanzella) and 094.A-0115B (P.I.: J. Richard) and consist of a single square of $\sim 1.23 \text{ arcmin}^{-2}$ area, situated in the North-East of the cluster and totaling an integrated exposure time of $\sim 17.1 \text{ h}$.

The data for MACS J1206 has been taken in GTO program IDs 095.A-0181(A) and 097.A-0269(A) (P.I.: J. Richard) and covers 3 pointings spanning an area of 2.63 arcmin^{-2} and an average depth of $\sim 4 \text{ h}$. One of the pointings is centered around the cluster's BCG, the other two are offset by $\sim 35''$ to the East and West, respectively.

The two lensing clusters MACS J0329 and MACS J1931 were taken with the program IDs 095.A-0525(A) and 096.A-0105(A) (P.I.: J.-P. Kneib) and constitute one single pointing for each cluster, spanning $\sim 1 \text{ arcmin}^{-2}$ and with a depth of $\sim 2.5 \text{ h}$.

We chose these four specific lensing clusters because they have similar redshifts (between 0.35 and 0.45) and so a comparable lensing strength as a function of background source redshifts. For more details on the data

reduction and source detection other than $\text{Ly}\alpha$ of these clusters, please refer to Caminha et al. (2017b, 2019); Bergamini et al. (2021); Chen et al. (2021) and Vanzella et al. (2021).

Finally, we used the standard reduction pipeline (Weilbacher et al. 2006, 2012, 2014) along with the MUSE Python Data Analysis Framework (Bacon et al. 2016; Piqueras et al. 2017) and the Zurich Atmosphere Purge (ZAP) (Soto et al. 2016) to create the final data cubes from the raw exposure and calibration files we retrieved on the ESO archive.

3.3 MUSE $\text{Ly}\alpha$ SPECTRAL ANALYSIS

We selected our $\text{Ly}\alpha$ emitter sample in the COSMOS field by searching for sources through visual inspection in our data cubes and then measuring their redshift based on prominent emission and absorption lines in the same way as described in Rosani20. We make the redshift catalog with these new sources available with this publication. For the lensing cluster pointings, we made use of the publicly available catalogs presented in Caminha et al. (2017b, 2019) and Vanzella et al. (2021). After we identified the $\text{Ly}\alpha$ emission sample, we extracted our spectra again by defining an area where the line emission was at least 3σ above the surrounding noise level. We do this to ensure that we collect all the light from our source and exclude background emission, which could have been contaminating our spectra had we used a circular extraction.

We then used a simple multi-gaussian fitting routine to define the amount of flux detected for each spectra. The routine randomly samples the spectrum around an input wavelength position until it minimizes the residuals between the data and the number of Gaussians selected by the user. In this way we obtain both the flux measured directly from the data and the flux associated to the fitted Gaussian subtracted by the continuum contribution. We use the latter for our analysis, as it is less influenced by the intrinsic noise of the spectrum.

Finally, for the galaxies that we detect in our lensing cluster pointings, we used lensing models obtained in previous works (Caminha et al. 2017b, 2019; Bergamini et al. 2021; Vanzella et al. 2021) to identify the multiple images of a lensed background source. We select the image with the highest flux contribution and the least amount of contamination and re-scale its observed flux (and consequently the derived luminosity) to account for the lensing magnification. This results in making evident the more faint objects in our sample.

3. PHYSICAL PROPERTIES OF THE LYMAN- α PROFILE SHAPE

Table 3.1: Table showing the free parameters of the `tlac` radiative transfer code used to create the “shell-model” spectra. We describe the physical meaning of each parameter and show their allowed range.

Parameter	Range	Type	Description
v_{exp}	$[-490, 490] \text{ km s}^{-1}$	Discrete	Expansion velocity of the dust and hydrogen shell. Positive for outflows, negative for inflows.
$\text{Log}_{10}(N_{\text{HI}})$	$[16, 21.8]$	Discrete	Column density of the neutral hydrogen present in the expanding shell.
T/K	$[3, 5.8]$	Discrete	Logarithm of the effective temperature of the ISM in the expanding shell.
σ	$[1, 800] \text{ km s}^{-1}$	Continuous	Intrinsic Gaussian width of the emission line before encountering the expanding shell.
τ_{d}	$[0, 5]$	Continuous	Logarithm of the optical depth of the dust present in the expanding shell.
$EW_{\text{intrinsic}}$	$[1, 6000]$	Continuous	Intrinsic equivalent width of the emission line before encountering the expanding shell.

We use the flux obtained from the gaussian fitting routine (corrected for magnification in the lensing fields) to define the lower-limit $\text{Ly}\alpha$ luminosity of our objects. Furthermore, since the routine allowed us to match the shape of the different lines with one or more Gaussians, we used this first approach to define a profile shape classification scheme as described in Section 3.4.3. Since this classification heavily relies on our visual inspection of the profile shape, we will call this first approach to profile identification as “visual classification”.

3.3.1 Shell-model fitting

We used the “shell-model” fitting pipeline described in Gronke et al. (2015) which utilizes a suite of pre-computed spectra compiled following the full radiative transfer equation using the Monte Carlo radiative transfer code `tlac` (Gronke & Dijkstra 2014) to perform a quantitative analysis of the $\text{Ly}\alpha$ line. The code propagates an initial $\text{Ly}\alpha$ emission, characterized by an intrinsic Gaussian width (σ) and an initial equivalent width (EW), originating at the center of our object through an expanding shell composed of neutral hydrogen and dust. The shell can be thus described by the hydrogen column density N_{HI} , the optical depth of the dust component

of the shell τ_d , the effective temperature of the gas T , and the expansion velocity of the gas v_{exp} (> 0 for outflow, < 0 for inflow).

The ranges allowed for the mentioned quantities are as follows: σ is a continuous quantity in the range $[1,800]$ km s^{-1} , τ_d is also continuous in the range $[0,5]$, and the considered EWs range instead from $[1,6000]$. The remaining variables are discrete and create a grid of 12960 models by propagating 20000 “Ly α ” photons with a gaussian line shape centered at 0 and with $\sigma = 800$ km s^{-1} and 150000 “UV” photons with a uniform intrinsic spectrum in the range ± 2700 km s^{-1} . The ranges considered for these quantities are as follows: $v_{\text{exp}} = [0,490]$ km s^{-1} with a 10 km s^{-1} step (except for the initial values of 2 km s^{-1} , 5 km s^{-1} , 8 km s^{-1})¹, $\log N_{\text{HI}} = [16,21.8]$ and $\log T/\text{K} = [3,5.8]$ on the other hand are spaced uniformly. Table 3.1 summarizes what has just been described.

With the models defined as above, we followed these steps to fit our spectra:

- We fix a redshift prior using the catalog we created for the initial classification and assign an error of 0.01 to our redshift estimation as we only have the Ly α line to guide our measurement.
- We also notice that some spectra are very faint and that in some cases there are largely negative spikes around the Ly α line. Since such negative flux values interfere with the fitting routine, we reassign the negative spikes that go below $-25 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ to a flux value of zero. This does not substantially change the shape of the line, but allows the routine to perform the fit without issue. We also smoothed the synthetic spectra to the instrument light spread function (LSF, on average ~ 2.7 $\text{\AA}$) to mirror the spectral resolution of the data.
- The actual routine first finds the global likelihood maximum of the parameters by combining a basin-hopping algorithm over the discrete parameters with a local maximization of the continuous parameters.
- From this position, a reiterative Monte-Carlo simulation finds the best fitting configuration of the parameters.
- Finally, the median values and their uncertainties are computed from the Monte-Carlo chains obtained in the previous step.

For a more detailed explanation of the fitting routine, we refer the reader to Gronke et al. (2015). Finally, after our spectra are fitted with a model spectrum, we visually inspect the shape of the best fit emission profile

¹Inflows are modeled by mirroring the spectra around the systemic velocity leading to an effective range of $v_{\text{exp}} = [-490, 490]$ km s^{-1} .

suggested by the routine and assign a profile classification to our objects based on said shape.

3.4 RESULTS

3.4.1 Sample of Lyman α emitters

In this work, we analyzed a total of 144 Ly α emitters in a 3.21 arcmin² area of the COSMOS field and in four MACS clusters. Table 3.2 lists the observational details of our MUSE pointings, the number of Ly α emitters we detected, along with the FOV detection density, which we defined as the number of Ly α emitters divided by the area covered. This table allows us to compare the effectiveness in Ly α detection of the different pointings, based on their depth and area covered. We note how the most important factor in detecting Ly α emission for our data seems to be the exposure time, regardless of FOV area and the presence of lensing. This is hardly surprising, but we do notice how a lensing cluster seems to have a similar FOV detection density to the field at equal exposure time.

3.4.1.1 The field population

Fig. 3.1 shows how redshift and luminosity relate to each other in our field sample and their respective distributions. We compare this new data (in red) with the sample we presented in Rosani20 (in gray). The two differ both in area covered and in exposure time: the Rosani20 sample spans 20.79 arcmin² with a depth of $\sim$ one hour, while our deep field sample is on average 4 hours deep, but covers only 3.21 arcmin² of the COSMOS field. We first notice how the detection density of the deeper MUSE pointings is $\sim$ 2.6 times higher than that of the shallower data, if we define it as the number of objects detected per arcmin². Furthermore, we notice how in the central panel the luminosity increases with redshift in both samples, as expected.

If we consider the distributions in redshift shown in the upper panel of the figure, we see how both samples cover the entire range available to MUSE, but how the deep sample shows a flat distribution, instead of decreasing with higher redshift. The deep field pointing was chosen towards a COSMOS region with a presumed galaxy proto-cluster at $z \sim 5.3$. While we do not detect objects close enough in space and/or redshift to confirm the presence of the proto-cluster, we do see more objects around $z \sim 4$ than we would expect, causing the z distribution of our new sample

Table 3.2: Table showing the target of our observations, the area covered by the MUSE FOV, the exposure time and the number of Ly α sources detected. Furthermore, we list the FOV detection density, the median redshift and Ly α luminosity of the sample. Due to low number statistics and similar exposure times, the clusters MACS J0329 and MACS J1931 have been listed as one pointing. The de-lensed area is calculated by projecting the MUSE FOV to the source plane and averaging this projection based on the redshift of the detections.

Obj. Observed	FOV Area (De-lensed) [arcmin ²]	Exp. Time h	N _{Lyα}	Det. Density (De-lensed) [arcmin ⁻²]	z _{median}	L _{median} Log ₁₀ [erg s ⁻¹]
Rosati20 Field	20.79	~ 1	102	4.9	3.7	42.4
Deep Field	3.21	~ 4	42	13.1	4.0	42.4
MACS (J0329+J1931)	1.94 (0.28)	~ 2.5	20	10.3 (71.9)	4.6	41.6
MACS J0416	1.23 (0.30)	~ 17.1	45	36.6 (149.0)	4.1	41.3
MACS J1206	2.63 (0.38)	~ 4	37	14.1 (98.7)	3.8	41.6

Figure 3.1: We compare the field Ly α population of this study in red with the population of Ly α emitters presented in Rosani20 in gray. In the central panel we plot the trend of luminosity with redshift, while the upper and right-hand panels show the distribution of redshift and luminosity, respectively, for both our samples.

Figure 3.2: Histogram showing the flux distribution of our new field Ly α emitters (in red) compared to the distribution of the emitters in Rosani20 (in gray). As expected, the flux distribution of the Ly α emitters from the deep field peaks at lower values compared to those of the shallow field.

Figure 3.3: Same as Fig. 3.1, but for our lensing samples. Due to similar exposure times and low number statistics, the clusters MACS J0329 and MACS J1931 have been grouped together. The dashed line in the central panel represents the lowest luminosity objects in the field and acts as a comparison guideline.

to flatten. The position of these objects, however, both on the sky and in redshift, does not suggest that they belong to the same physical structure.

Finally, the luminosity distributions of the two samples shown in the right-hand panel overlap almost entirely. We point out that this overlap is most likely caused by the different redshift distributions, rather than by the two pointings detecting a similar population even at different depths. To justify this claim, we show in Fig. 3.2 the distribution of the fluxes measured by MUSE in the two samples. Here we can clearly see that the new field sample (again in red) peaks at lower fluxes compared to the old sample, as we would expect from deeper MUSE pointings.

3.4.1.2 The strongly lensed population

In Fig. 3.3 we show the redshift and luminosity distributions for our lensing sample, as we did for the field earlier. We again point out how in the central panel the luminosity increases with redshift. For the purpose

of this comparison, we grouped clusters MACS J0329 and MACS J1931 together, as they both have the same depth and significantly lower numbers compared to the other two clusters. The dashed line in the plot represents the lowest luminosity objects in the field sample and acts as a visual guideline. We will, however, directly compare the lensing and field population in the next figure.

The upper panel shows the redshift distributions of the Ly α emitters in the cluster pointings. We can see that most of our objects are concentrated at lower redshifts ($z < 4.5$) for clusters MACS J0416 and MACS J1206. MACS J0416 further shows an over-density at $z \geq 5.8$, while the clusters MACS J0329 and MACS J1931 have a flatter distribution.

Looking at the right-hand panel, the luminosity distribution of these objects seems to not differ much between the MACS J1206 and the combined MACS (J0329+J1931) clusters. This is further reinforced by comparing the luminosity median in the two clusters as shown in Table 3.2. The much deeper MACS J0416, however, clearly shows a luminosity distribution skewed to lower values. This is once again in line with what is expected.

3.4.2 Field vs. lensed Ly α comparison

Finally, Fig. 3.4 shows the direct comparison between field and lensed Ly α emitters (in red and blue, respectively). Once again, we see an increase in luminosity with redshift for both samples and we can clearly see that the lensing sample tends towards lower luminosities compared to the field, as the dashed line identified in the previous plot.

The redshift distribution shown in the upper panel shows a higher detection at $z \sim 3, 4$ and 6 for the lensing sample, with an underlying decreasing relative number of galaxies when going to higher redshifts. The field sample is once again flatter in its distribution for the same reason as before.

The right-hand panel of the figure confirms very clearly how the lensed Ly α emitters peak at lower luminosities than the field sample. We notice, however, that the upper tail of the blue histogram does not reach luminosities as high as the red one. We suspect that the reason we do not see high luminosity objects in our lensed clusters, is that the lensing magnifies a smaller area behind the cluster, compared to the FOV of the MUSE pointing. Since high luminosity objects are expected to be less numerous than faint ones, a smaller area translates into a lower probability of observing such high luminosity objects and this results in the lensed cluster sample not reaching luminosities as high as in the field. See

Figure 3.4: Same as Figs. 3.1 and 3.3. In this figure we compare our field population in red to our lensing population in blue. The dashed line once again represents the luminosity limit below which no field $\text{Ly}\alpha$ emitter is detected.

Figure 3.5: Figure showing examples of the six profile types used in our classification. We both show the data with its associated uncertainty in black and the best fit profile in red.

Table 3.2 for a comparison between the physical area covered in the field and the averaged de-lensed area covered behind the clusters.

We would also like to compare the total number of detections per unit FOV area of the field data to that of the lensing data. Looking at Table 3.2, we see that the exposure time is the main driving force behind the detection density of our sample, as stated before. Thus, while the lensing cluster enables us to detect lower luminosity objects, it also shrinks the physical area that we can probe compared to the field. This seems to result in roughly the same number of Ly α emitters per unit FOV area at equal exposure time (Field vs MACS J1206).

3.4.3 Qualitative classification of Ly α profiles

In our analysis of the Ly α line, we separate our sample qualitatively in six distinct line profile categories as listed below and shown in Fig. 3.5:

P1 (Single Peak) : The emission line is symmetric around its peak.

P2 (Red Tail) : The emission line shows a less steep decline in the red than in the blue.

P3 (Blue Bump) : The main emission line in the red is preceded by a smaller emission in the blue.

