

An extremely metal-poor Lyman- α emitter candidate at $z = 6$ revealed through absorption spectroscopy

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ABSTRACT

We report the discovery of a Lyman α emitter (LAE) candidate in the immediate foreground of the quasar PSO J158-14 at $z_{\text{QSO}} = 6.0685$ at a **projected distance ~ 29 pkpc** that is associated with an extremely metal-poor absorption system. This system was found in archival observations of the quasar field with the Very Large Telescope/Multi-Unit Spectroscopic Explorer (VLT/MUSE) and was previously missed in searches of absorption systems using quasar absorption line spectroscopy as it imparts **no detectable metal absorption lines** on the background quasar spectrum. The detected Ly α emission line at a redshift of $z_{\text{LAE}} = 6.0323$ is well aligned with the outer edge of the quasar's proximity zone and can plausibly cause its observed damping wing if it is associated with a proximate sub-damped Ly α absorption system with a column density of $\log N_{\text{HI}}/\text{cm}^{-2} \approx 19.8$. A > 10 hour medium-resolution spectrum of the quasar observed with the Magellan/Folded-port InfraRed Echellette (FIRE) and VLT/X-Shooter spectrographs reveals a metallicity constraint of $[Z/H] < -3$. Such low metallicity makes this system an extremely metal-poor galaxy candidate and provides an exciting site to study **possible signatures of Population III stars**.

1. INTRODUCTION

Finding Population III (Pop III) stars is one of the most sought-after endeavors in modern astrophysics due to their important role in the formation of the first structures in the early Universe (e.g. Klessen & Glover 2023). Pop III stars are the first generation of stars that collapsed from pristine, (nearly) metal-free gas produced

by the Big Bang nucleosynthesis. They are thought to create the first heavy elements and their remnants possibly provide the initial seeds for the earliest supermassive black holes (SMBHs). Their direct detection remains elusive as the majority of Pop III stars are thought to have mostly formed early in the history of the Universe ($z \sim 20 - 30$) and their likely heavy masses (e.g. Abel et al. 2002; Bromm 2017) caused them to have very short lifetimes (\sim a few Myr). Furthermore, they are thought to reside in minihalos (Hirano et al. 2015; Schauer et al. 2019) with luminosities that should be challenging to

detect at such high redshifts even with the sensitivity of the James Webb Space Telescope (JWST) (Schauer et al. 2020).

Despite the challenges in directly detecting Pop III stars, significant progress has been made in studying their signatures indirectly through observational probes and theoretical modeling. Examples include the study of extremely metal-poor ($[\text{Fe}/\text{H}] < -3$) stars in the Local Group (Pop II, e.g. Beers & Christlieb 2005; Frebel & Norris 2015) or the imprints of Pop III stellar feedback on the largest scales (Madau & Dickinson 2014). Recently, substantial progress has been made on developing new optical emission-line diagnostics that could enable the study of this elusive stellar population in the early Universe (e.g. Nakajima & Maiolino 2022; Katz et al. 2023; Vanni et al. 2024; Katz et al. 2024). In fact, a handful of metal-poor systems at high-redshift have already been identified through their emission-line properties (e.g. Vanzella et al. 2023; Cameron et al. 2024; Maiolino et al. 2024; Cullen et al. 2025; Fujimoto et al. 2025; Naidu et al. 2025), with metallicities as low as $12 + \log(\text{O}/\text{H}) < 6.3$, or $[\text{O}/\text{H}] < -2.4$ (Vanzella et al. 2023).

