Recovering the systemic redshift of galaxies from their Lyman-alpha line profile

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ABSTRACT

The Lyman alpha (Lyα) line of Hydrogen is a prominent feature in the spectra of star-forming galaxies, usually redshifted by a few hundreds of km s\(^{-1}\) compared to the systemic redshift. This large offset hampers follow-up surveys, galaxy pair statistics and correlations with quasar absorption lines when only Lyα is available. We propose diagnostics that can be used to recover the systemic redshift directly from the properties of the Lyα line profile. We use spectroscopic observations of Lyman-Alpha Emitters (LAEs) for which a precise measurement of the systemic redshift is available. Our sample contains 13 sources detected between \(z \approx 3\) and \(z \approx 6\) as part of various Multi Unit Spectroscopic Explorer (MUSE) Guaranteed Time Observations (GTO). We also include a compilation of spectroscopic Lyα data from the literature spanning a wide redshift range \((z \approx 0 \text{–} 8)\). First, restricting our analysis to double-peaked Lyα spectra, we find a tight correlation between the velocity offset of the red peak with respect to the systemic redshift, \(V_{\text{red peak}}^\text{red}\), and the separation of the peaks. Secondly, we find a correlation between \(V_{\text{red peak}}^\text{red}\) and the full width at half maximum of the Lyα line. Fitting formulas, to estimate systemic redshifts of galaxies with an accuracy of \(\leq 100\) km s\(^{-1}\) when only the Lyα emission line is available, are given for the two methods.

Key words: ultraviolet : galaxies – galaxies : statistics – galaxies : starburst – galaxies : high-redshift

1 INTRODUCTION

In the last few decades, large samples of high-redshift galaxies \((z > 2)\) have been assembled from deep photometric surveys based on broad/narrow-band selection techniques

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Several studies have demonstrated that the Lyα emission line is not exactly tracing systemic redshift (e.g. Shapley et al. 2003; Rakic et al. 2011; McLinden et al. 2011; Song et al. 2014; Hashimoto et al. 2015). Instead, the line profiles often show a complex structure which arguably originates from the propagation of resonant Lyα photons in neutral gas within the interstellar medium and/or in the vicinity of galaxies. Among the broad diversity of Lyα profiles in Lyα emitting galaxies, we identify the most common two categories: (i) spectra with a redshifted single peak (∼2/3 of Lyα emitting Lyman Break Galaxies, called LBGs, from Kulas et al. (2012)), and (ii) double-peaked profiles, with a prominent red peak and a smaller blue bump (∼2/3 of the remaining 1/3 of Lyα emitting LBGs which are multiple peaked, from Kulas et al. (2012)); 40% of the LAEs observed by Yamada et al. (2012)). We will refer to the latter as blue bump LAEs in the remainder of this paper. Understanding the nature of blue bump LAEs and studying their occurrence and evolution with redshift will be the goal of a forthcoming study. The vast majority of objects display a red peak shifted by a variable amount peaking around ∼400 km s$^{-1}$ for Lyα emitting Lyman Break Galaxies (LBGs, e.g. Shapley et al. 2003; Kulas et al. 2012), ∼200 km s$^{-1}$ for LAEs (LBGs, e.g. Hashimoto et al. 2013; Song et al. 2014; Erb et al. 2014; Triay et al. 2015; Henry et al. 2015; Hashimoto et al. 2015), and less than ∼150 km s$^{-1}$ for a small sample of 5 local Lyman Continuum Emitters (Verhamme et al. 2017).

If not accounted for, this offset with respect to the systemic redshift can be problematic when addressing astrophysical issues which require accurate systemic redshift measurements (e.g. galaxy interactions, gas kinematics, baryonic acoustic oscillations, IGM-galaxy emission/absorption correlations). The scope of this paper is to investigate whether the Lyα profile shape can be used to determine the systemic redshift of galaxies. The outline of this Letter is as follows: in Sect. 2, we gather recent spectroscopic data from MUSE GTO surveys and from the literature that have sufficient spectral resolution to investigate the Lyα line properties, as well as reliable systemic redshift measurements. In Sect. 3, we present two diagnostics which can be used to recover the systemic redshift from Lyα, that we compare to models in Sect. 4. Sect. 5 summarizes our findings.

