Compact to extended Lyman-α emitters in MAGPI: Strong blue-peak emission at $z \gtrsim 3$

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ABSTRACT

We report the discovery of three double-peaked Lyman-α emitters (LAEs) exhibiting strong blue-peak emission at $2.9 \lesssim z \lesssim 4.8$ in the VLT/MUSE data obtained as part of the Middle Ages Galaxy Properties with Integral Field Spectroscopy (MAGPI) survey. These strong blue-peak systems provide a unique window into the scattering of Ly$\alpha$ photons by neutral hydrogen (H i), suggesting gas inflows along the line of sight and low H i column density. Two of them at $z = 2.9$ and $z = 3.6$, are spatially extended halos with their core regions clearly exhibiting stronger emission at the blue peak than at the red peak. However, spatial variations in the peak ratio and peak separation are evident over $25 \times 26$ kpc ($z = 2.9$) and $19 \times 28$ kpc ($z = 3.6$) regions in these extended halos. Notably, these systems do not fall in the regime of Ly$\alpha$ blobs or nebulae. To the best of our knowledge, such a Ly$\alpha$ halo with a dominant blue core has not been observed previously. In contrast, the LAE at $z \sim 4.8$ is a compact system spanning a $9 \times 9$ kpc region and stands as the highest-redshift strong blue-peak emitter ever detected. The peak separation of the bright cores in these three systems ranges from $\Delta_{\text{peak}} \sim 370$ to $660$ km/s. The observed overall trend of decreasing peak separation with increasing radius is supposed to be controlled by H i column density and gas covering fraction. Based on various estimations, in contrast to the compact LAE, our halos are found to be good candidates for Lyman-continuum (LyC) leakers. These findings shed light on the complex interplay between Ly$\alpha$ emission, gas kinematics, and ionizing radiation properties, offering valuable insights into the evolution and nature of high-redshift galaxies.

Key words. cosmology: observations–galaxies: evolution–galaxies: high-redshift

1. Introduction

Investigations of the circumgalactic medium (CGM) have significantly added to our understanding of the mechanisms driving galaxy formation and evolution. Interactions involving gas exchanges between galaxies and the surrounding intergalactic environment shape the evolution of galaxies. Lyman-α (Ly$\alpha$) emission is a key tracer of CGM gas around high-redshift star-forming galaxies. Extended Ly$\alpha$ emission has been observed in various galactic environments: (i) Ly$\alpha$ halos around individual galaxies (Kunth et al. 2003; Steidel et al. 2011; Matsuda et al. 2012; Hayes et al. 2013; Leclercq et al. 2017) and (ii) Ly$\alpha$ blobs (LABs) associated with multiple sources (Francis et al. 1996; Fynbo et al. 1999; Matsuda et al. 2011; Cai et al. 2017). The origin of this diffuse Ly$\alpha$ emission in these halos remains a subject of ongoing debate, with several possibilities proposed, including scattering from star-forming regions, Ly$\alpha$ fluorescence, gravitational cooling radiation from accretion and emission from satellite galaxies (Haiman et al. 2000; Zheng et al. 2011; Byrohl et al. 2021). Complex radiative transfer and resonant scattering of Ly$\alpha$ photons have given rise to diverse spectral profiles, with the double-peaked profile being particularly intriguing (Gronek et al. 2016; Verhamme et al. 2017). The escape of ionizing photons ($\lambda < 13.6$ eV) into the intergalactic medium (IGM) played a pivotal role in cosmic reionization, with faint, low-mass, early star-forming galaxies (Bunker et al. 2010; Finkelstein et al. 2015) contributing significantly. However, the interplay between the emission and escape of ionizing radiation, particularly Lyman-continuum (LyC) photons ($\lambda < 912$ Å), remains a puzzle. This enigma is partly due to the inherent opacity of the neutral IGM (Madau 1995; Inoue et al. 2014). This opacity of the IGM to LyC radiation beyond $z \gtrsim 4.5$ makes direct observation of LyC emission challenging (Vanzella et al. 2018). Double-peaked profiles serve as a probe to indirectly infer characteristics related to LyC leakage at higher redshifts. The peak separation, correlated with the neutral hydrogen (H i) column density ($N_{\text{H}}$), plays a pivotal role in determining the LyC escape fraction, $f_{\text{esc}}$, in high-redshift galaxies (Verhamme et al. 2015; Kakiichi & Gronke 2021). Furthermore, observations and simu-
The majority of double-peaked profiles observed in Lyα emitters (LAEs; Shapley et al. 2003; Izotov et al. 2018a; Kerutt et al. 2022) and LABs (e.g., Matsuda et al. 2006) predominantly exhibit a dominant red peak, indicating gas outflows. A dominant red peak is obvious as intergalactic absorption tends to extinguish the blue peak. However, some $z > 6$ LAEs display double-peaked Lyα profiles where the blue peak has a high probability of being scattered by the increasingly neutral IGM at higher redshifts (Hu et al. 2016; Hayes et al. 2021; Endsley et al. 2022). Despite the common association of strong LAEs with low-redshift LyC leakers (Bian & Fan 2020), the opposite is not necessarily true. An interesting distinction arises: Lyα double-peaked profiles with a stronger and broader blue peak than the red peak —implying gas inflows (Blaizot et al. 2023)— have been detected in two Lyα nebulae at $z \sim 3$ (Vanzella et al. 2017), two LABs (Ao et al. 2020; Li et al. 2022) and, only in the outskirts of $z \sim 2$ Lyα halos (Erb et al. 2018, 2023). Besides these extended halos and luminous blobs, where two peaks typically originate from different portions within an extended halo or spatially separated regions within the blob, only two compact and stronger blue-peak LAEs have been reported to date (Fur tak et al. 2022; Marques-Chaves et al. 2022), with the authors claiming that both blue and red peaks originate from the LAE itself.