Theoretical models predict that pristine gas pockets and Pop III star formation can persist beyond $z \sim 6$ (Tornatore et al. 2007; Johnson & Aykutalp 2019). One method to search for such isolated environments is via absorption systems along sightlines to distant quasars (e.g. Becker et al. 2011, 2019; D’Odorico et al. 2022; D’Odorico et al. 2023). Quasar absorption line spectroscopy has proven extremely useful in studying chemical enrichment across cosmic time (e.g. Simcoe et al. 2002; Schaye et al. 2003; Ryan-Weber et al. 2009; Cooke et al. 2011; Davies et al. 2023b; Welsh et al. 2024, refer to Fan et al. 2023 for a review), particularly through damped Lyman- α absorption systems (DLAs, $\log N_{\text{HI}}/\text{cm}^{-2} > 20.3$). DLAs produce distinctive features in a quasar spectrum. The neutral hydrogen produces a saturated Voigt absorption line profile with a Lorentzian damping wing in the Ly α forest. This is accompanied by low-ionization metal absorption lines at the same redshift due to the metals present in the gas. More diffuse systems that are still optically thick to Ly α , such as Lyman limit systems (LLSs) and sub-damped Lyman- α absorption systems (sub-DLAs) with $17.2 \leq \log N_{\text{HI}}/\text{cm}^{-2} \leq 20.3$, are of particular importance in searching for pristine, isolated environments as their densities are not sufficient to sustain star formation that would cause chemical enrichment by further generations of stars (Fumagalli et al. 2011; Salvadori & Ferrara 2012; Fumagalli et al. 2016; Saccardi et al. 2023).

At $z \gtrsim 5$, the increasingly neutral intergalactic medium (IGM) suppresses the Ly α forest and renders identifying absorption systems therein significantly more challenging (e.g. Gunn & Peterson 1965; Simcoe et al. 2020; Fan et al. 2023). Searches for such high-redshift HI-rich gas clouds are thus mostly restricted to cases where the absorber lies in the region of increased flux transmission in the immediate foreground of the quasar, known as the proximity zone (e.g. Cen & Haiman 2000, Madau & Rees 2000, Haiman & Cen 2001, Fan et al. 2006; also note recent work doing this in galaxy sightlines by Heintz et al. 2025). Such systems have been found near a handful of high-redshift quasars as proximate DLAs (pDLAs; D’Odorico et al. 2018; Bañados et al. 2019; Davies et al. 2023a). Even then, disentangling the quasar’s Ly α damping wing due to the proximate absorber from the imprint of the neutral IGM has only been enabled through the detection of metal absorption lines in the quasar spectrum, which concurrently provide a valuable constraint on the metallicity of the intervening gas cloud (Bañados et al. 2019; Simcoe et al. 2012; Wang et al. 2020).

Given the required presence of metal absorption lines, the identified pDLAs near Reionization-era quasars are not pristine anymore, as they already show significant metal enrichment (D’Odorico et al. 2018; Bañados et al. 2019). Therefore, to identify the most metal-poor systems that could potentially host Pop III stars, one has to look for proximate absorption systems in high-redshift quasar sightlines that do not produce strong associated metal line absorption. This is especially challenging during the Epoch of Reionization, as metal-poor proximate absorption systems can be easily confused with Ly α damping wings caused by the IGM. In this letter, we report on the discovery of such a proximate absorption system in the field of a $z = 6$ quasar.

Throughout this paper, we use the flat Λ CDM cosmology with $h = 0.67$, $\Omega_M = 0.31$, $\Omega_\Lambda = 0.69$ (Planck Collaboration et al. 2020).

2. EVIDENCE FOR A METAL-POOR ABSORPTION SYSTEM IN PSO J158-14

2.1. IGM damping wing or absorption system?

The quasar PSO J158-14 at $z_{\text{QSO}} = 6.0685$ (Chehade et al. 2018; Eilers et al. 2020) exhibits a somewhat unexpected damping-wing-like Ly α transmission profile (Fig. 1, also see the top panel of Fig. 3). All current constraints on the history of reionization (Eilers et al. 2018; Bosman et al. 2018; Yang et al. 2020; Āurovčiková et al. 2024; Bosman et al. 2022) imply a very low volume-averaged neutral gas fraction at this redshift ($\bar{x}_{\text{HI}} \lesssim 0.2$), which makes seeing strong damping wings due to the

