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TRACING HI DISTRIBUTION AND IONIZING PHOTON ESCAPE IN STAR-FORMING GALAXIES ACROSS COSMIC TIME WITH CURRENT AND UPCOMING IFS

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Abstract. We summarize how current integral field spectroscopy (IFS) instruments (e.g., VLT/MUSE, Keck/KCWI) have revolutionized gas mapping around high-redshift and local galaxies using Lyman-alpha (Lyα) emission and other nebular lines (Mg II and [O II]). We also present recent work connecting gas distribution with the escape of ionizing photons (the Lyman continuum, LyC) in a statistical sample of confirmed local LyC emitters. Finally, we provide an outlook on future IFS instruments (e.g., BlueMUSE, WST), which will enable further characterization of the gaseous galactic ecosystem and thereby advance our understanding of galaxy growth and evolution, as well as their role during cosmic reionization.

Keywords: galaxies: evolution; galaxies: formation; galaxies: halos; galaxies: ISM; reionization; integral field spectrograph;

1 Introduction

Probing the spatial configuration of H I in and around galaxies provides key insights into gas flows, which are essential for understanding galaxy growth and evolution. Moreover, since the geometry of neutral gas regulates the escape of ionizing photons, it determines how ionizing radiation (Lyman continuum, LyC) propagates through the interstellar medium (ISM) and circumgalactic medium (CGM) before reaching our telescopes. This is particularly important for assessing how ionizing photons escape from galaxies into the intergalactic medium (IGM), thereby constraining cosmic reionization – the crucial epoch in the history of the universe at $z > 5$ when the predominantly neutral IGM was ionized by the first luminous sources (see, e.g., Robertson 2022).

Lyman-alpha (Lyα) is now widely used to trace and characterize the H I distribution in star-forming galaxies, notably through integral field spectroscopy (IFS; Wisotzki et al. e.g., 2016; Leclercq et al. e.g., 2017; Claeyssens et al. e.g., 2022 with VLT/MUSE). The Mg II $\lambda\lambda 2796, 2803$ Å doublet, with an ionization potential of 15 eV, also traces neutral gas and has recently been used with IFS such as MUSE to map H I in and around galaxies (Zabl et al. 2021; Leclercq et al. 2022).

Connecting the spatial H I distribution – that is the scattering medium through which LyC photons propagate – to the escape of ionizing photons is, however, challenging. It requires both a characterization of the H I geometry and a measurement of the ionizing flux, which is only feasible at low redshift, where the IGM is transparent enough to allow direct LyC detection. This effort is currently being carried out with the Low-redshift Lyman Continuum Survey (LzLCS), a 134-orbit HST program targeting 66 star-forming galaxies at $z \sim 0.3$ (Flury et al. 2022), reporting 35 new LyC detections at $> 2\sigma$ significance. The LzLCS survey thus provides the first statistical sample of both LyC emitters and non-emitters, enabling robust investigations of the relationships between galaxy properties and LyC escape.

2 Connecting LyC escape to HI distribution in low redshift star-forming galaxies

We summarize here the results of three studies that aim to link the LyC escape of local galaxies with the H I distribution, using IFS (Keck/KCWI and HET/LRS2; Sect. 2.1) and HST (COS, ACS/SBC, and WFC3/UVIS; Sect. 2.2) follow-up observations of the LzLCS sample.

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2.1 *Using Mg II as H I tracer*

Leclercq et al. (2024) present the first statistical study to link the neutral and ionized gas distributions to the LyC escape fraction ($f_{\rm esc}^{\rm LyC}$) in a sample of 22 confirmed LyC leakers and non-leakers at $z \approx 0.35$, observed with the Keck Cosmic Web Imager (Keck/KCWI) and the Low Resolution Spectrograph 2 (HET/LRS2). Our integral-field spectroscopic data enable the detection of neutral and low-ionization gas, traced by Mg II, and ionized gas, traced by [O II], extending beyond the stellar continuum for seven and ten objects, respectively. Most galaxies with extended emission are weak or non LyC leakers ($f_{\rm esc}^{\rm LyC} < 4\%$), but we find a large diversity of neutral and low-ionization gas configurations around these weakly LyC-emitting systems. Conversely, the strongest leakers ($f_{\rm esc}^{\rm LyC} > 4\%$) appear uniformly compact in both Mg II and [O II]. The results of our stacking experiment are shown in Fig. 1.