In this letter, we report the discovery of three strong “blue-peak” LAEs, spanning redshifts 2.9 < $z$ < 4.8 and obtained as part of the Middle Ages Galaxy Properties with Integral Field Spectroscopy (MAGPI\textsuperscript{1}) survey (Foster et al. 2021). The structure of this letter is as follows. In § 2, we provide details of observations and data reduction including MAGPI survey Lyα identification. In § 3, we present our results, followed by a discussion in § 4. Throughout this letter, we assume a standard flat ΛCDM cosmology with parameters $H_0 = 70$ km s\(^{-1}\) Mpc\(^{-1}\), $\Omega_m = 0.3$ and $\Omega\Lambda = 0.7$.

\footnotesize{\textsuperscript{1} Based on observations obtained using the Multi Unit Spectroscopic Explorer (MUSE) at the Very Large Telescope (VLT) of the European Southern Observatory (ESO), Paranal, Chile (ESO program ID 1104.B-0526).}

\textbf{2. Observations and data reduction}

The MAGPI survey is an ongoing Large Program (Program ID: 1104.B-0526) on the VLT/MUSE, targeting 56 fields (with stellar masses $>7 \times 10^{10} M_{\odot}$). As of September 2023, 48 fields have been completed. The primary objective of this survey is to conduct a detailed spatially resolved spectroscopic analysis of stars and ionized gas within 0.25 < $z$ < 0.35 galaxies (see Foster et al. 2021). Data are taken using the MUSE Wide Field Mode ($1' \times 1'$) with a spatial sampling rate of 0.25/pixel and an average image quality of 0.65'' FWHM. Each field is observed in six observing blocks, each comprising 2×1320 s exposures, resulting in a total integration time of 4.4 h. The survey primarily employs the nominal mode, providing a wavelength coverage ranging from 4700 Å to 9350 Å, with a dispersion of 1.25 Å. Ground-layer adaptive optics (GLAO) is used to correct atmospheric seeing effects, resulting in a 270 Å wide gap between 5780 Å and 6050 Å due to the GALACSI laser notch filter. Deeper MAGPI data resulted in the detection of both foreground sources within the local Universe and distant background sources, including LAEs up to $z \sim 6.4$.