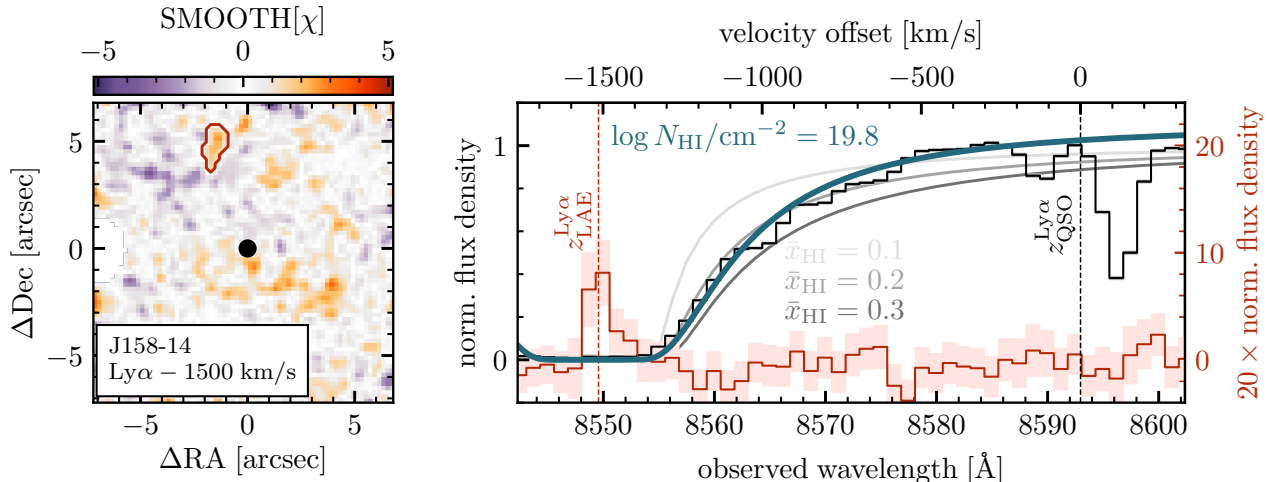


Figure 1. Left: A smoothed, PSF-subtracted SNR image (SMOOTH[χ]) from MUSE showing the newly identified LAE in the foreground of the quasar PSO J158-14 (offset by -1500 km/s from the Ly α emission of the quasar). Right: The LAE spectrum from the original (not PSF-subtracted) MUSE data cube extracted over the contour shown in the left panel is shown in red (1σ and 2σ uncertainties shown as shaded red regions). The quasar spectrum is shown in black with gray uncertainties, which are too small to be clearly visible, with its Ly α redshift marked by $z_{\text{QSO}}^{\text{Ly}\alpha}$. The redshift of the LAE, $z_{\text{LAE}}^{\text{Ly}\alpha} = 6.0323$ aligns with the end of the quasar’s proximity zone, and an absorber with a column density of $\log N_{\text{HI}}/\text{cm}^{-2} \approx 19.8$ (a sub-DLA) can be used to model the damping wing of this quasar. For comparison, we also overplot example damping wing profiles arising from a homogenous IGM at a volume-averaged neutral gas fraction of $\bar{x}_{\text{HI}} = 10\%$, 20% , and 30% (Miralda-Escudé 1998). Note that the LAE spectrum has been amplified $20\times$ for better visibility and no other emission lines are seen across the wavelength range of MUSE.

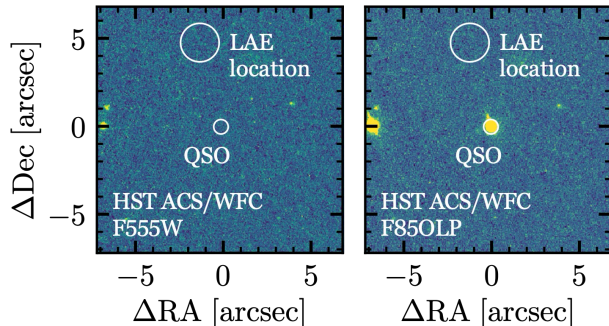


Figure 2. Archival imaging data of the quasar field from HST. Left: It is unlikely that this emission is not Ly α as no foreground emission is detected by HST ACS/WFC imaging with the F555W filter at a limiting magnitude of 26.88. Right: A non-detection in the F850LP filter at a limiting magnitude of 25.98 is consistent with the Ly α line flux measured in MUSE.