P4 (Double Peak) : The emission exhibits two peaks of comparable intensity.

Figure 3.6: Histograms showing the redshift and flux distribution of our profile 1 and profile 2 sources after our initial visual classification. The central panels show the overall distribution of the profiles, while the upper and lower panels compare the distribution of our field and lensing cluster sample for a fixed profile type. The solid vertical line is the median of the distribution, while the dashed lines are the first and third quartiles, respectively.

Figure 3.7: Similarly to Fig. 3.6, we compare the luminosity distribution of our profile 1 and 2 sources. Since it greatly differs between the field and lensing population, we decided to redefine the upper and lower panel and compare the two profiles directly in the same sample. As in Fig. 3.6, the solid vertical line is the median of the distribution, while the dashed lines are the first and third quartiles, respectively.

Figure 3.8: *Left panel*: Histogram comparing the distribution of profiles from the visual inspection (in black) to the one from the shell-model fitting (in gray). We notice how the multi-peak profiles (3, 4, 5, and 6) almost double for the “shell-model” classification, compared to the black histogram. *Right panel*: Distribution of the different profile types in redshift derived from the shell-model fitting. We see how the highest redshifts ($z > 5$) are only covered by profiles 1 and 2, with the exception of the profile 6 object.

P5 (Asymmetric Blue Bump) : The line shows both a Red Tail and a Blue Bump.

P6 (Red Bump) : The main emission line in the blue is followed by a smaller red emission.

We begin our profile analysis by visually inspecting our data and separating the symmetric and the asymmetric profiles. We then compare the redshift, measured fluxes and luminosity distribution of these initial sub-samples (called P1 and P2 here) and notice that the symmetric sample is present only at the lower fluxes and presents slightly lower luminosities, while the redshift distribution does not appear to be significantly different. Figs. 3.6 and 3.7 show the trends described. As of now, we cannot exclude in this case that the symmetric profile not being detected at higher fluxes could be due to the signal-to-noise (S/N) being too low for some of our objects.

Considering possible S/N issues influencing the profile shape we see, we decided to fit our data with the “shell-model” spectra generated with the `tlac` radiative transfer code to both provide physical quantities to the Ly α emission and to define a best fitting profile shape. The result of this analysis is presented in the next subsection.

3. PHYSICAL PROPERTIES OF THE LYMAN- α PROFILE SHAPE

Figure 3.9: Histograms showing the distributions of the properties derived using the expanding shell-model. The solid vertical line again represents the median and the dashed lines the first and third quartile.

Figure 3.10: Same as Fig. 3.9, but showing the comparison in distribution between profile 1 and 2 objects. We see how the parameter that shows a significant difference between the sub-samples is the neutral hydrogen column density (LogNHI).

3.4.3.1 Shell-model fitting

When we run our spectra through the “shell-model” fitting routine (Section 3.3.1), we notice that we can recover a total of 132 secure profile classifications out of the 144 Ly α emitters in our sample. The 12 spectra that we reject are characterized by flux levels close to 3σ noise limit and/or are close to bad pixels where the uncertainty on the flux spikes. Compared to our initial classification, the routine recognizes more detail and the main effect that this has on our profile distribution is a shift from symmetric single-peak objects to multi-peak profiles. Fig. 3.8 shows in its left panel how the “shell-model” distribution compares to our initial visual classification and how the multi-peak spectra (profiles 3, 4, 5, and 6) roughly double in number. This distribution allows us to compare two profile sub-samples, namely the single-peak profiles 1 and 2 against the multi-peak profiles 3, 4, 5, and 6. From here on out we will refer to these groups as SINGLE and MULTI, respectively.

The right panel in Fig. 3.8 shows instead how the redshift distribution of our profiles look for the shell-model fitting. We can see that while the MULTI profiles fill the area of $3 \lesssim z < 5$, the highest redshifts are almost exclusively covered by SINGLE objects. This is most likely due to a more opaque intergalactic medium at $z \gtrsim 5$ absorbing the blue Ly α peak (Dijkstra et al. 2007; Laursen et al. 2011; Byrohl & Gronke 2020).

Fig. 3.9 shows the distribution of the properties obtained for all our spectra, without separating them into the different sub-samples. We see how v_{exp} is mostly positive, peaks around 100 km/s but also presents negative values. We tested these objects and found that the fits do not worsen significantly if we force the routine to assign positive velocities in these 19 cases. As we want to introduce the least amount of bias in our analysis, we keep the negative values assigned when the fit was totally free, but caution against over-interpreting them as evidence for gas infall.

The values for N_{HI} exhibit a bimodal distribution, allowing for both a low and intermediate-high hydrogen column density. The value for T/K is relatively flat and spans all of its allowed range. The histogram for σ peaks around 150 km/s and is almost symmetric in its distribution. The one of τ_d peaks at low values, which we could expect from Ly α emitters visible in the optical, but also has a rather extended tail. Finally, the EW distribution is very much concentrated at the lowest possible values the fit can obtain.

We again separate our sample into profile 1 and 2 objects after updating our classification for the shell-model fitting, as these two are still the most common individual profiles. We do this to stay consistent between choosing

a profile type and the method used to derive the properties. The comparison between the two sub-samples then yields what is shown in Fig. 3.10. We can clearly see that all derived properties tend to have similar distributions, except for the values of N_{HI} . Profile 1 galaxies prefer a lower value of this quantity, while profile 2 has a wider, but flatter distribution with a higher median value. We expect to see this kind of behavior from profile 1, as a low column density is believed to favor a more narrow and symmetric profile for the Ly α emission.

Finally, we compare multi-peak profiles to the behavior the single-peak emission. Fig. 3.11 shows how these distributions behave and we can see how this time the significant variation in distribution is evident in the σ parameter. This would mean that in general, multi-peak profiles tend to have a broader emission before the Ly α photons meet the expanding medium. This difference in distribution could be due to the fit requiring a broader emission initially, compared to a single-peak, to accommodate the position of the multiple peaks. To make sure that this is not just an effect caused by the way the lines are fitted, we plotted the values of N_{HI} against σ . This is because a high column density would allow the routine to still fit the two peaks even starting from a narrow initial emission.

Figure 3.12 shows the width of the intrinsic spectrum versus the shell HI column density for our MULTI and SINGLE samples and we can see that the MULTI object's σ stays indeed on average above the SINGLE sample. It is evident that the MULTI spectra are created with a wide emission plus a central absorption. A similar effect was already noticed for “green pea” galaxies (Yang et al. 2016; Orlitová et al. 2018). There, in fact, the intrinsic spectrum is wider than the measured Balmer lines' width leading to discussion whether this is due to additional radiative transfer effects (Gronke et al. 2018; Li et al. 2021).

One can, furthermore, notice from Fig. 3.12 that there is a significant fraction of spectra with low column density $N_{\text{HI}} \lesssim 10^{17} \text{ cm}^{-2}$, which indicates ionizing photon escape (Lyman Continuum (LyC) leakage). While both theoretical (Verhamme et al. 2015; Dijkstra et al. 2016; Kimm et al. 2019b; Kakiichi & Gronke 2021) and empirical studies (Verhamme et al. 2017; Izotov et al. 2021) have established a firm connection between Ly α and LyC escape, the column densities obtained here have to be taken with caution due to the quality of our spectra. Nevertheless, it is interesting that not only a number of (narrow) multi-peak spectra which are known to trace LyC leakage (e.g., Verhamme et al. 2015; Izotov et al. 2021) but also several single-peak spectra are reproduced with such low N_{HI} . This can in principle be true if, e.g., Ly α photons escape through holes in a HI screen (e.g., Dijkstra et al. 2016; Rivera-Thorsen et al. 2019) but would

Figure 3.11: Same as for Fig. 3.9 and 3.10, but showing the distribution for the MULTI and SINGLE sub-samples. We notice how most properties seem to follow a similar distribution between the two, except for σ , where the MULTI sample shows higher values.

have to be confirmed with follow up observations to verify that the spectra of the SINGLE sample are indeed single-peaks at line center (and not, e.g., a single red peak as also commonly observed).

3.5 SUMMARY AND CONCLUSIONS

We used publicly available MUSE data both in the COSMOS field and in a selection of CLASH lensing clusters to analyze a sample of 144 Ly α emitting sources. The goal of this study is to investigate the Ly α emission line profiles and their possible correlation to the ISM properties. We visually identified 6 distinct line emission profiles that we then fitted with a suite of “shell-model” spectra. In this way we obtain physical properties of the emission and the surrounding gas and dust shell.

The results presented in Section 3.4 show that the exposure time mainly drives the number and detection density of our sample in the MUSE FOV, while the area covered or the presence of a lens seem to not impact the

Figure 3.12: Relation between σ and the neutral hydrogen column density, comparing the MULTI and SINGLE sub-samples. We notice how σ remains higher for the MULTI sample, even when a higher column densities do not require the fit to use a broader initial line to fit a multi-peak. Furthermore, the vertical solid line shows the limit below which our sample is expected to show LyC leakage.

Table 3.3: Table summarizing the sizes of our total sample, the secure profile classifications, and the different sub-categories of profile shapes.

Total Unique Sources	144
Good Visual Classification	120
Profile 1	41
Profile 2	56
Good Shell-Model Fitting	132
MULTI	48
SINGLE	84
- Profile 1	29
- Profile 2	55

detection density much. We argue that while a lens enhances the luminosity of the objects it magnifies, the magnification also shrinks the area that can be studied, thus balancing its effects on the FOV detection density. Another effect of the lensing is evident when we compare the lensing and field sample. Since the lens allows for fainter objects to be detected by MUSE and the area studied is smaller than for the unmagnified field, we see a clear shift in the lensed objects luminosity distribution towards lower values. We note that the luminosity distribution of our sources is in line with what was reported in the literature so far, specifically as summarized by de La Vieuville et al. (2019) and Richard et al. (2021) for field and cluster studies.

Furthermore, we studied the redshift distribution both globally and after separating field and lensed sources, and depth of the pointing. We notice no clear preference both for profile type and Ly α luminosity. Comparing instead the deeper pointings of the field to the ones we studied in Rosani20, we notice that the measured fluxes of our new objects are lower than the old sample, but that the different redshift distribution in that particular area of the COSMOS field results in a similar luminosity distribution.

We performed a preliminary profile classification by pure visual inspection and found that the single-peak profiles 1 and 2 are the most common, cover our entire redshift range, and their distribution does not significantly vary between field and lensing cluster. We suspect that the quality and the intensity of the measured flux influence the details of the profile we are able to see (Gronke 2017). We notice in fact that the profile 1 objects tend to have lower fluxes and overall slightly lower luminosities, while their redshift distribution seems to not vary compared to the profile 2 sources.

We caution about over-interpreting this trend, however, as the profile shape of the low flux objects is more subject to noise fluctuations compared to a more robust signal. Since the symmetric shape classification depends on the wings of the line, which are in this case at and below the level of the noise, we cannot be completely certain that our profile 1 sources are indeed emitting a symmetric line. Though we still decided to treat them as symmetric, because we cannot test if and how much influence the noise fluctuations had on the shape of the single lines, reader discretion is advised on the matter.

The main results of our paper have been obtained by fitting the “shell-model” spectra generated using the `tlac` radiative transfer code (Gronke & Dijkstra 2014; Gronke et al. 2015) to the observed Ly α emission. These fits allowed us to associate physical properties to the observed emission

profiles. Firstly, we found a significant amount of multi-peak profiles (48 out of 132, $\sim 36\%$) in our high- z sample. This percentage is in line with what other studies have found for their $\text{Ly}\alpha$ emitting objects at comparable redshifts (Kulas et al. 2012; Trainor et al. 2015). Furthermore, we also compare our results to what has been measured for “green pea” galaxies at low redshift. Such objects have been theorized to be analogs to high- z star-forming galaxies and show a clear preference for multi-peak profiles (Henry et al. 2015; Yang et al. 2016, 2017; Kim et al. 2021). Most notably, both low- and high- z studies show an average v_{exp} peaked around 200 km/s as opposed to peaking around 100 km/s as we find in this work. Our average v_{exp} is thus more in line for what has been found in Orlitová et al. (2018) for their sample of 12 low redshift GPs. We also notice that 30 ($\sim 23\%$) of our 144 objects show low HI column densities ($N_{\text{HI}} \lesssim 10^{17} \text{ cm}^{-2}$), which hints at the possibility of LyC leakage for these galaxies (Gronke 2017).

The novelty of this work is that we look at the statistics of the physical properties not just in general, but by separating the observed $\text{Ly}\alpha$ emission into profile families that we then can compare to each other. Such a direct statistical approach to studying the physical properties linked to the $\text{Ly}\alpha$ emission, starting from the profile shape rather than a specific physical quantity (i.e. the HI column density or v_{exp}), has not yet been presented. To do this data-driven direct comparison, we defined the two profile families SINGLE and MULTI, where we used the presence of a single or multiple peaks, respectively, to sort our data.

Table 3.3 summarizes the samples and sub-samples considered for the “shell-model” and for the initial visual classification along with the number of objects they contain. Our overall comparison between profile types yields that most physical properties are comparable both in range and median between the SINGLE and MULTI and also between the symmetric profile 1 and the asymmetric profile 2. It would seem that while the shape of the $\text{Ly}\alpha$ line for a single object is determined by the physical state of the galaxy and its surrounding medium, for most properties there is, statistically speaking, little difference between one family of profiles and the other.

The differences we notice, however, appear to be robust within our analysis. Namely, we see that the initial emission of the MULTI profiles seems to be consistently broader than that of the SINGLE profiles, regardless of the column density of the neutral hydrogen. And if we instead compare profiles 1 and 2 again, we see that the more symmetric profile 1 objects tend to have lower neutral hydrogen column densities, confirming what is expected from an expanding shell-model in the case of lesser scattering.

Our overall conclusion of this analysis is that we are able to obtain good quality fits from the data and construct statistically significant samples based on the Ly α profile shape to compare the derived physical characteristics. We see that while all properties considered in this work influence in some way the final shape of the Ly α emission, there are only two cases of significant differences in distribution for the samples we compared. It is clear that the process of Ly α photon propagation is still very degenerate and that if there are more differences in behavior in our profile families, we are currently unable to detect them. The differences found in this work, however, leave the possibility open that deeper observations, thanks to upcoming instruments (i.e. NIRSpec on JWST), in combination with detailed models, might in the future yield a clearer separation between the preferred physical properties of these profile families.

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Based on observations collected at the European Southern Observatory under ESO Programme IDs 094.A-0115B, 094.A-0487(A), 094.A-0487(B), 094.A-0487(C), 094.A-0487(D), 095.A-0181(A), 095.A-0525(A), 096.A-0105(A), 097.A-0269(A), 0100.A-0763(A). This research made use of Astropy,² a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018).