## 2 A SAMPLE OF LAES WITH KNOWN SYSTEMIC REDSHIFT

In order to investigate the link between the shape of the Lyα line and the systemic redshift, we collect a diverse sample of LAEs with a precise measure of the systemic redshift. Our sample consists of high-redshift (z > 2) LAEs with detected CIII$\lambda\lambda$1907, 1909, [Oiii]$\lambda\lambda$4959, 5007 or Hα$\lambda$6563 emission, and low redshift (z < 0.4) LAEs with Lyα observations in the UV rest-frame obtained with the Cosmic Origins Spectrograph onboard HST, and ancillary optical spectra from the SDSS database containing several nebular emission lines from which the redshift is determined with great accuracy. We present these data in the following paragraphs. For each Lyα spectrum, we measure $V_{\text{peak}}$ as the location of the maximum of the Lyα flux redwards of the systemic redshift, and FWHM as the width of the part of the spectrum uncorrected for instrumental broadening with flux above half of the maximum, both directly on the data, without any modeling.

### 2.1 LAEs from MUSE GTO data

Stark et al. (2014) reported the detection of CIII$\lambda\lambda$1907, 1909 emission from low mass star-forming galaxies. When observed, this doublet is the strongest UV emission line after Lyα, and, in contrast to Lyα, it is an optically thin nebular line, tracing the systemic redshift 1 of the Lyα production site. The redshift window where Lyα and CIII$\lambda\lambda$1907, 1909 are both observable within the VLT/MUSE spectral range is 2.9 < z < 3.8. MUSE is an optical Integral Field Unit (IFU) spectrograph with medium spectral resolution (from R ≃ 2000 in the blue to R ≃ 4000 in the red).

Within several projects in the MUSE consortium using Guaranteed Time Observations (GTO, Bacon et al. 2017; Inami et al. 2017; Brinchmann et al. 2017; Maseda et al. 2017; Herenz et al. 2017; Mahler et al. 2017; Caruana et al. 2018) and Science Verification (SV) or commissioning data (Patricio et al. 2016), we find 13 LAEs with reliable CIII$\lambda\lambda$1907, 1909 detections, that is, non contaminated by sky lines and with a S/N > 3. We list these objects in Table 1 (see Maseda et al. 2017, for a systematic study of CIII emitters in the MUSE GTO data from the Hubble Ultra Deep Field). For each of these LAEs we measure the shift of the Lyα emission compared to CIII$\lambda\lambda$1907, 1909, $V_{\text{peak}}$, the observed FWHM, and the separation of the Lyα peaks for the 8 blue bump LAEs among them.

### 2.2 High-z data from the literature

Stark et al. (2017) reported the detection of CIII$\lambda\lambda$1907, 1909 emission observed within the highest redshift Lyα emitters ever observed (z ∼ 7.750) with $V_{\text{peak}}$ = 340 km s$^{-1}$: the Lyα FWHM = 360 km s$^{-1}$ is measured by Oesch et al. (2015). Vanzella et al. (2016) report a narrow Lyα line observed at medium spectral resolution using VLT-Xshooter of a magnified star-forming galaxy at z = 3.1169, with $V_{\text{peak}}$ = 100 km s$^{-1}$ and $V_{\text{peak}}$ can be used as a redshift indicator when the two components of the doublet are well resolved, i.e. when R ≃ 2000, because their relative strength depends on the density.
FWHM(Lyα) \sim 104 \text{ km s}^{-1}. \text{ From Hashimoto et al. (2015, 2017), we select the 6 LAEs observed with MagE (R=4100). Their systemic redshifts have been obtained with either Hα or [Oiii] lines. Three of these objects are blue-bump LAEs, for which we also measure the separation of the peaks. Kulas et al. (2012) reported that a significant fraction (\sim 30\%) of their Lyα emitting LBGs show a complex Lyα profile, with at least one secondary peak. Blue bump objects (their Group I) represent the majority of their profiles (11 out of 18 objects). We add these 11 objects to our sample of blue bumps LAEs.}