IGM unlikely. There is growing evidence of neutral islands and damping wings persisting at $z < 6$ (Becker et al. 2024; Zhu et al. 2024; Spina et al. 2024; Sawyer et al. 2025) due to a patchy reionization topology, however, simulations have shown that the likelihood of PSO J158-14 having a damping wing due to our sightline randomly crossing a neutral patch in the IGM is $< 0.2\%$ (Satyavolu et al. 2023). Satyavolu et al. (2023) also noticed weak extended flux just blueward of the proxim-

ity zone indicating that this quasar’s damping-wing-like absorption profile might in fact not be due to the IGM. Despite this fact, no metal absorption lines associated with a proximate absorption system have been found in the spectrum of this quasar (Eilers et al. 2020; Davies et al. 2023b). This suggests that if a proximate absorber is the cause for the observed damping wing, it must be composed of metal-poor gas.

Using deep (~ 8.5 hr) observations with the Very Large Telescope/Multi-Unit Spectroscopic Explorer (MUSE, Bacon et al. 2010), we have identified a likely Ly α emitter (LAE) with an integrated line flux of $F_{\text{Ly}\alpha}^{\text{LAE}} \approx 2 \times 10^{-18}$ erg/s/cm 2 in the immediate foreground of the quasar PSO J158-14 at a transverse distance of $\sim 5''$ (~ 29 pkpc; left panel of Fig. 1). Note that the displayed pseudo-narrowband image, collapsed over a spectral width of 100 km/s, shows other patches of comparable signal-to-noise (SMOOTH[χ]); however, only the pixels marked by the LAE contour show a clear, isolated emission line structure in the velocity space. At the position of this LAE, we detect no other emission lines over the wavelength range of MUSE. We refer the reader to Āurovčíková et al. (2025) for details on the MUSE observations and data reduction.

In order to test whether the detected emission line could be from a lower-redshift galaxy, we inspected archival imaging data of this quasar field taken with