²<http://www.astropy.org>

4. RELATING THE PROPERTIES OF LYMAN α EMITTERS AT $z=2.9-6.7$ DERIVED FROM SPECTROSCOPIC AND PHOTOMETRIC ANALYSES

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We used independent MUSE spectroscopy and HST photometry of lensed galaxies in the CLASH lensing cluster MACS J0416 to study the physical properties of Lyman α emitters based on their emission profile shape. The depth of the MUSE data, combined with the magnification of the cluster, allowed us to select faint objects in a small region of the sky without the need for target pre-selection. The goal of this work is to characterize and compare the different profile shape families both using spectroscopic and photometric data. For this purpose we made use of the SED fitting code LePhare to obtain the physical information of our sources from the HST photometry available, and used the “shell-model” spectra obtained with a radiative transfer code to further characterize the Lyman α emission. We find that our samples mostly follow a similar distribution in parameters, except for the initial width of the Ly α emission σ , which is broader for the multi-peak profiles, while the symmetric profile has lower HI column densities compared to the asymmetric red single-peak emission. We also find that the de-lensed M_ correlates with σ , while the SFR_{UV} and the T/K parameter show an anti-correlation. Finally, we compared the position of our data points on the M_* -SFR plane and found that they agree with previous works and follow both the main sequence and starburst line. We also tested the distribution of our LyC leakage candidates and found that they do not follow a different behavior from the rest of the sample.*

4.1 INTRODUCTION

The study of star formation processes at high redshift as seen in the optical currently relies mostly on the Lyman α ($\text{Ly}\alpha$) emission line. The detection of this spectral feature is a sign the galaxy is undergoing a phase of prominent and generally unobscured star formation. The resonant nature of the line, however, means that the presence of hydrogen around the host galaxy is capable of scattering the light coming from the center, lowering the surface brightness of the line by spreading the emission on a larger area. The presence of dust, on the other end, extinguishes the $\text{Ly}\alpha$ photons entirely. The spatial distribution and kinematics of gas and dust further influence the intensity and the shape of the line profile. Investigating this process at high redshift thus allows us to glimpse into the first few billion years of the cosmic star formation history (Shapley et al. 2003; Dijkstra 2017; Hernán-Caballero et al. 2017; Karman et al. 2017; Vanzella et al. 2018; Marchi et al. 2019). For more details, Ouchi et al. (2020) give a complete review of the state of the $\text{Ly}\alpha$ observations in recent years.

A very successful instrument in studying the $\text{Ly}\alpha$ emission is the Multi Unit Spectroscopic Explorer spectrograph (MUSE, Bacon et al. 2010). MUSE is invaluable if one wants to serendipitously detect sources between $2.9 \lesssim z \lesssim 6.6$ using their prominent $\text{Ly}\alpha$ emission. The instrument allows the user to detect all the light present in its field of view (FOV), provided it is bright enough, and thus does not need target pre-selection to compile the source catalog.

Combining MUSE with the magnification effect of a lensing cluster further enhances its capabilities to study high- z objects (Bradley et al. 2014; Richard et al. 2014; Atek et al. 2014, 2015, 2018; Treu et al. 2015; Karman et al. 2015, 2017; Caminha et al. 2019; Erb et al. 2019). This is due to the fact that this particular combination pushes the limit of detection towards very low fluxes and luminosities (de La Vieuville et al. 2019).

To study the $\text{Ly}\alpha$ emission profile of these faint objects we can make use of radiative transfer models to simulate the effects of gas and dust on the initial emission. From the early examples shown in Tenorio-Tagle et al. (1999) and Mas-Hesse et al. (2003), where a simple shell of expanding gas interacts with the light and produces the blue and red part of the line, these models have evolved into more complex simulations that allow us to infer the expansion velocity of the gas along with the column density of the neutral hydrogen and the optical depth of the dust among other properties (Verhamme et al. 2008; Gronke 2017; Verhamme et al. 2018; Kakiichi & Gronke 2019). This allows us to further shed some light into the complicated, but fundamental aspect of prominent star formation.

One possible line of study is to try to link the observed shape of the $\text{Ly}\alpha$ emission to preferred physical configurations of the emitting host galaxy. Linking the profile shape to specific physical conditions not only would allow us to characterize the host galaxy and the medium surrounding it (Kulas et al. 2012; Yamada et al. 2012; Trainor et al. 2015; Leclercq et al. 2020), but it could also potentially bridge the gap between low and high redshift studies of $\text{Ly}\alpha$ emitters. In our previous work (Rosani et al., submitted, and hereafter Ros21), we defined two profile families for this type of study, by using the presence of one or more peaks in the observed $\text{Ly}\alpha$ profile to sort our spectra into these two different profile families. What we found was that the multi-peak profiles showed a broader initial emission compared to the single-peak profiles. We also saw that the symmetric single-peak profile tended to have lower HI column densities compared to the asymmetric single-peak profile. In this work we will extend our analysis to include more physical properties, derived from *Hubble Space Telescope* (HST) photometry, to further characterize the profile shape.

MUSE is not the only powerful instrument which can be combined with lensing clusters to enhance the study of faint and distant galaxies. Combining a lensing cluster with HST observations has been proven to enhance the number of detected objects (Coe et al. 2015). Furthermore, this combination applied to the Hubble Frontier Fields has yielded the detection of the faintest galaxies yet known and believed to be likely responsible for the re-ionization of the Universe at $z \sim 6$ (Livermore et al. 2017; Atek et al. 2018). The cluster we studied in this work, MACS J0416, is one of the clusters analyzed in the Hubble Frontier Fields and presents both deep spectroscopic MUSE data, as well as HST imaging in multiple bands (Lotz et al. 2017).

The scope of this paper is to characterize and compare our sources showing different $\text{Ly}\alpha$ profile shapes using both physical properties derived from photometry and spectroscopy. We aim to verify if the different profile families defined in Ros21 follow specific relations with stellar mass (M_*) and/or star formation rate (SFR) and if they have preferred values for the physical properties obtain from the photometric data. We further test the distribution of all the properties derived in this paper for a group of Lyman-Continuum (LyC) leakage candidates compared to our general sample. Finally, we place our data points on the M_* -SFR relation found in previous works (Caputi et al. 2021 and Rinaldi et al., in preparation).

In Section 4.2 we introduce the data we used, in Section 4.3 and 4.4 we describe our method and the models we used to fit both our spectroscopic and photometric data, in Section 4.5 we outline our results and in Section 4.6 we summarize and draw our conclusions. Throughout

In this paper, we adopt a flat Λ CDM cosmology with $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.286$ and $\Omega_\Lambda = 0.714$, while the SED fits employ a Chabrier initial mass function (IMF) (Chabrier 2003). All the magnitudes measured are in the AB system (Oke & Gunn 1983).

4.2 DATA

In this paper we combine spectroscopic data obtained with the MUSE (Bacon et al. 2010) instrument with photometry taken with HST. Specifically, we focus our efforts on the MACS J0416.1-2403 lensing cluster in order to study the physical properties of the Ly α emitters magnified by the cluster.

The spectroscopic data relating to the cluster was publicly available on the MUSE data archive under program IDs 0100.A-0763(A) (P.I.: E. Vanzella) and 094.A-0115B (P.I.: J. Richard). The area covered consists of a single square of $\sim 1.23 \text{ arcmin}^2$ spanning the North-East of the cluster with a total exposure time of $\sim 17.1 \text{ h}$. Furthermore, taking the magnification and the average redshift of the lensed sources into account, we estimate that the physical area behind the cluster probed by the lensing is $\sim 0.30 \text{ arcmin}^2$. A more detailed description of the data reduction process is presented in Vanzella et al. (2021).

The exceptional depth of these MUSE pointings, combined with the intrinsic capability of the instrument to detect serendipitous sources, makes this cluster extremely interesting. The MUSE field-of-view (FOV) covers 1 arcmin^2 of the sky with a seeing limited spatial resolution sampled with a pixel size of 0.2 arcsec . The instrument then spans the wavelength range from $4750 \text{ \AA}$ to $9350 \text{ \AA}$ with a spectral bin of $1.25 \text{ \AA/pixel}$, which corresponds to an average resolving power $R \approx 3000$ at $\lambda \sim 7500 \text{ \AA}$ or a resolution of $\Delta\lambda \approx 2.4 \text{ \AA}$. With these characteristics, we are able to probe this portion of the sky by identifying a particularly faint sample of Ly α emitters without the need for pre-selection.

To reduce our raw exposures and calibration files we used the standard reduction pipeline (Weilbacher et al. 2006, 2012, 2014) in combination with the MUSE Python Data Analysis Framework (Bacon et al. 2016; Piqueras et al. 2017) and the Zurich Atmosphere Purge (ZAP) (Soto et al. 2016) to clean the residual skylines from our final data cube.

The photometric data used in this analysis has been taken with HST, specifically in the Hubble Frontier Fields (HFF) program (P.I.: J. Lotz; Koekemoer et al. 2014; Lotz et al. 2017). The angular resolution of the images is 0.03 arcsec per pixel and the PSF in the F160W band has a full width half maximum (FWHM) of 0.20 arcsec . MACS J0416.1-2403 has

been chosen as one of the clusters to be observed, both for its lensing strength and moderate Galactic background, and for its ability to be observed by many different facilities. HST employed 140 orbits to reach a depth of $\sim 28.7\text{--}29$ magnitudes, considering the lensing magnification, however, the effective depth can be much higher (e.g. a factor of ~ 4.3 in magnitude for a magnification factor $\mu \sim 50$). The HFF data consists of three filters (F435W, F606W, and F814W) for the Advanced Camera for Surveys (ACS) and four filters (F105W, F125W, F140W, and F160W) for the Wide Field Camera 3 (WFC3) taken from the Mikulski Archive for Space Telescope. More detailed information on the HST data can be found in Rinaldi et al. (in prep., hereafter Rin21).

4.3 MUSE $\text{Ly}\alpha$ SPECTRAL ANALYSIS

We used the publicly available catalogs presented in Vanzella et al. (2021) to construct our list of $\text{Ly}\alpha$ emitters. We then extracted their spectra by selecting a pixel area for which the signal was at least 3σ above the surrounding noise. Contrary to a simple circular extraction, this method allowed us to recover most of the signal and at the same time exclude the contribution of the sky by matching the extraction area to the observed morphology of the object as closely as possible.

With the spectrum and its redshift known, we then used a simple multi-Gaussian fitting routine to measure the flux of the $\text{Ly}\alpha$ line around a user-defined wavelength position by minimizing the residuals between the number of Gaussians selected by the user and the data. We used the flux derived from the fitting Gaussians as our measurement, as it is more stable than the flux obtained directly from the data, which is influenced by the noise fluctuations present in the spectrum.

We define a lower limit $\text{Ly}\alpha$ luminosity using the measured flux and redshift, then apply the Kennicutt conversion factor to derive an $\text{H}\alpha$ luminosity first and then an associated SFR (Kennicutt 1998). We again underline that this SFR is a lower-limit, as we cannot correct the $\text{Ly}\alpha$ luminosity for dust extinction. Furthermore, we use the lensing models presented in previous works for this cluster (Caminha et al. 2017b; Bergamini et al. 2021) to correct the $\text{Ly}\alpha$ luminosity for the magnification factor given by the lensing before calculating the SFR.

The second step in our spectroscopic analysis is to fit the data with a “shell-model” that will both give us physical properties linked to the observed line emission and will allow us to classify our sample based on the profile shape observed.

4. PHYSICAL PROPERTIES OF LYMAN- α PROFILE SHAPE FROM MUSE AND HST

Table 4.1: Table showing the free parameters of the `tlac` radiative transfer code used to create the “shell-model” spectra, their allowed range and a brief description of their meaning.

Parameter	Range	Type	Description
v_{exp}	$[-490, 490]$ km s $^{-1}$	Discrete	Expansion velocity of the dust and hydrogen shell. Positive for outflows, negative for inflows.
$\text{Log}_{10}(N_{\text{HI}})$	$[16, 21.8]$	Discrete	Column density of the neutral hydrogen present in the expanding shell.
T/K	$[3, 5.8]$	Discrete	Logarithm of the effective temperature of the ISM in the expanding shell.
σ	$[1, 800]$ km s $^{-1}$	Continuous	Intrinsic Gaussian width of the emission line before encountering the expanding shell.
τ_{d}	$[0, 5]$	Continuous	Logarithm of the optical depth of the dust present in the expanding shell.
$EW_{\text{intrinsic}}$	$[1, 6000]$	Continuous	Intrinsic equivalent width of the emission line before encountering the expanding shell.

4.3.1 Shell-model fitting

We chose to fit the spectra obtained using the radiative transfer code `tlac` (Gronke & Dijkstra 2014) with the “shell-model” fitting pipeline described in Gronke et al. (2015), as we did for our previous work. The radiative transfer code generates these spectra by first propagating an initial Ly α emission, with a set of intrinsic Gaussian (σ) and equivalent widths (EWs), radiating from the center of our object through an expanding shell consisting of neutral hydrogen and dust. This shell is characterized by the expansion velocity of the gas v_{exp} , which is positive for outflows and negative for inflows, the hydrogen column density N_{HI} , the effective temperature of the gas T , and the optical depth of the dust component τ_{d} .

From the cited quantities, three are continuous in this framework, while the others are discrete. The radiative transfer code creates a grid of 12960 models by propagating 20000 “Ly α ” photons (centered at 0, with a Gaussian line shape and $\sigma = 800$ km s $^{-1}$) and 150000 “UV” photons with a uniform intrinsic spectrum in the range ± 2700 km s $^{-1}$ through the shell. Apart from the ranges given in the table, the steps considered to create the grid are spaced uniformly for all values except v_{exp} , for which the initial values are 2 km s $^{-1}$, 5 km s $^{-1}$, 8 km s $^{-1}$ before the property adopts a 10 km

s^{-1} step¹. Table 4.1 summarizes the ranges of our “shell-model” parameters and also provides a brief description of their meaning.

For fitting these spectra, we applied the following steps. First, we fixed the redshift prior and assigned an error of 0.01 to it, because our redshift measurement is based solely on the $\text{Ly}\alpha$ line. We attenuated the more extreme negative noise spikes around the $\text{Ly}\alpha$ line, because the routine has trouble dealing with such anomalies. To not change the shape of the line, we simply assigned a value of zero flux to all fluxes in our spectra lower than $-25 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$. We then smoothed the synthetic spectra to the instrument light spread function (LSF, on average $\sim 2.7 \text{ \AA}$) to match the resolution of our data. At this point, the routine finds the global likelihood maximum of the parameters using a basin hopping algorithm over the discrete parameters in combination with a local maximization of the continuous parameters. From this position, a reiterative Monte-Carlo simulation finds the best fitting values. Finally, the routine outputs the median values and their uncertainties using the results from the previous step. For a more indepth explanation of this routine, please refer to Gronke et al. (2015).

After the “shell-model” fits are done, we can then classified our spectra based on their emission line shape and following the criteria described in our previous work. As a brief reminder, here is the list of the six distinct profile types we used:

- P1 (Single Peak)** : The emission line is symmetric around its peak.
- P2 (Red Tail)** : The emission line shows a less steep decline in the red than in the blue.
- P3 (Blue Bump)** : The main emission line in the red is preceded by a smaller emission in the blue.
- P4 (Double Peak)** : The emission exhibits two peaks of comparable intensity.
- P5 (Asymmetric Blue Bump)** : The line shows both a Red Tail and a Blue Bump.
- P6 (Red Bump)** : The main emission line in the blue is followed by a smaller red emission.

4.4 HST DATA

We used the software Source Extractor (SExtractor) in dual image mode on all our filters and in combination with the initial MUSE catalog of

¹Inflows are modeled by mirroring the spectra around the systemic velocity leading to an effective range of $v_{\text{exp}} = [-490, 490] \text{ km s}^{-1}$.

Vanzella et al. (2021) to detect and extract our sources for the HST photometry. We configured the extraction process such that it was optimized for faint and small-sized sources (hot detection mode), the matching radius is 0.5 arcsec, and set a minimum error on the derived magnitudes of 0.05, which is the minimum systematic error for all HST data. To calculate the magnitudes, we chose to perform aperture photometry using a diameter of 0.4 arcsec for most of our sources, and to allow for a 0.8 diameter in the cases where the images showed a more extended emission profile. We also adopt a Kron aperture treatment to account for sources that do not have a point-like, but rather an elongated shape due to the magnification effect and distortion of the lens (Kron 1980).

We also performed a sanity check by comparing our detected sources to the ASTRODEEP catalog in clusters MACS J0416 and Abell 2744 and found that we are in good agreement. Careful visual inspection also allowed us to verify that the sources we found were not contaminated by other nearby bright sources. During this inspection we found that for some sources the Ly α emission does fall between two detections in a way that does not allow us to determine to which of the two sources it belongs to. In such cases, we assigned the emission to both and treated them separately by using the same redshift and magnification factor. Finally, we applied both aperture corrections (using the appropriate aperture size for each source) and Galactic extinction corrections following the values of Schlafly & Finkbeiner (2011). A more detailed description of how these sources were obtained can be found in Rin21.