MUSE data reduction was performed using pynmspipe\textsubscript{2}, a Python wrapper for the MUSE reduction pipeline (Weilbacher et al. 2017).
Fig. 2. Flux-ratio and peak-separation maps: (Top row) Pixel by pixel map color-coded according to blue-to-total flux ratio. (Bottom row) Peak separation map. These are arranged from left to right in increasing order of redshift (z = 2.9, 3.6, and 4.8). Peak separation maps are scaled within the range of 200 – 600 km/s.

Table 1. Properties of strong blue-peak LAEs.

<table>
<thead>
<tr>
<th>Field ID</th>
<th>RA</th>
<th>Dec</th>
<th>z</th>
<th>Flux ratio ($F_{\text{blue}}/F_{\text{total}}$)</th>
<th>$\Delta_{\text{peak}}$ (km/s)</th>
<th>$f_{\text{esc}}^{\text{LyC}}$ (ergs/s)</th>
<th>log $L$ (ergs/s)</th>
<th>EW$_{\lambda1450}$ (\AA)</th>
<th>FWHM$_{\text{blue}}$ (km/s)</th>
<th>FWHM$_{\text{red}}$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1534</td>
<td>14:52:20.88</td>
<td>−00:58:25.20</td>
<td>2.94</td>
<td>0.74</td>
<td>370.14</td>
<td>0.050</td>
<td>42.65</td>
<td>60.67 ± 3.43</td>
<td>654.1 ± 34.1</td>
<td>592.9 ± 63.1</td>
</tr>
<tr>
<td>2302</td>
<td>22:40:47.20</td>
<td>−34:42:34.34</td>
<td>3.61</td>
<td>0.60</td>
<td>402.40</td>
<td>0.035</td>
<td>42.52</td>
<td>85.05 ± 23.0</td>
<td>360.8 ± 32.9</td>
<td>446.4 ± 84.7</td>
</tr>
<tr>
<td>1208</td>
<td>12:19:55.30</td>
<td>−02:29:04.30</td>
<td>4.78</td>
<td>0.69</td>
<td>658.21</td>
<td>0.010</td>
<td>42.72</td>
<td>7.160 ± 0.65</td>
<td>415.9 ± 61.7</td>
<td>174.6 ± 32.6</td>
</tr>
</tbody>
</table>

3. Results

We find dominant blue-peak emission features in three newly discovered double-peak LAEs at redshifts of $z = 2.9$, $z = 3.6$, and $z = 4.8$, corresponding to MAGPI field IDs 1534, 2302, and 1208, respectively (see Table 1). Alongside strong Lyα emissions, the MUSE data also reveal various faint rest-frame UV emission and absorption lines: i) For LAE at $z = 2.9$, we identify emission lines such as C iv $\lambda 1548$, 1550, and C iii $\lambda 1908$, as well as multiple absorption lines from both high- (Si iv and C iv) and low-ionization (Si ii and O i) transitions. ii) In the case of $z = 3.6$ LAE, we tentatively observe C iv $\lambda 1548$, 1550 and C iii $\lambda 1908$ emissions and absorption lines from C iv and low-ionization Si ii transitions. iii) For $z = 4.8$ LAE, we detect Si iv $\lambda 1393$, 1402, and C iv $\lambda 1548$, 1550 emission lines, as well as absorption lines from high (Si iv and C iv) and low ionization (Si ii and O i) transitions. For the former two, C iii $\lambda 1908$ lines are either too faint or have insufficient S/N to derive an accurate systemic redshift (Bacon et al. 2021) while for the latter, C iv is outside the spectral window. Following Verhamme et al. (2018), an approximate systemic redshift can be derived by taking the average of the mean wavelengths of the two asymmetric Gaussians fitted to the two Lyα peaks, which gives the following values: $z_{\text{sys}} = 2.9484$, $z_{\text{sys}} = 3.6136$ and $z_{\text{sys}} = 4.788$.