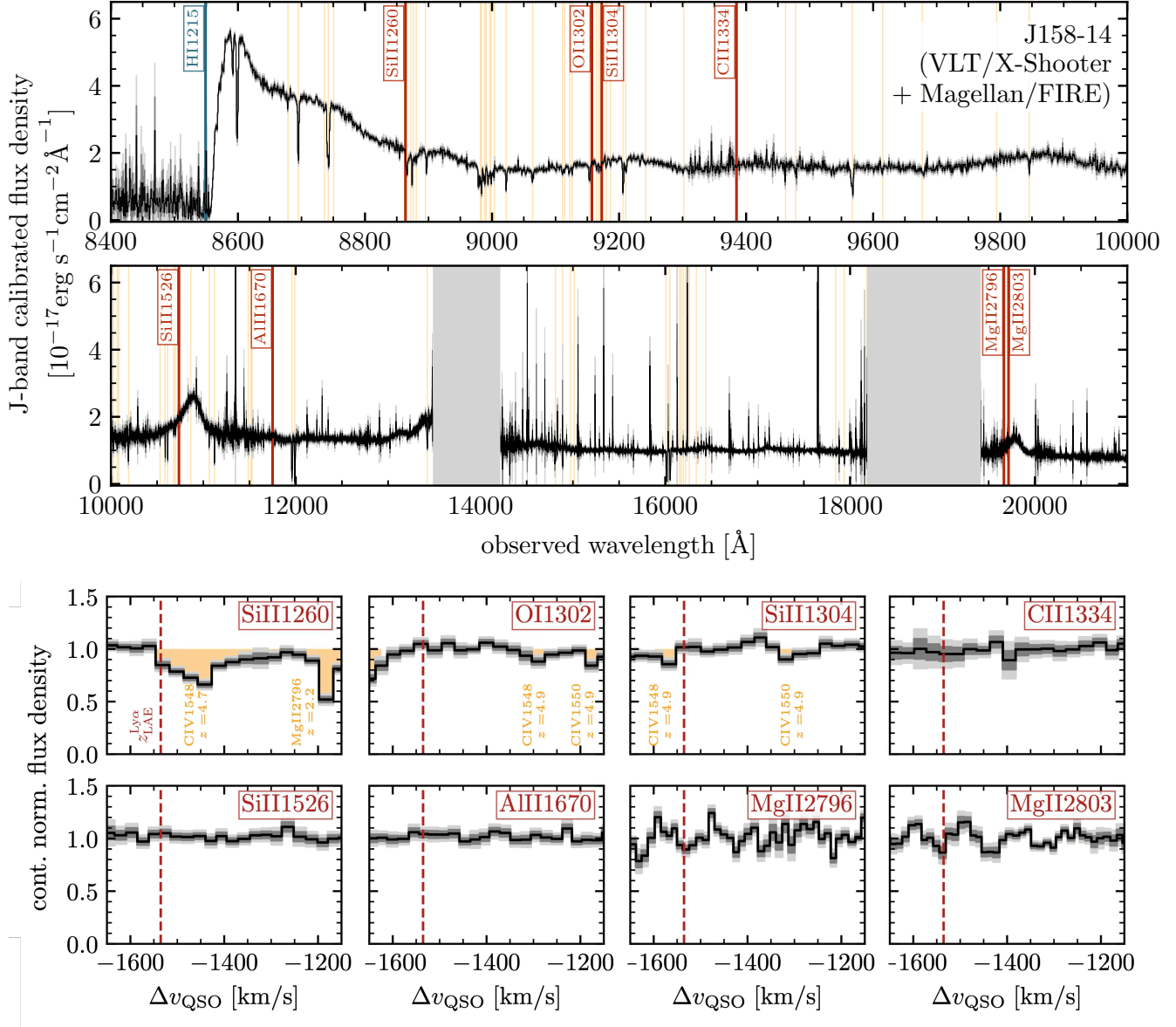


Figure 3. Top: A deep (10.2 hr) medium-resolution J-band calibrated spectrum of the quasar PSO J158-14, observed with the Magellan/FIRE and VLT/X-Shooter spectrographs. This spectrum was further continuum normalized (see main text) and used to stack regions corresponding to low-ionization absorption lines (shown as vertical red lines) that could be associated with the foreground LAE (marked by the blue vertical line). The orange vertical lines mark all absorption lines due to foreground systems identified by Davies et al. (2023b). Bottom: Zoom-in on the absorption line regions in the continuum-normalized spectrum that could be associated with the foreground absorber, in velocity relative to the quasar’s rest frame. The dashed red line corresponds to the redshift of the LAE identified in MUSE observations, and orange regions mark absorption features due to other foreground systems (Davies et al. 2023b). In both parts of the figure, the 1σ and 2σ uncertainties are shown as gray and light gray shaded regions.

the Advanced Camera for Surveys (ACS) aboard the Hubble Space Telescope (HST; Proposal ID: 16756, PI: Eilers; previously analyzed by Yue et al. 2023). Neither of the two ~ 30 min exposures, taken with the Wide Field Channel (WFC) F850LP and F555W filters, show a detection at the location of this LAE (Fig. 2). A non-detection in the F850LP image (which has a 3σ limiting

AB magnitude of 25.98 over the area of the LAE, implying an observed equivalent width of $\text{EW}_{\text{obs}} \gtrsim 33 \text{ \AA}$) is not surprising as the line flux detected from MUSE would correspond to a source with $m_{\text{AB}} \approx 29.9$ in this image. A non-detection in the F555W image is also consistent with this emission line being Ly α at $z \sim 6$ as its foreground flux would be suppressed by the IGM. If

this source were, however, a foreground interloper, the low-redshift galaxy would have to be fainter than 26.88 magnitude (which is the 3σ limiting AB magnitude over the LAE area)¹.

Thus, we assume that the detected line is indeed Ly α and the centroid of this emission line yields a redshift of $z_{\text{LAE}}^{\text{Ly}\alpha} = 6.0323$, which aligns with the spectral region where we would expect an associated absorption system to be placed, i.e. the outer edge of the quasar’s observed proximity zone (right panel of Fig. 1). Using a Voigt profile (shown in blue), we find that the observed absorption profile can indeed be modeled using a sub-DLA with an estimated H I column density of $\log N_{\text{HI}}/\text{cm}^{-2} \approx 19.8$ and an estimated broadening parameter of $b \approx 10$ km/s.