These observations suggest that, on average, strong and weak LyC emitters exhibit different nebular (neutral and ionized) configurations, with strong LyC emitters having compact neutral gas halos. We therefore propose nebular spatial compactness as a new indirect indicator of LyC escape in high-redshift galaxies.

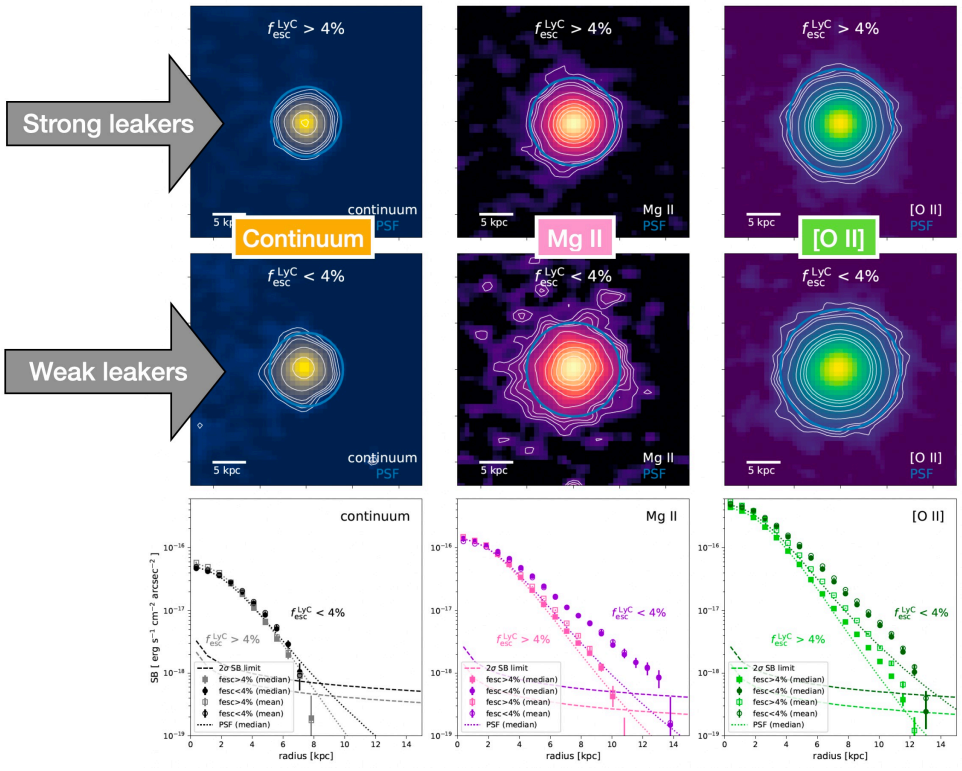

Fig. 1. Composite images of strong ($f_{\rm esc}^{\rm LyC} > 4\%$, top row) and weak and non ($f_{\rm esc}^{\rm LyC} < 4\%$, middle row) LyC leakers observed with KCWI. The UV continuum, Mg II and [O II] mean stacks are shown from left to right, respectively. The bottom row compares the continuum (left), Mg II (middle) and [O II] (right) radial SB profiles of the two subsets composites images. – Adapted from Fig. 7 of Leclercq et al. (2024).

2.2 *Using Lyα as H I tracer*

Saldana-Lopez et al. (2025) aim to establish the link between the properties of extended Lyα emission and the physics of LyC escape, using data from the Lyman-alpha and Continuum Origins Survey (LaCOS), an HST imaging campaign targeting 42 LzLCS galaxies. Examples of the Lyα distribution for two galaxies (a weak leaker, J1159, and a strong leaker, J1305) are shown in the first panels of Fig. 2. When comparing the Lyα spatial extent to $f_{\rm esc}^{\rm LyC}$ (second panel), we find that LyC emitters display more compact Lyα morphologies than non-LCEs. This result is consistent with the Mg II study (Sect. 2.1; Leclercq et al. 2024), although the galaxy samples differ because of observability constraints (no LzLCS galaxy has both Lyα and Mg II imaging).