For our detections, we use the Python/MPDAF package (Bacon et al. 2016) designed for MUSE data cube analysis. We generate continuum-subtracted Lyα narrow-band (NB) images from the MUSE data cube. We perform double-skewed Gaussian fitting to 1D Lyα emission profiles, utilizing the Python/pyplatefit package (Bacon et al. 2023). Lyα NB images along with corresponding 1D profiles are shown in Fig. 1. To quantify the strength of the blue peak, we measure blue-to-total flux ratios ($F_{\text{blue}}/F_{\text{total}}$; where $F_{\text{total}} = F_{\text{blue}} + F_{\text{red}}$). Hence, $F_{\text{blue}}/F_{\text{total}} > 0.5$ implies a stronger blue peak. We also estimate other parameters including peak separations ($\Delta_{\text{peak}}$), Lyα luminosities, total rest-frame equivalent widths (EW$_{\lambda}$), and the full width at half maximum (FWHM) of the blue and red peaks. We determine the LyC escape fraction ($f_{\text{esc}}^{\text{LyC}}$) based on the empirical relationship between $f_{\text{esc}}^{\text{LyC}}$ and $\Delta_{\text{peak}}$ from Izotov et al. (2018b). These results, along with respective source coordinates (right ascension (RA) and declination (DEC) of the bright cores), are summarised in Table 1. We also estimate LyC escape using C iv $\lambda 1550$/C iii $\lambda 1908$ following the work of Schaerer et al. (2022). To investigate spatial variations in 1D profiles of our sources, we generate pixel-by-pixel maps color-coded according to $F_{\text{blue}}/F_{\text{total}}$ and $\Delta_{\text{peak}}$ on the Lyα NB images (see Fig. 2).

Our double-peak Lyα spectral profiles are unique, showing prominent and stronger blue peaks than the red peaks. We observe a variety of spatial distributions of Lyα emissions, where...
the continuum-subtracted Ly\(\alpha\) NB images reveal two extended Ly\(\alpha\) halos and one compact, point-like LAE (Fig. 1, top row). Arranged by increasing redshift, these LAEs at \(z = 2.9, z = 3.6\), and \(z = 4.8\) span regions measuring 24.8\(\times\)26.4 kpc, 19.2\(\times\)28.2 kpc, and 8.7\(\times\)8.7 kpc, respectively. Notably, the extended halos at \(z = 2.9\) and \(z = 3.6\) exhibit spatially varying spectra, featuring varying \(F_{\text{blue}}/F_{\text{total}}\) and \(\Delta_{\text{peak}}\) in different spatial locations. In contrast, the compact LAE predominantly displays an overall blue-peak-dominated spectral profile, with mild variations in the outskirts. Below we break down our spectral and spatial analysis for each of the three cases:

i) \(z = 2.9\) LAE (field ID 1534) shows a compact “continuum-like” bright core and an extended halo (Fig. 1, left panel in top row). Such spatial profiles are characterized by a “two-component model” (seeWisotzki et al. 2016; Leclercq et al. 2017). Two “tail-like” regions are identified within the halo. A faint continuum is also detected at the source location. Due to source crowding, faint continuum emissions from neighboring sources were also detected. To address this, we subtracted the continuum emissions from neighboring sources to obtain pure emission lines of our source. Subsequently, we spectrally collapsed this processed data cube over the Ly\(\alpha\) wavelength range in order to construct a continuum-subtracted Ly\(\alpha\) NB image showing an extensive Ly\(\alpha\) halo spanning 24.8\(\times\)26.4 kpc. The halo displays spatially varying double-peaked spectra, with the brightest core featuring the strongest blue peak with \(F_{\text{blue}}/F_{\text{total}} = 0.74\) (EW\(_{\text{blue,0}} = 46.3\pm 3.7\) Å and EW\(_{\text{red,0}} = 14.4\pm 1.7\) Å). Figure 1 (bottom row, left panel) presents a continuum-subtracted 1D profile of the core extracted adopting a circular aperture of \(8.8''\) radius. The overall 1D profile of the halo reveals a symmetric double peak with a slightly stronger blue peak. This spatial variation is evident in the \(F_{\text{blue}}/F_{\text{total}}\) map (Fig. 2, top row, left panel), showing that the blue peak dominates in the bright core and in its associated tail in the upper part of the halo, while the red peak dominates in the lower regions and in the outskirts. There is a smooth gradient from blue-dominated regions to red-dominated regions, with a boundary of \(F_{\text{blue}} = F_{\text{red}}\) in the central region of the halo. We also observe a significant spatial variation in Ly\(\alpha\) peak separation (see Fig. 2, bottom row, left panel), ranging from \(\sim 200\) to 750 km/s with larger separations (\(\geq 480\) km/s) in the central region and smaller ones (\(\geq 400\) km/s) in the bright core and outskirts. We measure a C \(\text{v/C [m]}\) ratio of 0.83 for this source.