4.4.1 SED fitting

To obtain the physical properties of our sources using the HST photometry, we use the code LePHARE by fixing the redshift to their spectroscopic values and then fitting the HST photometry using model SED spectra. These models are characterized either by an exponentially declining SFR such that $\text{SFR}(t) \propto \exp^{-(t-t_0)/\tau}$, or by a single starburst event for which $\text{SFR}(t) \propto \delta(t)$. The models used to create the SED are the stellar population synthesis (SPS) models from Bruzual & Charlot (2003) adopting a Chabrier IMF (Chabrier 2003) and two metallicities: solar and sub-solar ($Z = 0.2 Z_{\odot}$). The age range allowed for our models goes from the time of the universe at the measured redshift of the object down to young ages such as 1 Myr. We go so far down in age because we noticed that setting a higher lower limit resulted in an accumulation of sources at said lower limit. Finally, to correct for internal extinction we adopted a modified version of the Calzetti et al. (2000) law to extend the correction to lower wavelengths. The last

Table 4.2: Number of sources in our sample of Ly α emitters in MACS J0416 analyzed here. We quote total numbers and numbers segregated by profile shape.

Total Unique Sources	35
MULTI	13
SINGLE	22
- Profile 1	10
- Profile 2	12

step in our analysis to derive the physical properties of our objects was to account for the magnification factor and rescale the UV light and the derived mass accordingly. Fig. 4.1 showcases two examples of HST stamps and the according result of the SED fit for two of our objects.

4.5 RESULTS

After cross-matching our photometric HST and spectroscopic MUSE catalogs, the latter updated to contain only good profile fits, we found that we can identify 35 high redshift Ly α emitters in the lensing cluster MACS J0416 for which we have information from both data sets. We classified our Ly α emission based on the six profile types described above and defined two profile families into which we separated our sample: MULTI and SINGLE. The MULTI family contains 13 objects for which all profile shapes present a multi-peak, namely P3, P4, P5, and P6. The SINGLE family on the other hand contains 22 objects that show a single-peak profile, namely P1 and P2. Since P1 and P2 have been shown in our previous work to be the most prevalent profile types when it come to high- z Ly α emission, we also split the SINGLE family into these two profiles and compare them to each other. Table 4.2 summarizes the sub-samples we considered and the number of objects they contain.

4.5.1 Physical properties distributions in our sample

The first approach to comparing our samples to each other is to look at the distribution of the physical properties we derived. We will first compare the MULTI and SINGLE families, then do the same for the P1 and P2 profiles. The properties derived here are both obtained from HST photometry (E(B-V), Age, M_* , L_{UV} , SFR_{UV} , and $sSFR_{UV}$) and from MUSE spectroscopic data (redshift, $L_{Ly\alpha}$, $SFR_{Ly\alpha}$, $sSFR_{Ly\alpha}$, V_{exp} , N_{HI} , T/K, σ , τ). Because of the small

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Figure 4.1: Example of the HST postage stamps and best SED fitting for two of our Ly α emitters. *Top stamps:* MACS0416_00001596, *Bottom stamps:* MACS0416_00001984

Figure 4.2: Histograms showing the distribution of the MULTI and SINGLE sub-samples for the physical properties obtained through the photometric analysis in the top four panels along with the spectroscopic redshift obtained through the Ly α line. The bottom two panels show the distribution of the luminosity of our sources in the UV and the Ly α . The solid vertical line represents the median of the distributions, while the dashed lines show the position of the 1st and 3rd quartile.

Figure 4.3: Same as Fig. 4.2, but for the P1 vs P2 comparison.

sample size and the broad range in value for all our properties, we use the median of the distribution and the 1st and the 3rd quartile to help us compare the two distributions.

Figs. 4.2 and 4.3 show the distribution in redshift and luminosity of our sample along with the physical parameters obtained from the photometry. Going through the figure from left to right, top to bottom, we can see that the $E(B-V)$ distribution of both MULTI vs SINGLE and P1 vs P2 is mostly concentrated at low values of extinction and that the distributions tend to be very similar. This is unsurprising for Ly α emitters, as we expect them to experience less reddening in order to be detected.

In the next panel, the age distribution, given in log-scale, shows very young objects and some of intermediate age, but there is mostly a lack of older galaxies in this sample (Age $\gtrsim$ 1 Gyr). Furthermore, the SINGLE sample shows a preference for younger objects compared to the MULTI sample. If we compare the P1 and P2 distributions we can see that both contribute to the young population and that the distributions are mostly the same.

The redshift distribution of the MULTI sample is concentrated towards lower redshift, while the SINGLE family has some sources at higher

redshifts. This is in line with what we found for the larger sample of Ros21, where the multi-peak profile tend to not be detected at as high a redshift as the single-peaks. Whether this is due to a physical process or simply to technical limitations is still up for debate. If we look at the P1 and P2 distributions, in fact, we see that they cover the same range of redshift and do not present large differences in distribution, with P2 slightly preferring higher redshifts.

The next panel presents the distribution of the de-lensed stellar masses of our objects. We can see no clear differences between the MULTI and SINGLE distribution, as well as between P1 and P2. The distributions are mostly flat and show no preferred masses, but we do see some very low mass objects, which are in line with what is observed in cluster fields (Rin21).

Finally, the two luminosity distributions, in the UV and from the $\text{Ly}\alpha$ line, have medians that mostly agree and they span a similar range. Both for the UV and the $\text{Ly}\alpha$, it appears that the MULTI sample might be slightly shifted towards lower luminosities, but the separation is too small for us to be able to conclude that they are indeed fainter. Also P1 seems to be slightly fainter than P2, which is in line with what we found in Ros21, but again a combination of low number statistic and the lack of a clear separation prevents us from drawing a definitive conclusion.

The second set of distribution comparisons focuses on the SFR and sSFR of our sample, along with the v_{exp} and N_{HI} parameters, which will later be directly compared to the SFR and sSFR of our sample in Figs. 4.13 and 4.14. Again we go from left to right, top to bottom through the panels of Fig. 4.4 for the MULTI vs SINGLE comparison and Fig. 4.5 for P1 vs P2.

We can again see that for the SFR_{UV} the medians agree quite nicely. We notice how the MULTI sample is broader in distribution than the SINGLE, as is P2 compared to P1. If we compare this to the distribution of $\text{SFR}_{\text{Ly}\alpha}$, we notice how the medians of this other distribution agree with the medians in the UV quite nicely. We also notice that the SFR calculated using the $\text{Ly}\alpha$ line reflects the distribution of the $\text{Ly}\alpha$ luminosity, which is unsurprising, since the way the SFR is derived is through use of only $L_{\text{Ly}\alpha}$ and fixed conversion factors to obtain the luminosity in $\text{H}\alpha$ and then the SFR (Kennicutt 1998).

The next two panels show the sSFR in the UV and $\text{Ly}\alpha$, respectively. We again see that the medians agree for both comparisons and that the $\text{Ly}\alpha$ distribution is broader than the UV. The MULTI family appears to have a lower median than the rest of the samples for the $\text{Ly}\alpha$, but both the range of the total distribution and within the quartiles make it compatible with the SINGLE distribution. In the P1 vs P2 comparison, we see that P1 tends

Figure 4.4: Similar to Fig. 4.2, but for the SFR and sSFR obtained both through the UV and Ly α . We also list the values for v_{exp} and N_{HI} in the bottom two panels, as we will compare them directly to the SFR and sSFR later. Once again, the solid and dashed vertical lines represent the medians and the quartiles of the distribution.

Figure 4.5: Same as Fig. 4.4, but for the P1 vs P2 comparison.

to be more concentrated than P2, which instead has a better defined tail towards lower sSFR in the UV.

The panel containing the distribution of v_{exp} shows that while the medians agree between MULTI and SINGLE, the former has no highly negative values and is mostly concentrated at low velocities (<200 km/s), the latter on the other hand is broader in distribution and has both very negative and positive velocities. If we look at the P1 and P2 comparison we can identify the P1 profiles as the main contributor to the negative velocities. This is due to the fact that the way the “shell-model” fits the observed emission allows more leeway to symmetric profiles, compared to profiles with a more distinct shape.

Finally, comparing N_{HI} between our samples we find that SINGLE spans a broader range compared to MULTI, which is mostly focused on intermediate values. We see that some of our objects still have column densities $N_{HI} < 10^{17} \text{ cm}^{-2}$ and are as such LyC leakage candidates. There are 10 in total of such sources and we will briefly describe their distributions separately in the next section. Regarding the P1 and P2 samples we still find what we found in Ros21. Namely, that the P1 sample has lower HI column densities than the P2 sample, but that this time the separation is

even more evident with the P2 objects having mostly only high column densities, as opposed to a more varied range as in our previous work.

The next set of plots shows the distribution of the physical properties associated to the “shell-model” that was used to fit the Ly α emission. We present the distributions of v_{exp} and N_{HI} again for completeness, but reference what has been said in the previous paragraphs regarding their distribution. Once again we go left to right, top to bottom and Fig. 4.6 shows the MULTI vs SINGLE comparison, while Fig. 4.7 shows P1 vs P2.

The first panel that we have yet to discuss is T/K. Here we notice that the SINGLE distribution is broader than MULTI, but that the medians ultimately agree. Both samples also span almost the entire range of allowed values. For the P1 vs P2 case, we see a clearer separation, as the P1 values are mostly concentrated in the lower half, while P2 covers the higher half of the range. We did not see this behavior in our previous work where our sample was larger but also more diverse, as it covered different lensing clusters and a region of the field.

The next panel shows the σ distribution for our samples. We find here again what we found in our previous work, that MULTI tends to have higher values of σ compared to SINGLE. For the P1 and P2 comparison, it seems that P2 tends to have a broader range of σ compared to P1, but their medians end up being very close. We will further comment on the MULTI vs SINGLE σ comparison once we plot their M_* - σ relation, where the σ here is still the initial width of the line and not the velocity dispersion of the stellar component of the galaxy.

The final panel in this comparison shows the distribution of τ_d . In this case, MULTI seems to prefer lower values of τ_d with the hint of a tail towards higher values. SINGLE on the other hand is rather flat and spans a broader range. If we compare P1 and P2 for this quantity, too, we notice that the samples cover the range sparsely with no clear preference in values, as the wide range between the 1st and 3rd in both distributions attests.

4.5.2 Distributions for the LyC Leak candidates

Using the $N_{\text{HI}} \leq 10^{17} \text{ cm}^{-2}$ criterion, we identify 10 LyC leakage candidates in our sample. Two of these belong to the MULTI family, while 8 belong to the SINGLE sample. Most of the latter are P1 sources, which is unsurprising since P1 tends to have lower values than P2 in N_{HI} and so falls more easily inside the criterion. LyC leakage candidates have been identified as important objects to study, especially at high redshifts, since their presence allows for more ionizing photons to escape the host galaxy and ionize the

Figure 4.6: Histograms showing the distribution of the physical properties associated to the “shell-model” for the MULTI and SINGLE sub-samples. The solid and dashed lines represent the median and quartiles of the distribution.

Figure 4.7: Same as Fig. 4.6, but for the P1 vs P2 comparison.

surrounding gas, thus contributing more to the re-ionization of the universe. We present here the distribution of the physical properties of these objects to compare them to the rest of our sample and potentially identify a property that might behave differently than the general population.

Fig. 4.8 presents mostly the photometrically derived quantities along with the redshift and the Ly α luminosity as described for the previous figures. We notice how the E(B-V) maintains the general trend of our samples, with values of 0.0 being the most common. We also notice, however, that higher values of E(B-V) are adopted for some of our LyC candidates. The distribution of the ages shows a varied picture, where we have both young and older objects in our current sample and mirrors what has been found for the masses of these objects, namely that LyC candidates seem not to be uniform in their properties. We notice how the range spanned renders the distribution flat compared to our general sample. If we look at the redshift, we see that most of our sources are concentrated at lower redshifts, with one source occupying the position around $z \sim 6.1$. As for the ages, we have both low-mass and intermediate-mass objects in a rather flat distribution. This is in line with the masses found in Izotov et al. (2021), but we notice that we not only span the same mass range, but that

Figure 4.8: Same as Figs. 4.2 and 4.3, but highlighting only the LyC leakage candidates regardless of profile type.

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Figure 4.9: Once again, same as Figs. 4.4 and 4.5, but highlighting only the LyC leakage candidates.

Figure 4.10: Same as Figs. 4.6 and 4.7, but only the LyC leakage candidates are shown.

our sources also touch even lower masses. Finally, both the luminosity distributions follow roughly what we saw for our general sample, with L_{UV} being flatter than $L_{Ly\alpha}$ but spanning a range similar to the general sample, where $L_{Ly\alpha}$ is more concentrated around $\log_{10}(L_{Ly\alpha}) \sim 41.5$.

Fig. 4.9 shows the next set of properties. We see that the SFRs, both using the UV and the $Ly\alpha$ to derive them, fall into a region of our parameter space that agrees with the average SFR of our general sample. The same can be said for the $sSFR_{UV}$ and the $sSFR_{Ly\alpha}$. The distributions here are of course flatter because of lower number statistics, but they seem to not concentrate on a specific area of the plot. Finally, our LyC candidates show both positive and negative v_{exp} centered roughly around slightly positive velocities. The values of N_{HI} are of course limited to being < 17 , since this is the definition criterion for this sample.

Finally, Fig. 4.10 shows us that again the properties displayed have no preferred value. T/K has more LyC candidates at lower values, but there are also two objects sitting on the other end of the allowed range. The values of σ are situated at around the average value of our general sample and finally τ_d is flat and spread out over the entire allowed range.

We conclude from this that the LyC leakage candidates do not show evidence of behaving differently from the rest of our sources, except in their values of HI column density, which is what defines them as a sub-sample.

4.5.3 Highlighting relations of different galaxy properties against M_* and SFR

We used the two more stable parameters that we get out of the SED fit to test some possible relations between the $Ly\alpha$ properties and the physical properties of our objects. We divided this analysis in two parts, the first focused on testing the relation of different properties with the de-lensed mass of our galaxies and secondly on the relation with the SFR, both obtained from the UV and $Ly\alpha$. Most of the quantities we tested yield no significant or interesting trends for our sample. Here we restrict our analysis to those properties which show a correlation with each other or would make for an interesting comparison with the literature.

We once again separate the MULTI vs SINGLE and P1 vs P2 comparison in different figures and will go through the panels as we did before. The first relation we tested in Figs. 4.11 and 4.12 is the M_* - SFR_{UV} relation. We notice how the SFR increases with increasing mass and seems to follow a clear trend. We have too little data to do a significant linear regression for this relation, but we note that if done, the slope of the MULTI samples follows what can be expected for a mixture of main sequence and starburst

Figure 4.11: Figure showing the relations between our derived properties for the MULTI and SINGLE sub-samples. *Top-left*: M_* after the lensing correction against SFR_{UV} . *Top-right*: M_* after the lensing correction against $SFR_{Ly\alpha}$. *Bottom-left*: Direct comparison between the two SFRs, where the solid black line represents the identity. The red circles are the LyC leakage candidates identified through $\log_{10}(N_{HI}) \leq 17$. *Bottom-right*: Relation between the de-lensed M_* and the σ describing the width of the initial $Ly\alpha$ emission prior to the resonant scattering. We also show a linear regression fit for this plot.

Figure 4.12: Same as Fig. 4.11, but for the P1 vs P2 comparison.

objects based on the work in Rin21. The SINGLE points instead have a flatter slope more in line with a main sequence only sample. Since these are the two more populous samples in our analysis, we will further compare this relation to previous works in Fig. 4.15.