2.2. Metallicity from absorption spectroscopy

To derive a metallicity constraint for this absorber, we obtain a high-SNR, medium-resolution spectrum of the quasar to search for associated metal absorption lines. We co-added archival, shallow VLT/X-Shooter (Vernet et al. 2011) observations of this quasar from January 24, 2017 (4320 s/1.2 hr; Program ID: 096.A-0418, PI: Shanks) with a newly observed deep spectrum taken with the Folded-port InfraRed Echellette (FIRE) spectrograph on the Magellan telescope (Simcoe et al. 2013). Magellan/FIRE observations come from January 13, 2023 (9600 s), July 14, 2024 (4800 s), and Jan 13, 2025 (18000 s), totaling 9 hours of exposure time. These observations were reduced using the PyPeIt package² (Prochaska et al. 2020; Prochaska et al. 2020) and we refer the reader to Āurovčíková et al. (2024) for a more detailed description of the FIRE data reduction. The final spectrum, at a resolution of ~ 30 km/s, thus includes 10.2 hours of exposure time and is shown in the top part of Fig. 3. Spectra from individual nights were calibrated to J_{AB} magnitude of 19.19 (Schindler et al. 2020) before co-adding to create the final spectrum displayed here³.

After fitting the quasar spectrum shown in the top part of Fig. 3 and predicting its continuum emission around Ly α following the methods in Āurovčíková et al.

(2020), we normalize the observed spectrum by the predicted continuum to search for metal absorption lines. We proceed by stacking regions of the continuum-normalized quasar spectrum where the accessible low-ionization metal lines at the redshift of the LAE would lie. We show these regions that contribute to the stack in the bottom part of Fig. 3, with the red dashed line marking the redshift where we would expect to find absorption lines associated with this LAE. Note that during this procedure, we mask all absorption features in the spectrum that have previously been identified as corresponding to foreground intervening absorption systems (shown as orange regions in Fig. 3; Davies et al. 2023b). We thus compute the mean stack of the regions shown in the bottom part of Fig. 3 and show the result in black in the left panel of Fig. 4, with gray and light gray 1σ and 2σ uncertainties, respectively. Note that the stacked spectrum is shown in terms of the velocity offset from the quasar – therefore, any absorption associated with the LAE would be seen at the location of the red dashed line marking $z_{\text{LAE}}^{\text{Ly}\alpha}$.

We detect no metal absorption lines at the redshift of the LAE beyond the noise level of the stacked, high-SNR spectrum, in agreement with previous studies that used shallower data (Eilers et al. 2020; Davies et al. 2023b). To quantify the metallicity of this LAE, we forward model stacked absorption line profiles for the aforementioned transitions corresponding to our estimated H I column density and broadening of this absorption system ($\log N_{\text{HI}}/\text{cm}^{-2} = 19.8$ and $b = 10$ km/s) at a range of metal abundance ratios $[Z/H]$. As this system is a sub-DLA and therefore not fully self-shielding, we take into account ionization corrections (Viegas 1995) when converting the observed hydrogen column density to the column densities of the metals considered here,

$$\log N_{Z_i} = [Z/H] + \log N_{\text{HI}} + \log \left(\frac{N_Z}{N_{\text{H}}} \right)_{\odot} - \text{IC}(Z_i). \quad (1)$$

Here, $\log N_{Z_i}$ is the column density corresponding to a particular ionization state of the metal Z, $\log N_{\text{HI}}$ is the column density of the neutral hydrogen (estimated from the quasar spectrum), $\log(N_Z/N_{\text{H}})_{\odot}$ is the solar abundance ratio (from Asplund et al. 2009), and $\text{IC}(Z_i)$ is the ionization correction for a given ionization state at a given metallicity.

To obtain these ionization corrections, we ran a grid of CLOUDY (v23.01, Ferland et al. 1998; Chatzikos et al. 2023) models at a range of metallicities, $-4.0 \leq [Z/H] \leq 0.0$ in steps of 1.0, and hydrogen densities, $-3.0 \leq \log n_{\text{H}}(\text{cm}^{-3}) \leq 3.0$ in steps of 0.5. We include the UV background from Haardt & Madau (2012), the cosmic microwave background (CMB) at the redshift of

¹ Note that if the emission line detected in MUSE were H α , this dwarf galaxy would be at $z = 0.3$ and its [O II]3727Å emission line would fall into the F555W filter. Additionally, H β and [O III] lines would fall into the wavelength range of MUSE, and could have been detected. Additionally, if the detected emission line were [O II]3727Å (corresponding to a galaxy at $z \sim 1.3$), we should be partially resolving its doublet shape. Therefore, also given the asymmetric profile of the observed line (Matthee et al. 2017; Hayes et al. 2021), it is likely to be Ly α at high-redshift.