ii) We find an extended halo around the \(z = 3.6\) LAE (field ID 2302), showing three distinct bright regions labeled as A, B and C (Fig. 1, top row middle panel), all displaying double-peak emission. Remarkably, these bright regions are spatially separated, a unique distribution seen in Ly\(\alpha\) halos. Due to source faintness and low S/N, a continuum light was not immediately visible. However, applying a median filter to the data cube revealed faint continuum light at the location of the brightest core. Region A, the brightest core, displays prominent, strong blue-peak emission with \(F_{\text{blue}}/F_{\text{total}} = 0.60\) (EW\(_{\text{blue,0}} = 47.2\pm 13.0\) Å and EW\(_{\text{red,0}} = 37.8\pm 11.8\) Å) and is encircled with an aperture of 0.8'' radius. The entire halo shows a symmetric double-peaked profile with almost equal peak strengths. The flux-ratio map illustrates (see Fig. 2, top row middle panel) the dominance of the blue component mainly in the bright core (A) and in the lower diffuse halo (C), with the red peak becoming more prominent as we move away from the core and the other bright regions. We further observe larger peak separations (\(\sim 400\)–600 km/s) in region A and at the center of the halo, and regions B and C exhibit peak separations of \(\sim 390\) km/s, while comparatively lower peak separation (\(\lesssim 370\) km/s) is seen in other regions within the halo and in the outskirts (Fig. 2, bottom row, middle panel). We find a C \(\text{v/C [m]}\) ratio of 1.1.

iii) The LAE at \(z = 4.8\) (field ID 1208) shows a compact spatial profile (Fig. 1, top row, right panel) resembling that of “point-source LAEs” as studied by Bacon et al. (2015). Continuum light is detected at the location of Ly\(\alpha\) emission in this source. The Ly\(\alpha\) profile shows a broader and stronger blue-peak emission. The flux-ratio map (Fig. 2, top row, right panel) confirms the prevalence of the blue component across most of the Ly\(\alpha\)-emitting region, with slight red-peak dominance in the outskirts. Similar to previous cases, we find larger peak separations (\(\gtrsim 600\) km/s) in the central region and smaller values (\(\lesssim 450\) km/s) in the outskirts.

4. Discussion

In this letter, we report three new double-peaked LAEs with dominant blue-peak emissions. These are \(\sim 9\%\) of the sample of double-peaked LAEs found in the MAGPI survey, which is consistent with the results obtained in cosmological zoom-in simulations (Blaziot et al. 2023). Ly\(\alpha\) emission profiles with dominant blue peaks have previously been observed in different spatially separated regions within LABs or luminous Ly\(\alpha\) nebulae. By comparison with the spatial size of LABs and nebulae (Vanzella et al. 2017; Li et al. 2022), we find that our extended LAEs are not in the regime of LABs or nebulae. However, we classify \(z = 2.9\) and \(z = 3.6\) LAEs as extended Ly\(\alpha\) halos (see discussions inWisotzki et al. 2016; Leclercq et al. 2017). The source at \(z = 2.9\) shows a similar spatial distribution to that described byWisotzki et al. (2016) and Leclercq et al. (2017), featuring a continuum-like bright core surrounded by an extended halo. On the other hand, the extended source at \(z = 3.6\) reveals a more complex Ly\(\alpha\) spatial distribution, displaying three bright regions within the halo. This complexity suggests complex kinematics involving gas inflows and outflows in this galaxy (Vanzella et al. 2017; Ao et al. 2020; Li et al. 2022; Erb et al. 2018). This could also indicate a merger system, where two progenitors are merging into a single descendent (e.g., Tilvi et al. 2011). A faint continuum light from these two sources is also detected in the MUSE data. However, lack of deep imaging data limits our ability to perform robust continuum subtraction and radial profile estimation.