For the P1 vs P2 comparison instead, we see again that P2 follows an increasing trend in SFR with mass, but note that P1 seems to just show a scatter and no significant trend. In fact, the P2 slope, if calculated, follows what we expect to see for a main sequence population in Rin21.

To the right of the previous panel we test the same relation but for $\text{SFR}_{\text{Ly}\alpha}$. We do this mostly to check whether the trend with mass holds even for SFRs calculated using the Ly α line and constituting in this way a lower limit to the SFR, rather than the true value itself. We see that the MULTI sample maintains the trend we saw before, even if the relation is not a tight, but the SINGLE sample shows a clear split after $M_* \sim 10^{6.5} M_\odot$, thus showing again more of a scatter than an ordered relation. We can further investigate this by comparing what happens with P1 and P2. As we saw for the previous panel, P1 does not show any significant trend with mass, but the same can now be said for P2. Considering this is a lower limit estimation of the SFR, we can say that the general effect of not being

able to collect all the light emitted in the star formation event weakens the trend with mass or breaks it up completely if it was weaker to begin with.

Since we compared the relation of the two SFRs with mass, we move to a direct comparison between them in this panel. The solid black line shows the identity ratio and we can see that most of our points are either below the line or agree with it within their errors. Considering the $\text{Ly}\alpha$ SFR is a lower limit, we expect such positions in this plot. What is puzzling, however, is that some of our points lie clearly above the identity line ($\text{SFR}_{\text{Ly}\alpha} > \text{SFR}_{\text{UV}}$), both for the MULTI and SINGLE sample. We first suspected that maybe the LyC leakage candidates might be involved, but we find that they do not have a particular preference of where they are in this plot (see the red circles).

Another reason why these points might be higher in SFR using the $\text{Ly}\alpha$ rather than the UV could be because the calibration of the $\text{SFR}_{\text{Ly}\alpha}$, while empirical, yields in general higher SFRs compared to the UV. Finally, and since most of the points that are above the line come from the SINGLE family, we can also see that the P1 and P2 samples both have points above and below the identity line, thus not identifying a specific profile that might be responsible for this discrepancy.

The last panel for this figure tests the relation between de-lensed stellar mass and the initial Gaussian width of the $\text{Ly}\alpha$ line. We find that this relation seems to correlate with mass, thus showing that objects with broader initial emission also seem to be in general more massive. Interestingly, we not only recover that MULTI objects have broader initial emission than SINGLE objects, like we saw in Ros21, but also that the slopes of the relation shown here are in agreement within their errors. It would seem that whatever mechanism broadens the emission in the MULTI sample, does so in the same way independent of mass. We test this trend also for P1 vs P2 and recover a similar behavior with mass.

For our second test of possible relations, we present Figs. 4.13 and 4.14 to showcase our results. We first would like to compare the SFR_{UV} to the effective temperature of the gas T . We immediately notice that the the MULTI sample shows a very clear anti-correlation between these two quantities. This might be explained by the fact that the warmer the gas is, the lower we expect the star formation efficiency to be, and this would translate to a lower SFR. It is interesting to note that the method to derive T/K and the SFR are clearly distinct, but that we do find a relation that we can expect nonetheless. The SINGLE family instead does not seem to follow a particular trend in this case, however. As we pointed out for the comparison with the M_* - SFR_{UV} , our sample size is quite small, so any lack of relation could also be due to the small number statistic. In fact, if we

Figure 4.13: Figure continuing to show the relations between our derived properties for the MULTI and SINGLE sub-samples. *Top-left*: SFR_{UV} against T/K. We also show the linear regression in solid lines for this relation. *Bottom-left*: v_{exp} vs sSFR_{UV}. *Top- and Bottom-right*: HI column density against SFR for both the Ly α and the UV, respectively. The solid black line indicates below which value our sources are considered LyC leakage candidates.

Figure 4.14: Same as Fig. 4.13, but for the P1 vs P2 comparison.

look at the P1 vs P2 comparison, we notice that P1 follows a slope similar to MULTI. The small range of SFR spanned though and the small number might just make this a coincidence. If we look at P2 in this example, we see that the points are definitely scattered to the point of not really following any type of linear relation.

The panel in the bottom-left of the two figures shows how the $sSFR_{UV}$ relates to the expansion velocity v_{exp} of the gas and dust shell. We argue that we do not see a linear trend here, both in the MULTI against SINGLE, and in the P1 vs P2 sample comparison. The scatter in the relation for all samples seems to cover any trend there might be. This is in line with what was presented in Karman et al. (2017).

Finally, we checked if we could identify any relation between the HI column density and the SFR derived using either the UV or Ly α line. In particular, we wanted to test whether the LyC leakage candidates occupied a specific spot in this plot. We notice that there seems not to be any clear trend of SFR with N_{HI} both for the MULTI and SINGLE comparison as well as for P1 and P2. We also notice that the LyC leakage candidates, all the points to the left of the black solid vertical line, have SFR that are in agreement with the average value of the sample, thus not standing out

from the rest of the points. This counts again for both comparisons. We conclude again that the LyC candidates do not appear to act in a particular way compared to the rest of the sample.

Finally, we take a more detailed look at the M_* -SFR_{UV} relation in Fig. 4.15. To allow for a better comparison with previous works, we plot our data superimposed on previously derived relations. Specifically, we make use of the linear regression found in Rin21 for main sequence and starburst galaxies, in red and blue respectively. The line type used indicates the redshift bin that has been considered for the linear fit. We also point out that the fits have a cutoff in mass at 10^8 for $z = 2.8 - 4$, $10^{8.5}$ for $z = 4 - 5$, and $10^9 M_\odot$ for $z = 5 - 6.5$. So we caution that for most of our sources, the relations seen here are extrapolations rather than part of the fit.

We also compared our sources to the relation found in Caputi et al. (2021) (hereafter KC21) for the lower envelope of the starburst galaxies defined as $\log_{10}(\text{sSFR}) = -7.60$. This lower envelope is derived from the results obtained in Caputi et al. (2017) where the authors presented the M_* -SFR relation for both the main sequence and the starburst cloud. We can see in Fig. 4.15 that $\sim 66\%$ of our sources (23 out of 35) lie on the starburst relation and that those that instead are closer to the main sequence relation of Rin21 come from both the SINGLE and MULTI samples.

We also notice that even in this case, the LyC leakage candidates show no preference for one or the other relation, with some being closer to the starburst while others fall closer to the main sequence. In fact, only 4 out of 10 LyC candidates lie above the lower envelope for the starburst sequence. We looked closer at the best fit ages of the 6 LyC candidates that fall into the main sequence relation and found that we both have 2 young ($\approx 10^7$ Gyrs), two intermediate ($\approx 10^8$ Gyrs), and 2 older objects ($\approx 10^9$ Gyrs). Again, we can find no clear preference in physical configuration for these objects.

4.6 SUMMARY AND CONCLUSIONS

We analyzed a sample of 35 lensed Ly α emitters detected in the region of the cluster MACS J0416 using both MUSE spectroscopy and HST photometry. We measured the line emission in our spectra and used the “shell-models” generated using the tlac radiative transfer code to assign physical properties to the initial emission and the expanding gas and dust shell scattering and extinguishing the Ly α photons. Following this analysis, we defined six different Ly α profile types, based on the visual shape of the line emission, and grouped our data into two profile families:

Figure 4.15: Figure showing a detailed comparison between our data points and the linear regression of the M_* - SFR_{UV} relation found in previous works. The solid black line shows the lower envelope for starbursts as defined by KC21, while the blue and red lines indicate the best fitting of the starburst sequence and the main sequence as obtained by Rin21, respectively.

MULTI and SINGLE. The former being all profiles that present a multi-peak shape (13 objects), the latter being all profile showing a single peak in their emission (22 objects). We further subdivide the SINGLE family to compare the symmetric Ly α shape to the profile showing an asymmetry in the red.

We made use of our photometric data to derive the physical properties of our galaxies by performing an SED fit using the fitting code LePHARE by fixing the redshift of our sources to the one measured using the MUSE spectroscopy. This allowed us to define a stellar mass, ages, the extinction parameter $E(B-V)$, along with using the UV luminosity of our source to determine SFRs and sSFRs. Finally, we combined these quantities with the parameters obtained from the “shell-model” to compare the behavior of our defined profile families and types with each other.

What we find is that, in general, our sample consists of young, low-mass, mostly unobscured Ly α emitters. This is unsurprising, as we expect most of the high- z Ly α emitter population to have lower extinction in order for their emission to be detected. We saw a similar trend in both our previous works as well. The combination of deep MUSE observations and a magnifying lensing cluster also enhance the probability of finding faint, low-mass objects, as we are effectively probing a very small area behind the cluster. As low-mass galaxies tend to be more common in the universe, we expect to see mostly such objects in a small area.

When we compare our defined profile families, we principally recover what we found in our previous work (Ros21): the MULTI family has generally a wider initial emission than the SINGLE family and the P1 profile tends to have lower HI column densities than the P2 profile. Furthermore, P1 has been shown in Ros21 to be lower in flux and Ly α luminosity than P2 and we can see a similar trend here, with $L_{\text{Ly}\alpha}$ being slightly lower for P1 than P2. Something that we did not find in our previous work, is that the T/K parameter is mostly low for the P1 sample and high for the P2 sample. We acknowledge this trend, but caution again over-interpreting it, as our samples are rather small and since this has not been observed in a larger, more general sample. For all the other parameters considered, we do not notice much of a difference between samples.

We also identified 10 LyC leakage candidates (2 in MULTI, 8 in SINGLE) by using the criterion $N_{\text{HI}} \leq 10^{17} \text{ cm}^{-2}$. These objects are interesting because they are able to emit more ionizing radiation into the universe and would be able to contribute more than a non-leaking Ly α emitter to re-ionization. We looked at the distribution of the physical properties of the LyC candidates in our sample and apart from the HI column density used to define them, they do not show clear differences in behavior with the rest

of our sources. We especially wanted to verify if their SFR showed higher values compared to our other galaxies, but we do not find any evidence of this. Finally, we compared our mass distribution to Izotov et al. (2021) and found that we cover a similar mass range, but reach lower masses compared to this previous study ($M_* < 10^{7.2} M_\odot$).

We also looked at possible correlations between properties across our sample. We find that plotting the de-lensed M_* against the initial Gaussian width of the $\text{Ly}\alpha$ line σ reveals a positive correlation between the two parameters. In fact, not only do we recover what we saw in our previous work, that MULTI has in general higher σ than SINGLE, but we also find that the M_* - σ relation shifts by about the same amount independent of mass. We conclude that this broadening of the emission in the MULTI sample might depend on a process that is independent on the mass of the host galaxy. Another relation that seems solid is the $\text{SFR}_{\text{UV}}\text{-T/K}$ relation, which shows a tight anti-correlation for the MULTI sample.

Finally, we compared our data points to the M_* -SFR relation found in Rin21 for both main sequence and starburst galaxies, and the lower envelope of the starburst cloud in Caputi et al. (2021). We find that our sources lie both on the starburst and the main sequence relation, with a slight preference for the starburst lines. We caution, however, that most of our sources lie below the cutoff in mass performed for the linear fit in these works. Effectively, our data points agree with the extrapolation of the relation, rather than the relation itself. Once again we highlighted the LyC leakage candidates and found they have no preference between the main sequence and starburst cloud.

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4. PHYSICAL PROPERTIES OF LYMAN- α PROFILE SHAPE FROM MUSE AND HST

Science Institute (STScI). This research made use of Astropy,² a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018).

²<http://www.astropy.org>

5. CONCLUSIONS AND FUTURE PROSPECTS

In this work I tested the complex picture surrounding high redshift Lyman α ($\text{Ly}\alpha$) line emission and its implications for the physical properties of the emitting population. I divided my sources into different samples so that I could compare line emitter galaxies to non-emitters and different line profile families to each other. I found that most $\text{Ly}\alpha$ objects are individually very different in both physical and emission parameters, but that the samples they belong to end up spanning a very similar parameter space to each other. Statistically speaking, I do not find significant differences between $\text{Ly}\alpha$ emitters and non-emitters, neither between the different profile types. The differences I do find are a broader initial emission for the multi-peak profile family compared to the single-peak family, and a lower hydrogen column density and effective temperature for the symmetric single-peak profile compared to the red asymmetric profile.

These findings will have to be investigated further with additional data and models to physically justify them. The new generation of telescopes starting to operate in the coming years will provide much a longer baseline for spectroscopy, allowing us to study rest-frame optical emission lines in high- z galaxies. The simultaneous study of $\text{Ly}\alpha$ and optical emission lines will yield a much clearer picture on the physical conditions in the interstellar media of these emitters.

In Chapter 2 I compared a sample of serendipitously discovered MUSE $\text{Ly}\alpha$ emitters to a sample of non-emitting high- z galaxies located in the same region of the sky and spanning the same redshift range. I found that

the overall distribution of the spectral energy distribution (SED) fitting properties of the emitter and non-emitter samples with SMUVS photometry do not differ substantially from each other, both before and after the mass-matching. I conclude that the Ly α emitters seem to be similar to the general SMUVS population. I also found, however, that the E(B-V), age and stellar mass distributions have some differences that might stand out more in a bigger Ly α emitter sample.

Especially the age distribution appears to be interesting. I found that it showed a bimodality for both SMUVS Ly α emitters and non-emitters and decided to further test the issue. I compared the average star formation rate (SFR) of my SMUVS Ly α emitters, obtained by dividing the best fit SED stellar mass with the best fit age, to the instantaneous lower limit SFR obtained from the Ly α emission. I expect this ratio to be in favor of the average SFR ($\frac{\text{SFR}_{\text{Ly}\alpha}}{\text{SFR}_{\text{avg}}} \leq 1$), if the emission from the Ly α comes from the same star formation event that formed the bulk of the stars that can be seen in the SMUVS photometry. I found, however, that the old emitters (> 1 Gyr) tend to have higher Ly α SFRs compared to their average SFR. This hints at the possibility that some of my old emitters are experiencing a second event of star formation, disjointed from the first that formed the bulk of their stars.

Additionally, the Ly α sources I found that are not detected in SMUVS are most likely below the mass completeness limit of the survey. I notice how, if I compare their Ly α luminosity ($L_{\text{Ly}\alpha}$) to the SMUVS Ly α emitters, the non-SMUVS sources reach luminosities clearly below the ones reached by SMUVS sources. Since the Ly α emission depends on the ionizing radiation and not on mass, this aspect of my sample is as of now still puzzling.

Finally, in this work I introduced an emission line shape classification scheme that grouped Ly α emitters together based on whether they showed a single symmetric line, a line with asymmetry towards the red (a.k.a a red tail) or two peaks, with the main peak being situated in the red, while a smaller peak was located in the blue (a.k.a a blue bump). I found that the first symmetric profile was the most numerous, but also that the lack of a continuum detection made it hard to determine if there were not more shapes hidden below the detection limit.

Starting from this last result, the next step in my thesis was to analyze deeper data to expand my profile classification and study the properties linked to the Ly α emission by fitting “shell-model” spectra generated using a radiative transfer code to the emission profiles. In Chapter 3 I show a sample of Ly α emitting galaxies detected in a blank field inside the COSMOS area and a sample of lensed Ly α emitters detected behind three

CLASH (MACS J0329, MACS J1206, MACS J1931) and one *Hubble* Frontier Fields (HFF) cluster (MACS J0416). The advantage in this new sample is that I can increase the profile shapes I recognize from 3 to 6. I detected not only a red asymmetry in some of the blue bumps, I also found double peak emission, where none of the two peaks appears much more prevalent than the other, and even one object with a red bump (prominent peak in the blue and smaller peak in the red). These profiles show no clear preference in redshift, when I tested it, but I found that the more detailed profiles do not appear at the highest redshifts ($z \gtrsim 5$). I used these new profile shapes to define two profile families: SINGLE, containing all the profiles showing just one peak, and MULTI, containing all the profiles with multiple peaks.