² <https://pypeit.readthedocs.io/en/latest/>

³ The spectrum is publicly available at <https://doi.org/10.5281/zenodo.15306220>

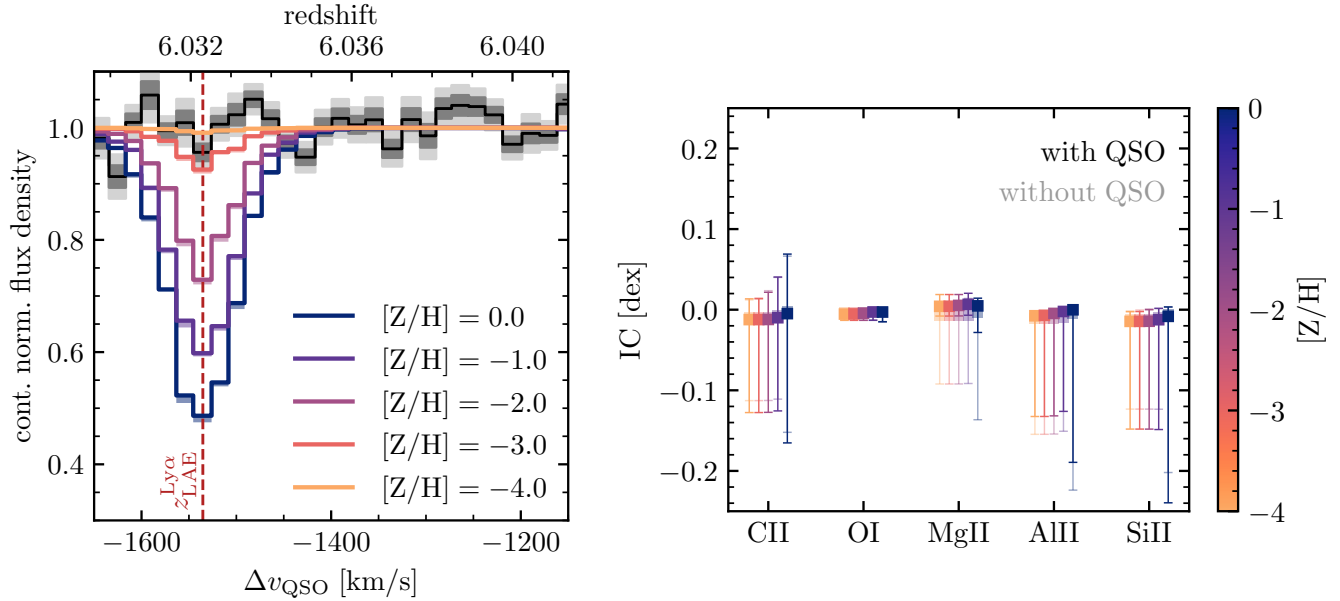


Figure 4. Left: Metallicity constraint on the newly found proximate absorption system. Here we show the stack of low-ionization absorption line regions in the continuum normalized spectrum of PSO J158-14, in terms of the velocity shift from the quasar’s rest frame, shown in the bottom part of Fig. 3 and also marked by vertical red lines in the top part of Fig. 3. The 1σ and 2σ uncertainties on the stacked spectrum are shown as gray and light gray shaded regions. There is no detectable absorption at the redshift of the LAE at this spectral resolution, yielding a metallicity constraint of $[Z/H] < -3$. This absorber thus constitutes an extremely metal-poor candidate. The shaded regions around the modeled absorption line profiles reflect the 1σ uncertainties on the ionization corrections derived from CLOUDY, as shown in the right panel. Right: Ionization corrections (with 1σ uncertainties from marginalizing over the modeled hydrogen densities) to the column densities of individual ions from CLOUDY used for absorption line profile modeling. Even though this absorption system is not fully self-shielding, the corrections are close to zero. This holds even when the radiation from the background quasar is taken into account (solid data points; compared to CLOUDY models without the quasar radiation shown as semi-transparent data points).