2.3 Low-z data from the literature

Green Pea galaxies (hereafter GPs) are LAEs in the local Universe (\sim 0.1 to 0.3; Jaskot & Oey 2014; Henry et al. 2015; Verhamme et al. 2017; Yang et al. 2017). The systemic redshift of these objects was compiled from the several nebular lines contained in their SDSS optical spectrum (e.g. Izotov et al. 2011). Note that the Ciii emission line is out of the UV spectral range probed by the available HST-COS observations. For a sample of 17 GPs from Jaskot & Oey (2014); Henry et al. (2015); Verhamme et al. (2017), we measure \(V_{peak}^{red}\) and FWHM on the data. For 21 new GP observations, we use the \(V_{peak}^{red}\) and FWHM values computed by Yang et al. (2017) given in their Table 2. GPs nearly always exhibit blue bump Lyα profiles (Jaskot & Oey 2014; Henry et al. 2015; Verhamme et al. 2017). For the blue bump GPs, we also measure the separation of the peaks.

3 DERIVING SYSTEMIC REDSHIFT FROM LYMAN-ALPHA

3.1 Method 1 : systemic redshift of blue bump LAEs

In this section, only blue bump spectra, i.e. double peaks with a red peak higher than the blue peak, are considered. We note that, for all blue bump LAEs studied here, the systemic redshift always falls in-between the Lyα peaks, as illustrated in Fig 1 for three blue-bump MUSE Lyα+Ciii emitters (see also Kulas et al. 2012; Erb et al. 2014; Yang et al. 2016). Fig. 2, left panel, shows a positive empirical correlation between \(V_{peak}^{red}\) and half of the separation of the peaks, \(\Delta V_{1/2}\), for blue bump LAEs with known systemic redshift. We fit the data using the LTS_LINEFIT program described in Cappellari et al. (2013), which combines the Least Trimmed Squares robust technique of Rousseau & van Driessen (2006) into a least-squares fitting algorithm which allows for errors in both variables and intrinsic scatter\(^2\). The best fit, shown by the red line on Fig. 2, is given by:

\[ V_{peak}^{red} = 1.05(\pm0.11) \times \Delta V_{1/2} - 12(\pm37) \text{km s}^{-1} \] (1)

This relation is so close to the one-to-one relation that we assume from now that the underlying “true” relation between \(V_{peak}^{red}\) and \(\Delta V_{1/2}\) is one-to-one, as expected from radiation transfer modeling (see Sect.4 below). The intrinsic scatter estimated from the linear regression is 53(\pm9) \text{ km s}^{-1}.

3.2 Method 2 : an empirical correlation between FWHM and systemic redshift

In this section, both single and double peaked profiles are considered. The measurements are always done on the red peak, and the red peak only. In the right panel of Fig. 2 we plot \(V_{peak}^{red}\) versus FWHM for the full sample of LAEs presented in Sect. 2 (new MUSE LAEs measurements are reported in Table 1). There is a correlation between \(V_{peak}^{red}\) and FWHM although less significant than for Method 1 (see the Pearson coefficients on each panel of Fig 2). We use the same method (Cappellari et al. 2013) to determine the empirical relation, which can be used to retrieve the systemic redshift of a galaxy:

\[ V_{peak}^{red} = 0.9(\pm0.14) \times FWHM(\text{Ly}α) - 34(\pm60) \text{ km s}^{-1} \] (2)

This relation is also compatible with the one-to-one relation, given the uncertainties in the fit parameters. The intrinsic scatter estimated from the linear regression is 72(\pm12) \text{ km s}^{-1}, slightly larger than with method 1.