Erb et al. (2018, 2023) report complex kinematics in double-peaked extended Ly\(\alpha\) halos at \(z \sim 2\), with the authors observing a dominant red peak in the central bright region with large peak separations, and a dominant blue peak at the edge of the halos where peak separations become narrower. For both of our extended halos, we find peak separation distribution similar to those described by Erb et al. (2018, 2023), but an inverse (core- to-halo) distribution for flux ratios. In both of our extended halos, the bright cores powering the Ly\(\alpha\) emission are dominated by blue peaks, while red peaks dominate as we move away from the bright cores towards the edges. This means that we have discovered the first two Ly\(\alpha\) halos at \(z = 2.9\) and \(z = 3.6\) with dominant blue cores.

In contrast, we find an overall blue-peak-dominated Ly\(\alpha\) spectral profile in the compact LAE at \(z = 4.8\). Furtak et al. (2022) discovered the first such compact lensed object at \(z = 3.2\). This was followed by a similar detection in a compact UV-bright star-forming galaxy at \(z = 3.6\) (Marques-Chaves et al. 2022). Furtak et al. (2022) further find that both the blue and red peaks originate from the compact LAE itself. Similar to their flux ratio map, we observe that the entire Ly\(\alpha\)-emitting region is domi-
nated by the blue peak, while the red peak becomes stronger at the edges.

Overall, we observe that Lyα peak separation decreases with increasing radius, which is consistent with the findings of Erb et al. (2018, 2023). This trend is primarily driven by $N_{HI}$, where greater $N_{HI}$ values result in larger peak separations. Lyα peak separation can be influenced by the cloud covering fraction (CF) within a clumpy outflow, where higher CF mimics higher $N_{HI}$ (Gronke et al. 2016) and impacts the velocity shift of escaping photons. However, this strongly depends on other parameters, such as velocity and gas temperature (e.g., Kakiichi & Gronke 2021; Li et al. 2022).

Verhamme et al. (2017) find that strong LyC emitters are strong LAEs with high-rest-frame EWs (≥ 70 Å) and large Lyα escape fractions. Simulations suggest a connection between double-peak separation and $N_{HI}$, indicating that for low $N_{HI}$, a narrow peak separation (≤ 400 km/s) serves as a strong indicator of LyC escape (Verhamme et al. 2015; Kakiichi & Gronke 2021). These predictions are confirmed observationally for low-redshift dates for LyC leakers. In contrast, we find a relatively large peak separation and a very low rest-frame EW for the compact LAE, implying a relatively high $N_{HI}$ in this system and almost no escape of LyC photons.

Radiative transfer simulations, incorporating shells or clumpy, multi-phase models with varying outflow velocities typically focus on double-peak profiles of LyC with stronger red peaks (Gronke & Dijkstra 2016; Erb et al. 2023). Cosmological hydrodynamics simulations suggest that red-dominated lines preferentially arise in face-on directions, while blue-dominated lines are seen in the edge-on directions (Bliazot et al. 2023). A Lyα line with a stronger blue peak than the red peak usually implies inflows of CGM gas along the line of sight during the accretion phase (Vanzella et al. 2017; Ao et al. 2020; Bliazot et al. 2023). In this context, our new discoveries suggest inflowing gas systems or edge-on morphologies, warranting further investigation in order to understand the complex gas kinematics and the environments of such rare LAEs. These investigations will help us to constrain the mechanisms that regulate their formation and evolution.

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T. Mukherjee et al.: Strong blue peak LAEs up to $z \approx 4.8$

Article number, page 5 of 5