the LAE as well as cosmic rays. Additionally, we include the radiation of the background quasar as this could play a significant role in the case of this sub-DLA. We do not include the effects of dust grains as these are known to be negligible at the low metallicities most relevant to this system (De Cia 2018; Vladilo et al. 2018; Hamanowicz et al. 2024). From these models, we derive $IC(Z_i)$ by comparing the total abundance of the element Z with respect to hydrogen to the ratio of the neutral hydrogen column density to the column density of the ionization state under consideration (Viegas 1995). Subsequently, we marginalize over the grid of modeled hydrogen densities to obtain a distribution of ionization correction for each ionic species across the different metallicities.

The derived ionization corrections are small ($\lesssim 0.3$ dex), especially at lower metallicities, even when the irradiation by the background quasar is taken into account (right panel of Fig. 4; results from CLOUDY runs without the quasar radiation are shown for comparison as semi-transparent data points). This is comparable to other sub-DLA corrections found in the literature (Berg et al. 2021; Welsh et al. 2024). Taking

these corrections (including their 1σ uncertainties) into account yields an upper limit on the metallicity of this absorber of $[Z/H] < -3$ (left panel of Fig. 4). Such metallicity constraint implies an extremely metal-poor absorption system in the foreground of PSO J158-14, consistent with the redshift of the foreground LAE at a projected distance ~ 29 pkpc.

3. CONCLUSION

Using integral field unit spectroscopy, we identified a new LAE in the immediate foreground of the quasar PSO J158-14 at $z \approx 6$ that likely represents an extremely metal-poor proximate absorption system at $[Z/H] < -3$. We detect no associated metal absorption lines in a deep, 10.2-hour medium-resolution spectrum of the quasar.

This high-redshift system is unique in that its low metallicity constraint is based on absorption spectroscopy, unlike other metal-poor galaxies identified at high-redshift with emission-line-based metallicities from JWST (Vanzella et al. 2023; Cameron et al. 2024; Maiolino et al. 2024; Cullen et al. 2025; Fujimoto et al. 2025; Naidu et al. 2025; Willott et al. 2025). In fact, our metallicity limit is even lower than the most metal-poor

high-redshift galaxies identified to date with metallicity constraints of $[O/H] < -2.4$ (Vanzella et al. 2023) and $[Z/H] < -2.3$ (Fujimoto et al. 2025).

The existence of this foreground LAE further implies that the proximity zone of the quasar is likely truncated, which in turn implies that the estimate of this quasar’s lifetime based on the extent of its proximity zone is underestimated. This is supported by the fact that the MUSE data reveal a large ($23.85^{+23.70}_{-9.17}$ pkpc) Ly α nebula around PSO J158-14 (Đurovčiková et al. 2025).

In order to confirm the redshift and the low metallicity of this absorption system, deep, high-resolution spectroscopic observations of the quasar are required to resolve such weak metal lines (as demonstrated by Welsh et al. 2023 in lower-redshift metal-poor DLAs). Detecting these possible absorption features would also enable us to expand this analysis beyond the assumptions of the solar abundance pattern. Additionally, at a projected distance of ~ 29 pkpc, the quasar sightline is likely probing gas outside of the virial radius of this LAE, suggesting that we might be probing its circumgalactic medium that has not been enriched. Therefore, in order to confirm the low-metallicity nature of its host

galaxy candidate, direct spectroscopic observations of the LAE itself are necessary. If its metallicity is confirmed, this newly detected source could prove to be the most metal-poor system currently known at high redshift and thus provide a unique opportunity to search for signatures of Pop III stars.

ACKNOWLEDGMENTS

We would like to thank Carlos Contreras, Matías Díaz, Carla Fuentes, Mauricio Martínez, Alberto Pastén, Roger Leiton, Hugo Rivera, and Gabriel Prieto for their help and support during the Magellan/FIRE observations. We would also like to thank Rongmon Bordoloi for helpful discussions. RAM acknowledges support from the Swiss National Science Foundation (SNSF) through project grant 200020_207349.

This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile.

Based on observations collected at the European Southern Observatory under ESO programs 106.215A and 096.A-0418.

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