\[ z_{sys} \text{ from Ly}α \]
Figure 2. Empirical relations to determine systemic redshift from the shape of the Ly\(\alpha\) emission. \textbf{Left}: correlation between the shift of the Ly\(\alpha\) red peak, \(V_{\text{red}}^{\text{peak}}\), and half of the separation of the peaks (\(\Delta V_{1/2}\)) for a sample of LAEs with a known systemic redshift: 7 Ly\(\alpha\)+C\(\text{iii}\) emitters with blue bump Ly\(\alpha\) spectra from the MUSE GTO data (red stars), blue bump LAEs among the Yang et al. (2017) GP sample (black dots), blue bump LAEs among the Hashimoto et al. (2015) MagE sample and Group I LBGs from Kulas et al. (2012) (black triangles). \textbf{Right}: correlation between \(V_{\text{red}}^{\text{peak}}\) and FWHM among Ly\(\alpha\)+ C\(\text{iii}\), H\(\alpha\), or [O\(\text{iii}\)] emitters. The black dashed line is the one-to-one relation. We checked that the correlation remains even discarding the two most upper left points. On both sides, the red curve is our best fit to the data, described by Eqs. (1) and (2). The Pearson coefficient and the probability of the null hypothesis are shown on each panel.

Figure 3. Comparison of the distributions of Ly\(\alpha\) redshift errors (\(= z_{\text{Ly\alpha}} - z_{\text{sys}}\), in black) with redshift distributions corrected with method 1 (in red, top panel) and with method 2 (in red, bottom panel).

3.3 Comparison of the methods

We check that the corrected redshifts from both methods give results that are closer to the systemic redshift of the objects than the ”Ly\(\alpha\) redshifts”, i.e. taking \(V_{\text{red}}^{\text{peak}}\) as the systemic redshift, as usually done (Fig 3). The standard deviation of the red histograms (corrected redshifts), reflecting both the intrinsic scatter and measurement errors, are comparable for the two methods, though slightly better for the blue bump method. We therefore propose to use half of the separation of the peaks as a proxy for the red peak shift of blue bump LAEs, and the Ly\(\alpha\) FWHM for single peaked spectra\(^3\). They allow to recover the systemic redshift from the Ly\(\alpha\) line, with an uncertainty lower than \(\pm 100\) km s\(^{-1}\) from \(z \approx 0\) to 7. This suggests that the same scattering processes, linking the line shift and the line width, are at play at every redshift, and that the effect of the IGM does not erase this correlation.

4 DISCUSSION

4.1 Effect of the spectral resolution

These two methods to retrieve the systemic redshift of a LAE from the shape of its Ly\(\alpha\) profile rely on measurements of either the positions of the blue and red Ly\(\alpha\) emission peaks or the (red peak) FWHM. Both of these measures are affected by the spectral resolution. Although the data points presented in Sect 3. were collected from the literature and MUSE surveys and span a range of spectral resolutions from \(R \sim 1000\) (LRIS) to \(R \sim 5000\) (X-Shooter, HST-COS), they all seem to follow the same relation.

We investigated the effect of spectral resolution on synthetic spectra constructed from Ly\(\alpha\) radiation transfer simulations. Poorer spectral resolution broadens the peaks, and since Ly\(\alpha\) profiles are often asymmetric, it also has the effect of shifting the peak towards longer wavelengths. The latter

\(^2\) \url{http://www-astro.physics.ox.ac.uk/~mxc/software/#lts}

\(^3\) We have also tested the relation between Ly\(\alpha\) EWs and \(V_{\text{red}}^{\text{peak}}\), but did not find any significant correlation.

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effect is weaker than the broadening. As a consequence, the effect of spectral resolution may flatten the slope but seems not to break the correlation.

4.2 Comparison with models

We now compare our results with numerical simulations of Lyα radiative transfer in expanding shells performed with the MCLya code (Schaerer et al. 2011; Verhamme et al. 2013). These models describe in a simple, idealized, way the propagation of Lyα photons emitted in HI regions through gas outflows which seem ubiquitous in star-forming galaxies, especially at high redshift (Shapley et al. 2003; Steidel et al. 2010; Hashimoto et al. 2015). Assuming a central point-source surrounded by an expanding shell of gas with varying HI column density \(N_{\text{HI}}\), speed \((V_{\text{exp}})\), dust opacity \((\tau_d)\) and temperature (described by the Doppler parameter \(b \propto \sqrt{T}\)), shell models have proven very successful in reproducing a large diversity of Lyα line profiles. Here, we use simulations with different intrinsic Gaussian line widths \(\sigma_{\text{intrinsic}}\) and various shell parameter values \(N_{\text{HI}}, V_{\text{exp}}, \tau_d, b\), degraded to mimic the MUSE spectral resolution. We measure FWHM, \(\Delta V_{\text{FWHM}}\) and \(\Delta V_{1/2}\) the same way as for the data.