I fitted my spectra with the aforementioned “shell-models” and obtained physical properties for the gas and dust shell surrounding the emitter galaxy. Additionally, the “shell-models” also provides information on the initial Ly α emission in the form of the Gaussian width σ and the intrinsic equivalent width. I found that if I compare SINGLE and MULTI, most of the properties agree across my samples. The Gaussian width σ is the only parameter that shows a difference in behavior between SINGLE and MULTI, with MULTI having larger σ s compared to the SINGLE objects.

Since once again the symmetric single line profile (P1) and the asymmetric single line (red tail, P2) were the most common profile types, I also compared them to each other. I found that the P1 profiles tend to have lower fluxes and luminosities compared to the P2 profiles. This might be due to physical reasons, but could also be caused by instrumental limitations and can at the moment not be investigated further. What I expected to see when comparing the two profiles, was P1 having lower neutral hydrogen column density (N_{HI}) compared to P2. In fact, a more symmetric profile is in part caused by having low N_{HI} . P1 and P2 show exactly this trend.

Finally, I highlight 30 objects for which $\log N_{\text{HI}} < 17$, which makes them Lyman continuum (LyC) leakage candidates. LyC leakers are believed to be an integral part of the re-ionization process as they are able to contribute a higher percentage of ultraviolet (UV) ionizing radiation compared to a non-leaker galaxy. In my next work I analyzed 10 of these objects further by using SED fitting to add more physical information to my source sample.

Chapter 4 considers the deepest cluster data I had to further analyze my sample of high- z Ly α emitters. I made use not only of MUSE data for MACS J0416, but also used the *Hubble* Space Telescope (HST) photometry available in the same area to fit SEDs to my emitter sample and so obtain physical properties linked to the galaxy rather than the Ly α emission. I looked at the parameter distribution and specific relations between

parameters for the sources that had both photometry and spectroscopy available. I found that my sources are mostly young, unobscured and low-mass objects. If I compare MULTI and SINGLE again, I found that for most properties these objects do not differ statistically. Once again, I found that the Gaussian σ of the intrinsic emission is higher in MULTI, but interestingly it also seems to positively correlate with stellar mass. Not only this, but the shift from the SINGLE single relation to the MULTI values appears to be constant, independently of mass.

I also studied P1 and P2 again and found that not only do they behave as they did in the previous chapter for luminosity and N_{HI} , but that the effective temperature of the expanding gas and dust shell is low for P1 and high for P2. I did not find this trend in the more general sample of Chapter 3, which could be due to low number statistics creating an artifact here, or the previous sample not being homogeneous in what kind of objects it detected, due to different exposure times between MUSE pointings.

I also isolated the LyC leakage candidates and looked at their properties distributions in comparison with the rest of my sample. I did not find any evidence for the LyC candidates to be physically different with respect to the rest of my sample, except for the N_{HI} which defines them. I found, however, that they reach lower masses than what has been until now found in the literature. It would appear that there is no particular configuration of physical properties that causes a possible LyC leakage, but rather that the only defining characteristic is the low N_{HI} .

Finally, I tested the M_* -SFR relation of my sample by projecting my sources onto the relations found in previous works. I saw that my galaxies both fall onto the starburst and the main sequence. On top of this, I also highlighted the LyC candidates and found that they do not prefer either sequence, but rather spread out evenly among them. I would also like to point out, that the masses of my objects are almost all lower than the cut-off mass used for the linear interpolation of these relations. This means that my sources agree with the extrapolation of the relation found in the literature, rather than with the relation itself.

5.1 FUTURE PROSPECTS

In this work I presented different issues of the study of the Ly α line that might be pursued further in the future. I have found hints of possible differences between my samples, but always fell short because of a lack of more detailed data to physically justify why these differences appear.

With the eventual launch of the *James Webb* Space Telescope (JWST), some of the problems I encountered might be solved. The larger range in wavelength of its spectroscopic instruments will allow for a more complete study of the Ly α emission.

One interesting aspect that JWST will be able to probe is obtaining spectroscopic information on multiple hydrogen lines from the same object and using the same instrument. This will allow us to have the same data quality for all the observed lines, and also ensure that the emission observed is caused by the same ionizing phenomenon. We will finally be able to see both the Ly α emission of a source jointly with its H α emission. Considering that we have a good idea of the ratio between hydrogen emission lines and since H α does not resonantly scatter in neutral hydrogen and is less affected by dust attenuation, we will be able to better understand the processes that remove Ly α photons from our line of sight.

While I only applied the “shell-models” generated by the radiative transfer code `tlac`, and did not actively work on developing them, I can still see how having more hydrogen emission lines available for a single object could open the doors to further improve our theoretical understanding of the processes shaping the Ly α line. With the ability to detect H α , or even Pa α , and the possibility of some lensed sources to have their star formation spatially resolved, we would be able to possibly break some of the degeneracies that are still present in today’s treatment of the origin of the Ly α line.

Finally, JWST and the Euclid space telescope will enlarge our sample of high- z galaxy photometry, thus allowing us to test for differences in behavior between Ly α emitters and non-emitters on a much larger scale. If any of the differences found in Chapter 2 need more objects to become evident, then this potential larger sample is the place to go look for them. The new space instruments will also allow us to test for rejuvenation on a much larger population of galaxies. In combination with more information on the actual amount of light lost to the Ly α provided by multiple hydrogen lines, we would then be able to compare a Ly α SFR that is now no more a lower limit, to the estimated average SFR of the population calculated assuming a single starburst event.

To conclude, once the new space telescopes are launched a new and exciting era for Ly α observations and modeling is sure to begin. And once the E-ELT is completed, ground-based observations will be able to further test this interesting topic.

5. CONCLUSIONS AND FUTURE PROSPECTS

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SUMMARY

Where we come from has always been a question that humanity has sought the answer to. Since the advent of science, and specifically astronomy and astrophysics, this question has driven our study of the stars and the Universe. In the last century, many discoveries advanced our knowledge of our reality and the way it came to be, specifically that we are only a tiny speck in the vastness of the Universe. This knowledge is incomplete, however, since it is very hard to pierce space and time and observe objects early in the history of our reality. Understanding where and how all the matter that we can observe today has been formed is one of the main questions that we need to answer as a scientific community. And since most astrophysical objects are birthed in galaxies, it is the evolution of the latter that we want to understand to glimpse into the history of our Universe.

There are mainly two ways of uncovering the past evolution of galaxies. One way is indirect and analyzes the remnants of previous stellar populations by looking for specific tracers in the current population making up the galaxy. This allows for greater detail in our study, since it looks at close-by galaxies that have a strong detectable signal.

The other method is more direct and aims at observing galaxies very far away from us to see the evolution happen in real-time. The further away a galaxy is from us, the more back in time we go, since the photons need longer and longer to reach us. This second method allows us to see what our own galaxy and our neighbors might have looked like in the past. The downside of this method is that the signal of a galaxy weakens the more distant it is, so powerful instruments like the upcoming *James Webb* Space Telescope (JWST) are needed to maximize the detail we can get.

In the last decade, the study of the formation and evolution of galaxies across the Universe has shown that most of the stars ever born have been formed about 10 Gyrs ago. Today's star formation is in decline as less material is available to form stars and before the 10 Gyrs mark, the star formation was increasing when the matter in the Universe began to condense into large scale structures.

Stars are the main driver that shapes the chemical abundances in our world and it is so important to understand how many and what type of stars were formed in the past. One way of seeing star formation happen is looking for ionized hydrogen atoms recombining and emitting photons at a specific wavelength. This emission is called Lyman α and is one of the strongest emission lines in the Universe. It has unfortunately some very complicated drawbacks that I will describe in the next sections.

In this thesis, I aimed to study the Lyman α emission of distant galaxies to test if this powerful line had any preferred physical state of its host galaxy. I compared emitters to non-emitters first to see if they looked different in some way, then I detailed the emission itself by using model spectra to match the shape of the emission profile. This later work allowed me to assign physical properties to the components responsible for the emission I observed. Finally, I used very deep and detailed observations to further characterize a sample of emitters and test if their configuration had a preferred state.

THE IMPORTANCE OF STUDYING DISTANT GALAXIES

Before we delve into the Lyman α line, I should spend some time setting the stage for the distant galaxies themselves. The distance these objects are at and the expansion of the Universe dim the light we can detect coming from them. The expansion of the Universe is responsible for shifting the rest-frame wavelength of the emitted photons towards longer values, effectively turning the light redder. This effect is what we call redshift.

Star formation in distant galaxies can be detected in many different ways, whether it be by measuring their rest-frame ultraviolet, infrared, or radio emission or by using emission lines linked to the formation of stars. Out of these possibilities, the ultraviolet and the infrared can normally be combined to paint a better picture of the star formation rate of the galaxy. The ultraviolet traces the emission of hot and young stars that have very short lifetimes and thus would only be present if there was ongoing star formation. The infrared comes from the thermal emission of the dust in and around the galaxy that has been heated by the ultraviolet photons emitted by the young stars. Since most of the radiation that comes from the infrared is radiation that has been subtracted from the ultraviolet, combining the two measurements allows us to reconstruct the total light emitted by the star formation event.

Using the radio emission of the galaxy is also a way of reconstructing its star formation rate, but with the radio comes a problem. Active galactic

nuclei also emit in radio frequencies and their total emission is so bright, that the entire rest of the host galaxy gets overshadowed and cannot be seen by our instruments.

Finally, one of the more reliable sources of information on the star formation rate is the study of emission lines. Certain elements can be excited by the infall of the gas or the compression happening when a star is forming. On top of this, radiation coming from new-born stars also excites the atoms surrounding it. When these atoms go back to their non-excited state, they emit a photon at a very specific wavelength that depends on the level of excitation and the type of atom that emits it. We can identify this emission as lines in the light spectrum that we observe and some of these lines we know are linked to star formation. Out of all the possible elements that we can use to characterize star formation, the hydrogen atom is the one that is less affected by other properties of the galaxy, such as the abundance of metals in their interstellar medium.

As I described before, hydrogen has one of the strongest emission lines in the Universe, but the Lyman α is not the most reliable line. We will see this in the next section. The hydrogen line that works best (so far) to determine the star formation rate of a galaxy is the H α line. This line is unfortunately quickly redshifted out of the wavelength coverage of most instruments, so if we want to study the hydrogen emission of distant galaxies, we still have to rely on the Lyman α line, which stays at optical wavelengths for longer. With the launch of JWST, however, studying the H α line in distant galaxies will become easier, since this new satellite has instruments that cover a large wavelength interval in the infrared.

There are specific areas in the sky where most high redshift studies have been performed, since acquiring data to do such studies is expensive both in time and money. Such areas are the Great Observatories Origins Deep Survey (GOODS), the *Hubble* Ultradeep Field (HUDF), and the COSMOS field. The extensive photometric catalogs available there allow for the study of high redshift galaxies at multiple wavelengths. Especially important are the redder wavelengths obtained with the *Herschel* and *Spitzer* telescopes, which help constrain both the stellar mass of high redshift objects, as well as their dust emission, which we mentioned before is important to have a complete picture on the star formation of these galaxies.

Finally, in this work, I used the *Spitzer* Matching Survey of the UltraVISTA Ultra-deep Stripes (SMUVS) to compare the physical properties of the Lyman α emitting galaxies that I detected in the COSMOS field against the properties of non-emitting galaxies found in SMUVS in the same area of the sky and redshift range. SMUVS is designed to combine the deepest data possible with the largest area we can cover. As I said

before, such combination of depth and area is hard to obtain because of how expensive it is. The SMUVS survey is thus uniquely qualified to cover a very important parameter space of high redshift galaxies that allows us to define their physical state and at the same time perform a vast statistical analysis.

LYMAN α EMISSION IN THE DISTANT UNIVERSE

The most common element in the Universe is hydrogen and as such it provides important information on the evolution of our reality. Whatever phenomenon we are observing, there is a high chance that hydrogen is somehow involved in shaping the properties of the light we see, whether by emitting light itself or by absorbing light at specific wavelengths. If we observe hydrogen in emission, one of the strongest lines we can observe in the Universe is the Lyman α line. While this line is very bright, it also comes with some issues that make observing it not straightforward.

The Lyman α line is emitted when ionized hydrogen (effectively a lone proton) catches an electron and becomes neutral hydrogen again. If the emitted photon encounters a neutral hydrogen atom in its path, it will be absorbed by the atom and the atom will lose its electron, becoming ionized. The photon will be emitted again in a different, random direction, if the newly ionized hydrogen recombines with an electron. Rinse and repeat, and what we have is called resonant scattering, where Lyman α photons keep being emitted and absorbed until they either leave the area where the neutral hydrogen is present or they manage to get redshifted out of the wavelength where the hydrogen can absorb them.

Additionally to resonant scattering, the line is also located in the ultraviolet part of the light spectrum. This means that dust grains are able to absorb it, warm up and then release their own radiation at longer wavelengths in the infrared. This phenomenon is different than resonant scattering, because instead of smearing the radiation over a larger area, but preserving the total amount of photons emitted, dust removes photons from the Lyman α line and adds them to the thermal infrared radiation. Those photons are effectively lost and cannot be recovered by measuring the thermal radiation of the dust, as can be done for the ultraviolet continuum, because the spatial distribution and velocity of the dust have a clear impact on how much light is absorbed and how this shapes the emission profile of the line. Until we can measure the accurate spatial distribution of the dust around a galaxy (which for now we cannot), the Lyman α radiation lost to dust will stay lost.

Figure 5.1: Example of a Lyman α profile presenting a red tail.

Modeling of the Lyman α line

As I described above, the Lyman α emission line is a complicated line to study. We need to not only take its origin into account, but also how it interacts with the gas and dust in the surrounding environment. The best way to approach this study is thus to simulate the emission and interaction of photons with a simplified version of reality. The way this has been done is by assuming a point-like origin for the Lyman α photons and propagate them through an expanding spherical shell of neutral hydrogen and dust. The complexity of these models scales with how much we know of the processes happening in and around a galaxy and how much of these phenomena we have observed.

Fortunately, the Lyman α line is special compared to other emission, as the shape of its profile often tells the story of how the photons ultimately escaped the galaxy. One major characteristic of the line profile is an asymmetry towards the red. What I mean by this, is that the line has a shallower decline towards the red, compared to the steeper curve in the blue (see Fig. 5.1). Initially, this “red tail”, as it is sometimes referred to, was believed to form because the surrounding medium was expanding and so the blue photons were scattered into resonance, while the photons at resonance or in the red were redshifted out of it. Recently, we found that the shape and prominence of the red tail depend also on the hydrogen column density (the density projected on our line of sight) and the obscuring capability of the dust.

Another feature of the Lyman α line is the presence of a blue peak, either much smaller than the red peak or about the same intensity. Such double-peak emission can again arise from the way the gas and dust shell moves with respect to the host galaxy or can be again due to how much hydrogen and dust are present. This makes it clear that if we want to describe this phenomenon, we need to not only take the movement of the shell into account, but also its composition.

The models that I used in this work take a number of parameters into account to describe the line emission observed. First of all they describe the initial emission, before the photons encounter any part of the gas and dust shell, as a point-like source that emits a Gaussian line profile with a Gaussian width σ and an initial equivalent width. The photons of the line then encounter the shell, that is described by a hydrogen column density, the optical depth of the dust (its obscuring power), an expansion velocity that if negative means that gas is falling in, rather than expanding outwards, and finally an effective temperature of dust and gas. All these parameters combined give rise to the profile we observe and can contribute to more than one detail in the emission. This makes the description of the line very degenerate and so the more observations we have, the better we can constrain what is happening in reality.