For 16 LzLCS galaxies, we have both spatial and spectral Lyα observations. Their Lyα spectra were

obtained at high resolution with HST/COS (PI Leclercq). The corresponding spectra for the two galaxies shown as examples in Fig. 2 are displayed in the third column. This COS program allowed us to confirm, on a statistical and complete sample of LyC emitters, the empirical trend between $f_{\rm esc}^{\rm LyC}$ and the Lyα velocity peak separation (fourth panel of Fig. 2; Leclercq et al., in prep.).

When jointly analyzing the spatial and spectral properties of the 16 galaxies with both imaging and spectroscopy, we find that Lyα halo sizes correlate with the Lyα velocity peak separation: stronger LyC leakers exhibit more compact Lyα configurations and smaller peak separations compared to weaker or non-leakers. We caution, however, that this is still a preliminary result.

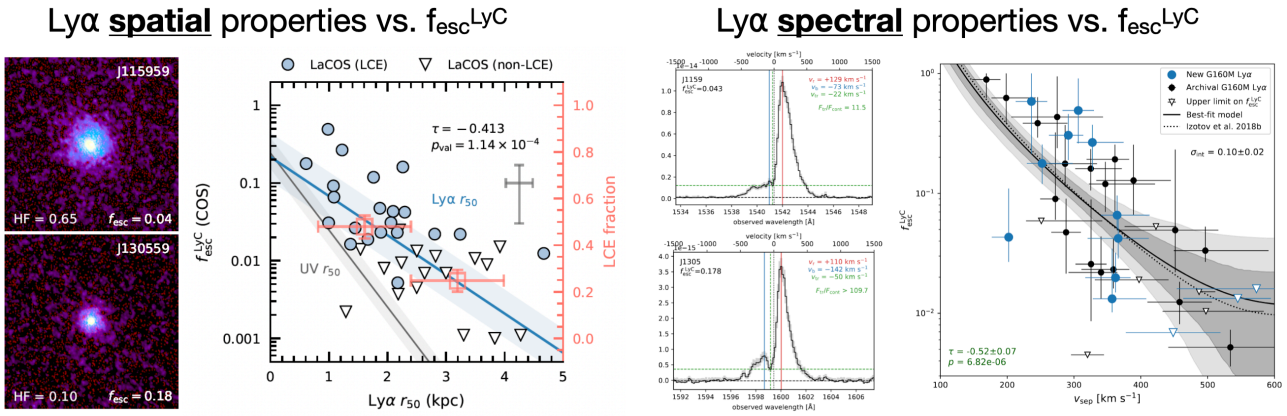

Fig. 2. First column (adapted from Fig. 2 of Saldana-Lopez et al. 2025): Examples of Lyα distribution for two LzLCS galaxies (one weak leaker J1159, and one strong leaker J1305). Second column (Fig. 4 of Saldana-Lopez et al. 2025): The relation between the ionizing escape fraction and the extent of the Lyα emission, as measured by the half-light radius. Third column (adapted from Leclercq et al. in prep.): High resolution Lyα spectra of two LzLCS galaxies. Fourth column (Leclercq et al. in prep.): relation between $f_{\rm esc}^{\rm LyC}$ and the Lyα peak velocity separation for the LzLCS sample.

3 HI mapping of high redshift star forming galaxies

The studies presented in the previous section demonstrate that it is now possible to link LyC escape with both the spectral and spatial properties of Lyα, and more generally with the H I configuration, in a statistical sample of local galaxies. Ideally, we would like to perform the same type of analysis at higher redshift, i.e., closer to the epoch of cosmic reionization.

At redshifts $z \sim$ 3-6, VLT/MUSE has revolutionized H I mapping around star-forming galaxies by enabling the detection of the emitting circumgalactic medium through Lyα (see examples in Fig. 3). Wisotzki et al. (2016) and Leclercq et al. (2017) have shown that Lyα halos are ubiquitous around galaxies at $z > 3$: they extend over tens of pkpc (10-30), and are on average ten times more extended than the UV continuum.

When comparing the low- and high-redshift Lyα halo samples from the LzLCS and MUSE data, respectively, we do not find evidence for an evolution in the extent of Lyα emission with redshift. This result suggests that the H I distribution properties could, in principle, be used to estimate LyC escape at high redshift. To confirm this and to test more robustly the relation between $f_{\rm esc}^{\rm LyC}$ and the H I spatial extent, the next step is to conduct large, blind IFS surveys to identify additional LyC leakers at high redshift.