We compare the observed correlation between \(\Delta V_{\text{FWHM}}\) and the separation between the peaks of blue-bump LAEs (\(\Delta V_{1/2}\)) with results from models that produce double-peak profiles (Fig. 4, left panel). Predictions from expanding shell models lie very close to the one-to-one relation and reproduce nicely the observed properties of the Lyα profiles. Objects with increasing \(\Delta V_{\text{FWHM}}\) and \(\Delta V_{1/2}\) correspond to expanding shells with larger HI column densities. This echoes the analytical solutions for Lyα RT in static homogeneous media (Neufeld 1990; Dijkstra et al. 2006) that yield profiles with symmetric peaks around the line centre, whose positions are primarily set by the HI opacity and correspond to \(V_{\text{peak}} \propto \tau_{\text{HI}}^{1/3}\). As shown in Fig. 4 (right panel), the correlation between the shift of the red peak and the FWHM of the Lyα line naturally arises from scattering processes. The slope predicted by the models is close to one whereas the relation derived from observations in Section 3 is shallower \((\approx 0.9\text{, red curve in the right panel of Figs. 2,4})\). However, it is worth pointing out that we explore a much larger range of FWHMs in the right panel of Fig. 4 (from 0 to 1200 km s\(^{-1}\)) compared to Fig. 2 where observed FWHMs vary from 214 to 512 km s\(^{-1}\). For FWHM values less than 600 km s\(^{-1}\), the model predictions lie closer to the FWHM-\(\Delta V_{\text{FWHM}}\) relation derived in Section 3. Although the exact location of each simulated object in the FWHM-\(\Delta V_{\text{FWHM}}\) plane seems to depend on each parameter, we see that models with higher HI column densities lead to broader lines and larger shifts of the peak (color-coded circles). A similar trend is found by Zheng & Wallace (2014) who performed Lyα radiation transfer simulations in anisotropic configurations (bipolar outflows) and inhomogeneous media (i.e. HI distributions with velocity or density gradients). Overall, this may suggest that the FWHM-\(\Delta V_{\text{FWHM}}\) correlation holds regardless of the assumed geometry and kinematics of the outflows, and that the HI opacity of the ISM and/or the medium surrounding galaxies (i.e. the CGM) is the main driver that shapes the observed Lyα line profiles.

5 CONCLUSIONS

The recent increase in the number of LAEs with detected nebular lines allows to calibrate empirical methods to retrieve the systemic redshift from the shape of the Lyα line. In addition to measurements from the literature, we report 13 new detections from several MUSE GTO programs. We searched for Lyα+CIII\] emitters in the MUSE-Deep survey (Bacon et al. 2017), behind \(z \approx 0.7\) galaxy groups (Contini et al, in prep), and lensed by three clusters (SMACSJ2031.8-4036 in Patricio et al, 2016, ASI063, MACS0416 in Richard et al, in prep).

We find a robust correlation between the shift of the Lyα peak with respect to systemic redshift \(\Delta V_{\text{FWHM}}\) and half of the separation of the peaks \(\Delta V_{1/2}\) for LAEs with blue bump spectra. The intrinsic scatter around the relation is \(\pm 53\text{ km s}^{-1}\). We also find a correlation between the shift of the Lyα peak with respect to systemic redshift \(\Delta V_{\text{FWHM}}\) and its width at half-maximum (FWHM), for LAEs with known systemic redshift. The intrinsic scatter is of the same order \((\pm 73\text{ km s}^{-1})\). These two relations have been approximated by linear fitting formulas as given in Eq (1) and (2). These formulae have been derived for data with spectral resolution \(1000 < R < 5000\), they should be used on data with similar spectral resolution.