Observations of the Lyman α line

Now that we have discussed the importance of detailed Lyman α observations, how can we acquire such data? One of the more successful instruments in finding and detailing Lyman α at high redshift (but ultimately any emission line detectable in its optical range) is the Multi Unit Spectroscopic Explorer (MUSE) instrument mounted on the Very Large Telescope (VLT) located on Cerro Paranal in the Atacama Desert of Chile. MUSE is capable of observing a portion of the sky and record a spectrum for each pixel in its field of view. Thus the only requirement for a Lyman α emitter to be detected with MUSE is that the line emission is bright enough to overcome the noise intrinsic to the detector.

MUSE is a spectrograph and as such it has the advantage over the aforementioned photometry to be able to record more details of the sources it detects. One such detail that photometry lacks, is the emission line profile we talked about earlier. This higher amount of details comes at the price of less area covered compared to photometry, however, and a higher cost in both money and time to take these observations. It is thus important to use both photometry and spectroscopy to detect Lyman α emitters and

emitter candidates and to make use of each method's strength to further our analysis of the line.

Finally, since hydrogen emission is linked to star formation, it is possible to use the Lyman α line to determine the lower limit of the star formation rate of our emitter galaxies. As we discussed above, not all the light emitted as Lyman α photons reaches us because of the interplay it has with gas and dust. So whatever value of star formation we obtain from this line, will be only the minimum amount of star formation needed to make up for the flux we observe. A more reliable line to obtain star formation rates is the H α mentioned above. This line is going to become more available, jointly with the Lyman α line, once JWST launches and becomes operational. For now, another method of enhancing the information we can obtain on faint and distant Lyman α emitters is to make use of the natural magnification that galaxy clusters provide.

GALAXY CLUSTERS AS “NATURE’S TELESCOPES”

We know from general relativity that mass bends space-time and that light follows the geometry of it. If enough mass is concentrated in one place, the distortion of space-time can be enough to curve light in way that transforms the foreground object(s) into a gravitational lens. Light can then be concentrated towards us if an astrophysical object such as a planet or a star or a galaxy passes in front of another object emitting light. If the object acting as a lens is a galaxy cluster, however, we can magnify an entire portion of the Universe behind the lens, rather than just a few objects. Clusters where this effect has been measured are known as lensing clusters.

If a background galaxy is lensed, its image will be distorted by the distinct mass distribution of the lensing cluster, as well as projected into multiple images. One or more of these images will provide greater spatial resolution and have enhanced surface brightness due to the lensing effect. This allows us to not only capture more details both in the light profile and the morphology of our targets, than we would normally without a lens, but also to detect sources that would otherwise be too faint to see. The downside of this effect, is that before we can analyze the spatial and spectral properties of a lensed galaxy, we need to reconstruct the original image from the multiple and distorted images we see on our telescope detector.

Fortunately, we can measure the mass distribution inside the cluster and use that information to create a lens model that replicates the effect

Figure 5.2: Picture illustrating the process of a foreground object magnifying a background source as a result of gravitational lensing. Credit: NASA, ESA & L. Calcada

of the real lens. Working backwards from the multiple, distorted images we detect, we can then reconstruct the portion of the Universe that was magnified by the cluster. This not only allows us to have a picture of what lies behind the lens, but also to re-scale the luminosity of the objects we detect to their unmagnified, original value. So, once again, lensing clusters not only provide more spatial information on the sources that are lensed, but allow us to detect fainter objects that we would otherwise not be able to see.

THIS THESIS

In this work, I studied the Lyman α emission of high redshift galaxies detected by the MUSE instrument and tested their physical properties against a sample of non-emitter galaxies and against each other. In the second chapter, I compared the physical properties of the emitter population against the properties of the non-emitter galaxies. I found that there appears to not be a great difference between the two populations physically and that the older objects in my emitter sample show signs of a second event of star formation happening.

In the third chapter, I compared the physical properties linked to the Lyman α emission of two samples of emitters defined by their profiles. I found that multi-peak emission and single-peak emission look statistically very similar for the properties linked to the gas and dust expanding shell, but that the multi-peak profiles appear to have an intrinsically broader initial emission. I also found objects in my sample that hint at ultraviolet continuum leakage. These objects are believed to contribute more light to making the Universe transparent to radiation in an event called re-ionization, that happened in the early stages of the Universe.

Finally, in the fourth chapter, I make use of deep lensing cluster data to compare the physical properties obtained from photometry of the same two profile families of Chapter 3. I found once again, that these two families do not differ substantially in their statistics, but could find a trend of the initial Gaussian width of the Lyman α line with their stellar mass. This trend itself shows a shift to higher values for the multi-peak family, as was observed in the previous chapter, and interestingly the shift appears independent of mass. This result strengthens the importance of what I found in the previous chapter. I also compared the continuum leakage candidates to the rest of my sources and could not find a statistical difference in their parameters. It appears that these objects differ from a normal galaxy only by their low hydrogen column density.

SUMMARY

In conclusion, I opened some questions on the Lyman α emission that will need to be further investigated in the future, both by obtaining deeper and more detailed data and by developing better and better models, once the new data allows for a more in-depth test of our predictions.

SAMENVATTING

De mensheid heeft altijd al een antwoord gezocht op de vraag waar wij vandaan komen. Sinds de opkomst van de wetenschap, en in het bijzonder de astronomie en astrofysica, ligt deze vraag ten grondslag aan onze studie van de sterren en het heelal. In de vorige eeuw hebben vele ontdekkingen onze kennis van onze werkelijkheid en haar oorsprong vergroot, met name ons besef dat wij slechts een stipje zijn in het uitgestrekte heelal. Deze kennis is echter onvolledig, omdat het erg moeilijk is om ruimte en tijd te doorgronden en zo objecten uit de vroege geschiedenis van onze werkelijkheid waar te nemen. Een van de belangrijkste kwesties die wij als wetenschappelijke gemeenschap moeten uitzoeken is waar en hoe alle materie die wij tegenwoordig kunnen waarnemen is ontstaan. Aangezien de meeste astrofysische objecten in sterrenstelsels worden geboren, willen we de evolutie van deze stelsels begrijpen om een glimp op te vangen van de geschiedenis van ons heelal.

Er zijn hoofdzakelijk twee manieren om de evolutie van sterrenstelsels dusver te achterhalen. Eén aanpak is indirect en analyseert de overblijfselen van eerdere stellaire populaties door te zoeken naar bepaalde sporen in de huidige sterren waaruit een melkwegstelsel bestaat. Hierbij wordt gebruik gemaakt van nabijgelegen sterrenstelsels die een sterk, detecteerbaar signaal afgeven waardoor ze in meer detail onderzocht kunnen worden.

De andere methode is directer en richt zich op het rechtstreeks observeren van galactische evolutie in sterrenstelsels die heel ver van ons af staan. Hoe verder een sterrenstelsel van ons verwijderd is, hoe verder we terugkijken in de tijd, aangezien de fotonen afkomstig uit dit sterrenstelsel steeds langer nodig hebben om ons te bereiken. Op deze tweede manier kunnen we uitzoeken hoe ons eigen melkwegstelsel en onze buurstelsels er in het verleden mogelijk uit hebben gezien. Het nadeel van deze methode is dat het signaal van een sterrenstelsel zwakker wordt naarmate het verder weg staat, zodat krachtige instrumenten zoals de aanstaande *James Webb Space Telescope* (JWST) nodig zijn om zoveel mogelijk details te vergaren.

In het afgelopen decennium heeft onderzoek naar de vorming en evolutie van sterrenstelsels in het heelal aangetoond dat het merendeel van sterren die ooit hebben bestaan ongeveer 10 miljard geleden zijn gevormd. Tegenwoordig neemt de stervorming af omdat er minder materiaal beschikbaar is om sterren van te maken. Bovendien nam de stervorming gedurende de eerste tien miljard jaar van het universum toe omdat de materie in het heelal zich begon te concentreren tot grootschalige structuren.

Sterren zijn de belangrijkste drijfveren achter de chemische samenstelling van onze wereld, waardoor het dus zeer belangrijk is om te begrijpen hoeveel en welke soorten sterren er in het verleden zijn gevormd. Een manier om stervorming te observeren is door te zoeken naar geioniseerde waterstofatomen die recombineren en daardoor fotonen op een specifieke golflengte uitzenden. Deze emissie wordt Lyman α -straling genoemd en is een van de sterkste emissielijnen in het heelal. Helaas heeft het een aantal zeer ingewikkelde keerzijdes die ik in de volgende alinea's zal beschrijven.

In dit proefschrift heb ik gepoogd de Lyman α -emissie van verre melkwegstelsels te bestuderen om na te gaan of deze krachtige spectrale lijn enige voorkeur heeft voor de fysische toestand van zijn gaststerrenstelsel. Eerst vergeleek ik zogenaamde Lyman α -stralers met sterrenstelsels uit welke dergelijke straling ontbreekt om mogelijke verschillen te achterhalen. Vervolgens specificeerde ik de emissie door modellen van spectra te vergelijken met het geobserveerde emissieprofiel. Op deze manier kon ik de fysische eigenschappen identificeren van de componenten die verantwoordelijk zijn voor de emissie die ik waarnam. Ten slotte gebruikte ik zeer diepe en gedetailleerde waarnemingen om een aantal Lyman α -stralers te bestuderen en zo te bepalen of hun fysische eigenschappen overeenkomen.

HET BELANG VAN ONDERZOEK NAAR VERRE STERRENS- TELSELS

Voordat we ons in de Lyman α -lijn gaan verdiepen, moet ik eerst de basis voor verre sterrenstelsels zelf leggen. De afstand tot deze objecten en de uitdijning van het heelal verzwakken het licht dat we van hen kunnen waarnemen. De uitdijning van het heelal zorgt ervoor dat de golflengte van de uitgezonden fotonen naar langere waarden verschuift waardoor het licht in feite roder wordt. Dit effect noemen we roodverschuiving.

Stervorming in verre melkwegstelsels kan op veel verschillende manieren worden waargenomen: bijvoorbeeld door het meten van hun

uitgezonden ultraviolet-, infrarood- of radiostraling of aan de hand van emissielijnen die verband houden met de vorming van sterren. Voor deze methodes geldt dat observaties van het uitgezonden ultraviolet- en infraroodspectrum gewoonlijk gecombineerd kunnen worden om een beter beeld te krijgen van de mate waarin het sterrenstelsel sterren vormt. Het ultraviolet licht is afkomstig van hete en jonge sterren die een zeer korte levensduur hebben en dus enkel aanwezig zouden zijn als er sprake was van voortdurende stervorming. Het infrarood licht wordt veroorzaakt door de thermische straling van stofdeeltjes in en rondom het melkwegstelsel, die door ultraviolette fotonen uit jonge sterren worden verwarmd. Omdat het merendeel van het infrarood licht dus indirect afkomstig is van ultraviolette straling, kunnen we beide metingen combineren en zo het totale licht reconstrueren dat vanwege stervorming wordt uitgezonden.

Een alternatieve methode om de mate van stervorming te bepalen maakt gebruik van de radio-emissie van het sterrenstelsel. Echter, problematisch voor deze aanpak is het feit dat actieve kernen van sterrenstelsels ook straling op radiofrequenties uitzenden. Die totale emissie is zo helder dat de rest van het gaststerrenstelsel wordt overschaduwd, welke daardoor niet met onze instrumenten kan worden waargenomen.

Ten slotte is het bestuderen van emissielijnen een van de betrouwbaardere manieren om informatie over de mate van stervorming te achterhalen. Bepaalde elementen kunnen worden aangeslagen door de instroom van gas of de compressie die plaatsvindt wanneer een ster wordt gevormd. Bovendien zorgt de straling afkomstig uit pasgeboren sterren ook voor de excitatie van omringende atomen. Als deze atomen terugvallen naar een toestand met een lagere energie zenden ze een foton uit met een zeer specifieke golflengte die afhangt van het energieniveau van de aangeslagen toestand en het soort atoom. Wij kunnen deze emissie identificeren als lijnen in het lichtspectrum dat wij waarnemen. Van sommige van deze lijnen weten wij dat ze in verband staan met stervorming. Van alle mogelijke elementen die we kunnen gebruiken om stervorming te kernmerken, wordt het waterstofatoom slechts matig beïnvloed door andere processen in het melkwegstelsel, zoals de aanwezigheid van metalen in het interstellair medium van het stelsel.

Zoals ik al eerder beschreef heeft waterstof een van de sterkste emissielijnen in het heelal, maar de Lyman α -lijn is niet de meest betrouwbare lijn. Waarom dit zo is zal in de volgende sectie duidelijk worden. De waterstoflijn die tot nu toe het meest effectief is gebleken om de mate van stervorming in een melkwegstelsel te bepalen, is de H α lijn. Echter zorgt roodverschuiving ervoor dat deze lijn al snel buiten het golflengtebereik van de meeste instrumenten valt. Als we de emissie

van waterstof in verre melkwegstelsels willen bestuderen, moeten we dus nog steeds vertrouwen op de Lyman α lijn, omdat deze ook voor verre sterrenstelsel in het optische spectrum valt. We verwachten echter dat met de lancering van de JWST het bestuderen van de H α in verre sterrenstelsels gemakkelijker wordt, omdat deze nieuwe satelliet instrumenten bevat met een groot golflengtebereik in het infrarood spectrum.

De meeste onderzoeken naar sterrenstelsels op hoge roodverschuiving zijn uitgevoerd in een paar specifieke gebieden aan de hemel omdat het vergaren van data geschikt voor dergelijke onderzoeken zowel kostbaar als tijdrovend is. Voorbeelden van zulke gebieden zijn de Great Observatories Origins Deep Survey (GOODS), de Hubble Ultradeep Field (HUDF) en de Cosmic Evolution Survey (COSMOS). Uitgebreide fotometrische catalogi, opgesteld uit waarnemingen in deze velden, maken het mogelijk het spectrum van melkwegstelsels met hoge roodverschuiving op verscheidende golflengten te bestuderen.

Telescopen die infrarood licht waarnemen, zoals Herschel en Spitzer, zijn vooral belangrijk, omdat hun data helpen bij het bepalen van zowel de stellaire massa van objecten met hoge roodverschuiving als hun emissie door stofdeeltjes, welke zoals eerder genoemd belangrijk is om een volledig beeld te krijgen van de stervorming in deze melkwegstelsels.

Ten slotte heb ik in dit werk gebruik gemaakt van de *Spitzer* Matching Survey of the UltraVISTA Ultra-deep Stripes (SMUVS) om de fysische eigenschappen van de Lyman α -stralers die ik in het COSMOS-veld heb waargenomen te vergelijken met die van sterrenstelsels in SMUVS die geen Lyman α -emissie uitstralen, maar zich wel bevinden in hetzelfde gebied aan de hemel en vergelijkbare roodverschuiving hebben. SMUVS is ontworpen om de diepst mogelijke observaties uit te voeren in een zo groot mogelijk gebied. Zoals ik al eerder noemde is een dergelijke combinatie van diepte en oppervlakte moeilijk te bereiken vanwege de hoge kosten. SMUVS is dus bij uitstek geschikt om bepaalde, zeer belangrijke eigenschappen van melkwegstelsels met hoge roodverschuiving te bestuderen, zodat we hun fysische toestand kunnen achterhalen en tegelijkertijd een uitgebreide statistische analyse kunnen uitvoeren.

LYMAN α -STRALING IN HET VERRE HEELAL

Het meest voorkomende element in het heelal is waterstof en daardoor biedt het belangrijke informatie over de evolutie van onze werkelijkheid. Welk verschijnsel we ook waarnemen, er is een grote kans dat waterstof op een manier betrokken is bij het vormen van de eigenschappen van het

geobserveerde licht, hetzij door zelf licht uit te zenden, hetzij door licht met specifieke golflengten te absorberen. De Lyman α -lijn, een emissielijn van waterstof, is een van de sterkste lijnen die we in het heelal kunnen detecteren. Deze lijn is weliswaar heel helder, maar bepaalde kwesties bemoeilijken het waarnemen van deze lijn.