4 The upcoming statistical revolution with future IFS

The upcoming ground-based IFS VLT/BlueMUSE will make it possible to increase IFS samples without preselection. Combined with MUSE, BlueMUSE will allow us to map H I in low-mass star-forming galaxies over 11 billion years of cosmic history, using tracers such as Mg II and Lyα. Most importantly, both tracers will be observable with MUSE+BlueMUSE at cosmic noon ($z \sim 2$), enabling us to better understand, decode, and calibrate these probes of neutral gas. BlueMUSE will also make it possible to identify new LyC emitters at $z \sim$ 3-4, thereby strengthening the link between the H I distribution and LyC escape for large, unbiased samples of high-redshift galaxies.

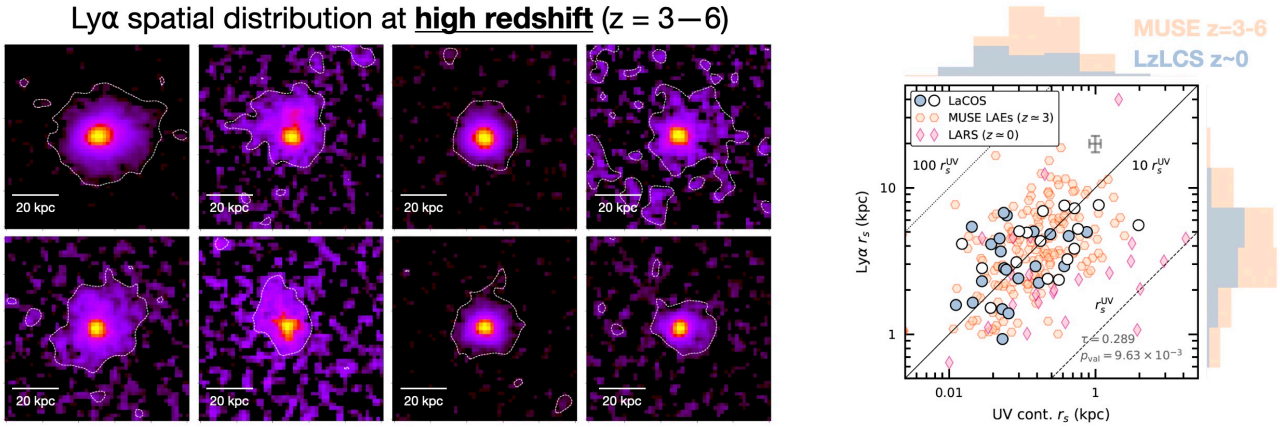

Fig. 3. Left (Leclercq et al. 2017): Examples of extended Lyα emission around high redshift star forming galaxies. Right (Fig. 8 of Saldana-Lopez et al. 2025): Lyα halo versus UV continuum scale lengths for low and high redshift samples.

Looking further ahead, survey facilities such as the Wide Field Spectroscopic Telescope (WST; Mainieri et al. 2024) will provide the statistical power to map millions of H I distributions across diverse galaxy populations, while uncovering many more LyC emitters at all redshifts.

5 Conclusion

We have summarized how current and upcoming IFS instruments have transformed, and will continue to transform, our understanding of galaxy growth, evolution, and their role during cosmic reionization as sinks for ionizing photons.

From low-redshift LyC studies, IFS H I maps of LyC emitters and non-emitters reveal that the distribution of neutral gas strongly impacts LyC leakage. We propose nebular compactness as a new indirect probe of LyC escape, while emphasizing that larger samples are required to confirm this result. We also showed that it is now possible to link LyC escape with both the spatial and spectral properties of Lyα in tens of galaxies.

At higher redshift ($z \sim$ 3-4), IFS Lyα-based H I maps are consistent with the low-redshift distributions, suggesting that H I morphology could serve as a promising indirect diagnostic of LyC escape during the epoch of cosmic reionization. However, establishing a direct connection between H I distribution and LyC escape remains challenging, given the small number of LyC emitters currently identified at $z \sim 3$. This underlines the need to drastically increase the statistics and to work with representative samples.

Finally, we highlighted that the future is bright: upcoming ground-based IFS facilities such as VLT/BlueMUSE and WST will (i) uncover many more high-redshift LyC emitters, and (ii) enable blind, homogeneous H I mapping across diverse galaxy populations over more than 11 billion years of cosmic history.

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