The relative redshift error if estimated from Lyα with \(\Delta V_{\text{FWHM}} = \frac{300\text{ km s}^{-1}}{\alpha}\) is \(\Delta z / z = ((1+z)\Delta V_{\text{FWHM}} / c) / z \approx 10^{-3}\) at \(z \approx 3\). The two methods presented in this letter can therefore help reduce systematic errors on distance measures. This is of great importance for redshift surveys at \(z \gtrsim 3\), where spectroscopic redshifts often rely on the Lyα emission line. Future observations with better spectral resolution should allow to refine the proposed relations.

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Figure 4. Points show the relationship between half of the separation of the peaks and the shift of the Lyα line, and between the FWHM and the shift of the Lyα line, for synthetic spectra from expanding shells, spheres or bi-conical outflows (Schaerer et al. 2011; Zheng & Wallace 2014). The trend is driven by the column density of the scattering medium, but holds for the different idealized geometries. The symbol colors scale with the column density (in cm$^{-2}$) of the shells and symbol sizes scale with the radial expansion velocity (from 0 to 400 km s$^{-1}$). The red line and dashed black line are identical as in Fig 2.

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Table 1. MUSE Lyα+C III] emitters. The 6th column indicates the separation of the peaks (i.e. $2\times \Delta V_{\frac{1}{2}}$, in km s$^{-1}$) for blue bump LAEs, and is left empty for single-peaked profiles. a : Patricio et al. 2016; b : Richard et al. 2018 in prep; c : Bacon et al. 2017, Inami et al. 2017, Maseda et al. 2017; d : Contini et al. 2018 in prep.

| ID     | RA        | DEC       | EW [Å]   | $V_{\text{red, peak}}$ [km s$^{-1}$] | FWHM [km s$^{-1}$] | $\Delta V$ [km s$^{-1}$] | $z_{\text{sys, CII}}$ | observations          |
|--------|-----------|-----------|----------|--------------------------------------|---------------------|-------------------------|---------------------|-----------------------|
| sys 1$^a$ | 307.97040 | -40.625694| 32       | 176 ± 11                             | 248 ± 9             | –                       | 3.5062              | commissioning          |
| mul 11$^b$ | 342.175042 | -44.541031| 222      | 215 ± 35                             | 150 ± 35            | 375 ± 35                | 3.1163              | AS1063                |
| mul 14$^b$ | 342.178833 | -44.535869| 20       | 385 ± 35                             | 300 ± 35            | –                       | 3.1150              | AS1063                |
| sys 44$^b$ | 64.0415559 | -24.0599916| 57      | 303 ± 35                             | 360 ± 35            | 570 ± 35                | 3.2886              | MACS0416              |
| sys 132$^b$ | 64.0400838 | -24.0667408| 62      | 331 ± 35                             | 288 ± 35            | 510 ± 35                | 3.2882              | MACS0416              |
| 106$^c$   | 53.163726 | -27.7790755| 72         | 379 ± 13                             | 414 ± 13            | 828 ± 35                | 3.2767              | udf-10                |
| 118$^c$   | 53.157088 | -27.7802688| 65      | 301 ± 28                             | 284 ± 28            | 568 ± 35                | 3.0173              | udf-10                |
| 1180$^c$   | 53.195735 | -27.7827171| 80      | 220 ± 23                             | 348 ± 32            | –                       | 3.3228              | udf mosaic            |
| 6298$^c$   | 53.169249 | -27.7812550| 83       | 582 ± 38                             | 512 ± 56            | –                       | 3.1287              | udf-10                |
| 6666$^c$   | 53.159876 | -27.7767193| 52      | 284 ± 13                             | 377 ± 11            | 754 ± 35                | 3.4349              | udf-10                |
| 50$^d$    | 150.149656 | 2.0612720  | 50       | 431 ± 42                             | 268 ± 39            | –                       | 3.8237              | GR30                  |
| 48$^d$    | 149.852989 | 2.4880990  | 68       | 294 ± 35                             | 214 ± 35            | 705 ± 35                | 3.3280              | GR34                  |
| 102$^d$   | 150.050268 | 2.600025   | 76       | 299 ± 15                             | 229 ± 15            | 385 ± 35                | 3.0400              | GR84                  |