De Lyman α -straling wordt uitgezonden als geoniseerd waterstof (wat in werkelijkheid een enkel proton is) een elektron opvangt en daardoor weer neutraal waterstof wordt. Als het uitgezonden foton een neutraal waterstofatoom tegenkomt, zal het door het atoom worden geabsorbeerd waarbij dit atoom zijn elektron verliest en dus wordt geoniseerd. Als dit pas geoniseerde waterstofatoom recombineert met een elektron wordt het foton opnieuw uitgezonden in een andere, willekeurige richting. Dit proces wordt resonante verstrooiing genoemd, waarbij Lyman α -fotonen herhaaldelijk worden uitgezonden en geabsorbeerd totdat ze het gebied verlaten waar de neutrale waterstof aanwezig is of roodverschuiving hun golflengte dusdanig aanpast dat waterstof de fotonen niet langer kan absorberen.

Naast dit feit dat Lyman α -lijn wordt beïnvloed door resonante verstrooiing, valt de lijn ook nog in het ultraviolette deel van het lichtspectrum. Dit betekent dat stofdeeltjes de Lyman α -straling kunnen absorberen, opwarmen en vervolgens uitstralen op langere golflengten in het infrarood. Dit verschijnsel is anders dan resonante verstrooiing, waar de fotonen over een groter gebied worden verspreid zonder dat het totaal aantal uitgezonden Lyman α -fotonen wordt aangetast. Kosmisch stof verwijdert namelijk fotonen van de Lyman α -lijn en voegt die toe aan het fotonbudget van thermische infraroodstraling. De bijdrage aan Lyman α -straling van deze verloren fotonen kan niet worden herleid uit metingen van thermische straling van stofdeeltjes, zoals dat wel mogelijk is met metingen van het ultraviolette spectrum. Dit komt doordat de ruimtelijke distributie en snelheid van het kosmische stof een aanzienlijke invloed hebben op de hoeveelheid geabsorbeerd licht en de vorm van het emissieprofiel van de lijn. Totdat we nauwkeurig de ruimtelijke verdeling van stof rond een melkwegstelsel kunnen meten (wat we momenteel nog niet kunnen), is de Lyman α -straling voor altijd verloren.

Het modelleren van de Lyman α -lijn

Zoals ik hierboven heb beschreven is de Lyman α -emissielijn een ingewikkelde lijn om te bestuderen. We moeten niet alleen rekening houden met zijn oorsprong, maar ook met de wisselwerking tussen de lijn en het gas en stof in de omgeving. De beste manier om deze lijn te onderzoeken

Figure 5.3: Voorbeeld van een Lyman α -lijnprofiel dat wordt gekenmerkt door een rode staart.

is daarom door de straling en de interacties van fotonen te simuleren met een vereenvoudigde versie van de werkelijkheid. Dit wordt gedaan door aan te nemen dat Lyman α -fotonen uit n punt ontstaan en dat deze zich vervolgens door een uitdijende bolvormige mantel van neutraal waterstof en stof voortbewegen. De complexiteit van deze modellen hangt af van hoeveel we weten van de processen die zich in en rond een melkwegstelsel afspelen en hoeveel van deze verschijnselen we hebben waargenomen.

Gelukkig is de Lyman α -lijn bijzonder in vergelijking met andere soorten straling, omdat de vorm van het lijnprofiel vaak weerspiegelt hoe de fotonen uiteindelijk uit het melkwegstelsel zijn ontsnapt. Een belangrijk kenmerk van het lijnprofiel is een asymmetrie jegens het rode deel van het spectrum. Ik bedoel hiermee dat de lijn minder snel afvalt in het rode spectrum vergeleken met de steile curve in het blauwe spectrum (zie fig. fig:LyA6). Aanvankelijk dacht men dat deze "rode staart", zoals hij soms wordt genoemd, gevormd wordt doordat het omringende medium uitdijt en de blauwe fotonen in resonantie worden verstrooid, terwijl de rode fotonen en de reeds resonante fotonen aangetast worden door roodverschuiving vanwege het uitdijende medium en dus zo kunnen ontsnappen. Onlangs hebben we ontdekt dat de vorm en de notabiliteit van de rode staart ook afhangen van de kolomdichtheid van waterstof (de dichtheid langs onze gezichtslijn) en het verduisterend vermogen van het kosmische stof.

Een ander kenmerk van de Lyman α -lijn is de aanwezigheid van een blauwe piek, die ofwel veel kleiner is dan de rode piek ofwel ongeveer dezelfde intensiteit heeft. Dubbele pieken in het lichtprofiel van de straling kunnen wederom het gevolg zijn van de manier waarop de gas- en stofmantel beweegt ten opzichte van het gaststerrenstelsel of van de aanwezige hoeveelheid waterstof en kosmisch stof. Het mag duidelijk zijn dat we niet alleen rekening moeten houden met de beweging van de mantel maar ook met zijn samenstelling als we dit verschijnsel willen beschrijven.

De modellen die ik in dit werk heb gebruikt bevatten een aantal parameters om de waargenomen lijnemissie te beschrijven. Allereerst beschrijven ze de initiale emissie, nog voordat de fotonen enig deel van de gas- en stofmantel tegenkomen, als een puntvormige bron die een Gaussisch lijnprofiel uitzendt met een Gaussische breedte van σ en een initiale equivalente breedte. De Lyman α -fotonen komen vervolgens in aanraking met de mantel, die wordt beschreven door een waterstofkolomdichtheid, de optische diepte van het stof (het verduisterend vermogen), een uitdijingssnelheid die, indien negatief, betekent dat het gas naar binnen valt in plaats van naar buiten uitdijt en ten slotte de effectieve temperatuur van stof en gas. Deze parameters vormen samen het lijnprofiel dat we waarnemen en kunnen dus bijdragen aan meerdere eigenschappen van de straling. Dit maakt de beschrijving van de lijn zeer ontaard en daarom geldt dat hoe meer waarnemingen we hebben, hoe beter we kunnen bepalen wat er in werkelijkheid gebeurt.

Waarnemingen van de Lyman α -lijn

We hebben het belang van gedetailleerde Lyman α -waarnemingen besproken, maar hoe kunnen we deze data daadwerkelijk verkrijgen? En van de meest succesvolle instrumenten voor het vinden en kenmerken van Lyman α -straling uit verre sterrenstelsels (en uiteraard alle andere emissielijnen die in het optische bereik van het instrument vallen) is de Multi Unit Spectroscopic Explorer (MUSE), dat is gemonteerd op de Very Large Telescope (VLT) op Cerro Paranal in de Atacama-woestijn in Chili. MUSE maakt het mogelijk tijdens het waarnemen van de hemel een spectrum te registreren voor elke pixel in zijn gezichtsveld. Daardoor is de enige voorwaarde voor het detecteren van Lyman α -stralers met MUSE dat het signaal sterker moet zijn dan de intrinsieke ruis van de detector.

MUSE is een spectrograaf en kan daardoor meer details vastleggen van de objecten die het detecteert vergeleken met de eerdergenoemde fotometrische data. Fotometrische instrumenten kunnen bijvoorbeeld geen

emissielijnprofiel meten, terwijl spectrografen dit wel kunnen. Deze mate van detail gaat echter ten koste van het waarneemoppervlakte ten opzichte van fotometrische observaties en de observaties kosten veel geld en tijd. Het is dus belangrijk zowel fotometrische als spectroscopische data te gebruiken om Lyman α -stralers en kandidaat-stralers te ontdekken en zo de kracht van beide methodes te benutten om de studie de Lyman α -stralers te vorderen.

Ten slotte, omdat waterstofemissie samenhangt met stervorming is het mogelijk een ondergrens op de mate van stervorming in de Lyman α -stralers te bepalen met behulp van de Lyman α -lijn. Zoals we hierboven hebben besproken, bereiken niet alle uitgezonden Lyman α -fotonen ons, vanwege de wisselwerking met gas en kosmisch stof. Hierdoor is de mate van stervorming die we uit deze lijn afleiden slechts de minimumwaarde die het licht dat wij observeren verklaart. Een betrouwbaardere lijn om stervormingspercentages uit af te leiden is de hierboven genoemde $H\alpha$ -lijn. In de toekomst zodra JWST wordt gelanceerd en werkzaam is zal deze lijn, samen met de Lyman α -lijn, vaker te observeren zijn. Tot dat moment bestaat er een alternatieve methode om meer informatie te krijgen over zwakke en verre Lyman α -stralers, die gebruik maakt van de natuurlijke vergroting die clusters van melkwegstelsels bieden.

CLUSTERS ZIJN “NATUURLIJKE TELESCOPEN”

Uit de algemene relativiteitstheorie weten we dat massa de ruimtetijd buigt en dat licht de geometrie daarvan volgt. Als de massaconcentratie op n plaats hoog genoeg is, kan de vervorming van de ruimtetijd voldoende zijn om het licht zo te krommen dat het object op de voorgrond verandert in een zwaartekracht lens. Wanneer een astrofysisch object, zoals een planeet, een ster of een sterrenstelsel, voor een ander object dat licht uitstraalt langs beweegt, kan het licht van het achtergrondobject richting ons worden gebundeld. Als het echter een cluster van sterrenstelsels is die als zwaartekracht lens fungeert, kunnen we een heel deel van het heelal achter de lens uitvergroten in plaats van slechts een paar objecten. Clusters waar dit effect is waargenomen staan bekend als lensclusters.

Als het licht van een achtergrondsterrenstelsel wordt afgebogen door een cluster vervormt het beeld van dit sterrenstelsel door de uitgesproken massaverdeling van het cluster. Daarnaast veroorzaakt de lens een vermeerdering van het aantal beelden wat wij ontvangen. En of meerdere beelden zullen een grotere ruimtelijke resolutie en oppervlaktehelderheid hebben door de lenswerking. Hierdoor kunnen we niet alleen het

Figure 5.4: Afbeelding die illustreert hoe een object in de voorgrond als een vergrootglas functioneert voor een achterliggend object via zwaartekracht lenswerking.

lichtprofiel en de morfologie van het achtergrondstelsel nauwkeurig vastleggen, maar kunnen we ook objecten detecteren die anders te zwak zouden zijn om te zien. Het nadeel van dit effect is dat om de spectrale en ruimtelijke eigenschappen van een gelensd melkwegstelsel te kunnen analyseren we eerst zijn oorspronkelijke beeld moeten reconstrueren uit de meervoudige en vervormde beelden die we met onze telescopen registeren.

Gelukkig kunnen we de massaverdeling binnen het cluster meten en die informatie gebruiken om een lensmodel te maken dat het effect van de echte lens nabootst. Met behulp van de meervoudige, vervormde beelden kunnen we reconstrueren hoe het deel van het heelal dat door het cluster is uitvergroet er in werkelijkheid uitziet. Hierdoor krijgen we niet alleen een beeld van wat er achter de lens ligt, maar kunnen we ook de helderheid van de objecten die we waarnemen herleiden naar hun oorspronkelijke, niet-vergrote waarde. Lensclusters bieden dus niet alleen meer ruimtelijke informatie over de objecten die worden gelensd, maar zorgen er daarnaast voor dat we zwakkere objecten kunnen detecteren die we anders niet zouden zien.

DIT PROEFSCHRIFT

In dit werk heb ik de Lyman α -emissie bestudeerd van sterrenstelsels met hoge roodverschuiving die door het MUSE-instrument zijn gedetecteerd en heb ik hun fysische eigenschappen onderling vergeleken met die van een verzameling sterrenstelsels die geen Lyman α -straling uitzenden. In het tweede hoofdstuk heb ik de fysische eigenschappen van de Lyman α -stralende populatie vergeleken met de eigenschappen van de non-stralers. Ik heb ontdekt dat er fysisch geen groot verschil tussen de twee populaties lijkt te zijn en dat de oudere objecten in mijn Lyman α -stralende populatie tekenen vertonen dat er een tweede vlaag van stervorming heeft plaatsgevonden.

In het derde hoofdstuk heb ik de fysische eigenschappen van de Lyman α -emissie van twee types Lyman α -stralers met verschillende lijnprofielen vergeleken. Ik heb ontdekt dat de gas- en stofmanteleigenschappen van stralers met een lijnprofiel bestaand uit meerdere pieken zeer vergelijkbaar zijn met die van stralers met een enkele piek in het lijnprofiel. Echter, profielen met meerdere pieken zijn intrinsiek breder van vorm. Ik heb ook objecten in mijn verzameling gevonden waar ultraviolet licht afkomstig uit het spectrale continuum lijkt te ontsnappen. Men neemt aan dat deze objecten meer licht bijdroegen aan het transparant maken

van het heelal voor straling, een proces dat reonisatie wordt genoemd en in de vroege stadia van het heelal heeft plaatsgevonden.

Ten slotte heb ik in het vierde hoofdstuk diepe metingen van lensclusters gebruikt om de fysische eigenschappen van de twee types Lyman α -stralers uit hoofdstuk 3 te vergelijken, maar ditmaal door middel van fotometrische waarnemingen. Ik vond wederom dat deze twee families niet wezenlijk verschillen in hun statistieken, maar ik heb wel een verband ontdekt tussen de aanvankelijke Gaussische breedte van hun Lyman α -lijnprofiel en stellaire massa. Deze trend laat zien dat de stralers met meerdere pieken in het lijnprofiel een breder profiel hebben, zoals bevonden in het vorige hoofdstuk. Opmerkelijk is de vondst dat deze verbreding onafhankelijk is van de stellaire massa. Dit resultaat benadrukt het belang van mijn ontdekking in het vorige hoofdstuk. Ik heb ook de sterrenstelsels waarbij mogelijk ultraviolet licht van het continuum ontsnapt vergeleken met de rest van mijn objecten en heb geen statistisch verschil kunnen vinden in hun eigenschappen. Het lijkt erop dat deze objecten alleen een lagere waterstofkolomdichtheid hebben vergeleken met normale melkwegstelsels.

Samenvattend: mijn proefschrift heeft een aantal nieuwe vragen opgeroepen over Lyman α -emissie die in de toekomst verder onderzocht moeten worden, zowel door het verkrijgen van diepere en gedetailleerdere data als door het ontwikkelen van steeds betere modellen, zodra de nieuwe data diepgaandere toetsing van onze voorspellingen mogelijk maken.

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Well, here we are, at the end of this manuscript and of my time with this project. It has been quite a rollercoaster ride these past four years and I for one am happy to have managed to finish this thesis in time with the end of my contract. For those wondering, it did not always look like I could manage. Anyway, I did it and it is now time to give props to the people who made this possible and who supported me throughout. I'm pretty spent after this last sprint, so I will keep it brief, but know that it is in no way less heartfelt.

Fist of all, a big thank you to Karina for offering me this job even though I was not part of her initial selection of candidates. I haven't been the easiest person to work with, I'm sure, and I'm sorry that I could not muster the same enthusiasm as you for high redshift studies. Nonetheless, without these four years I would not be where I am now and I'm really grateful for all the support you gave me when I finally came around to ask for help.

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Finally, it is time to slowly move away from work related people and into my purely personal sphere. To keep the gradient nice and shallow, I'd like to start with the "random outing" group for being fun and welcoming. I'm sorry I participated less in the discussion and activities in this last period. This is about to change, COVID permitting!

Another big thank you to the Italian "Elish" group! Playing out our whacky fantasies where cities burned and chickens killed guards was fun both in person and later online during the lockdown. I hope we will try playing again, and who knows, I might have a setting I could "master". Hint, hint...

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Alright, we reached the end of this document. As I said, it has not always been easy, but I made it in the end. And with this, I'm ready to close this chapter of my life and open the next one. Maybe I'll see you there; Giulio, out!