Title

Characterizing a highly ionized region during reionization with the highest-redshift transmission spike in the Lyman-beta forest

Abstract

During cosmic reionization, ionized regions grew and gradually overlapped in the intergalactic medium. The redshift and spatial distributions of ionized regions can thus directly reveal the timing and the topology of reionization, strongly informing the properties of the first luminous sources. Highly ionized regions in the IGM can be traced by transmission spikes imprinted in Lyman series forests of quasar spectra. Transmission spikes at $z > 6$ are new probes of the IGM evolution during reionization. However, to date, identification of transmission spikes at $z > 6$ is challenging with ground-based observations. We propose for HST WFC3/UVIS imaging of a $z = 6.7$ transmission spike identified in the Lyman-beta forest of a quasar ULAS J1120+0641 at $z = 7.1$. This $z = 6.7$ spike is the highest-redshift transmission spike with reliable detection. We will observe ULAS J1120+0641 and associated high-redshift galaxies at the Lyman-alpha wavelength of the $z = 6.7$ spike, using the FQ937N filter. WFC3/UVIS is the only narrow-band imaging instrument at the proposed wavelength range without sky contamination. We will: (1) verify the nature of the $z = 6.7$ spike and (2) measure its Lyman-alpha effective optical depth. This program will yield critical evidence to constrain the timeline of reionization and theoretical reionization models. This program will additionally study the spatial correlation between the $z = 6.7$ spike and high-redshift galaxies through Lyman-alpha emission, allowing a direct measurement of the ionizing photon escape fraction and investigating the contribution of galaxies to reionize the IGM.

■ Scientific Justification

Observations of ionized regions at $6 < z < 7$ can constrain the IGM evolution during reionization

During cosmic reionization, ionized regions gradually grew and overlapped in the intergalactic medium (IGM). The timeline and topology of reionization strongly informs the properties of first generation of galaxies and active galactic nuclei (Becker et al., 2015). The timeline of reionization can be constrained by observing the distribution of ionized regions in the IGM. Observations indicate that the IGM is highly ionized at $z < 6$ (Fan et al., 2006a; McGreer et al., 2015; Yang et al., 2020a), and at $z > 7$ the IGM is significantly neutral (e. g., Greig et al., 2017), suggesting a rapid IGM evolution at $6 < z < 7$ during reionization (see Figure 1). Unfortunately, there are few existing observational constraints on the IGM neutral fraction at $6 < z < 7$ with current measurements, resulting in various reionization theoretical models which can predict a IGM neutral fraction differing by 36% at $z = 7$ (Finkelstein et al., 2019; Naidu et al., 2020). New methods are thus required to constrain the IGM evolution at $6 < z < 7$ during reionization.

Transmission spikes imprinted in Lyman series forests of quasar spectra are powerful tracers of highly ionized regions in the IGM. Radiative transfer simulations show that the redshift distribution of transmission spikes is sensitive to the exact timing of reionization (Chardin et al., 2018). Yang et al. (2020a) utilize a sample of transmission spikes identified in 32 quasars to constrain the IGM effective Lyman α (Lyα) optical depth as upper limits at $z \sim 6$, illustrating the potential of transmission spikes as new probes of the IGM evolution. Observations of transmission spikes at higher redshift are thus a promising method to probe highly ionized regions at $z > 6$.

However, identifying transmission spikes at $z > 6$ is challenging, especially with ground-based observations. As such, few transmissions spikes have been studied between the critical redshifts of $6 < z < 7$. Deep observations of highly ionized regions at $6 < z < 7$, traced by transmission spikes in Lyman series forests, are urgently required to constrain the IGM evolution, and to further distinguish different reionization models.

We propose for deep HST WFC3/UVIS imaging of a $z = 6.7$ transmission spike identified in the Lyman β (Lyβ) forest of a quasar ULAS J1120+0641 at $z = 7.1$. This transmission spike is the highest-redshift transmission spike with a reliable detection. WFC3/UVIS is the only narrow-band imaging instrument that can make this measurement at the proposed wavelength range without sky contamination. This program will allow us to: (1) study the nature of the highest-redshift transmission spike, and (2) measure its Lyα optical depth and constrain the IGM evolution at $z = 6.7$, providing a new pathway for future similar studies with transmission spikes at $z > 6.5$. This will advance the key science theme of HST to reveal the structure of the universe, and will provide the necessary data to constrain theoretical models for the timeline of reionization. This program will additionally study the spatial correlation between the highest-redshift transmission spike and high-redshift galaxies through Lyα emission, allowing a direct measurement of the ionizing photon escape fraction and the contribution of galaxies to reionize the IGM.

Identification of transmission spikes at $z > 6$ is challenging with the ground-based observations

The transmission features in Lyman series forests are expected to be weak at $z > 6$, because the IGM neutral fraction increases rapidly at $z > 6$ (see Figure 1) and Lyα emission can reach complete absorption at $f_{\rm HI} \gtrsim 10^{-3}$ (Fan et al., 2006b). Furthermore, the Earth's atmosphere contributes to strong contamination in the observed spectrum of Lyman series forests at $z > 6$, making it difficult to identify transmission spikes. However, the rapid IGM evolution at $6 < z < 7$ is not efficiently constrained by other known methods, observations of transmission spikes at $6 < z < 7$ provide a new approach to study the IGM evolution.

Yang et al. (2020a) utilize a sample of 32 quasars at $6.3 < z < 7.0$ to identify transmission spikes up to $z = 6.3$, and they find that there is already a rapid decrease in the number of transmission spikes at $6.0 < z < 6.3$. To date, there are only few transmission spikes identified at $z > 6.5$ (Mortlock et al., 2011; Barnett et al., 2017), where these detections may be false owing to sky OH emission lines. Confirming the nature of rare transmission spikes at $z > 6.5$ reveals the time at which the first highly ionized regions appear in the IGM. These constraints will be placed at epochs much earlier than the nominal end of reionization at $z \sim 5.3$ (Bosman et al., 2021). As such, this proposed study will yield critical information to reconstruct the reionization timeline. *Identification of transmission spikes requires deep observations from space because of strong sky contamination and their weak signal strength.*

The highest-redshift transmission spike identified in the Lyβ forest

We identify a transmission spike at $z = 6.7$ in the Lyβ forest of a quasar ULAS J1120+0641 at $z = 7.1$ from an existing VLT/X-Shooter spectrum (see the upper panel of Figure 2). It is among the highest-redshift transmission spikes ever identified. This transmission spike likely traces a highly ionized patch at $z = 6.7$, giving us the *first* opportunity to confirm the timing of one of the first highly ionized regions appearing in the IGM. The analysis of this transmission spike will provide a new pathway for similar studies of transmission spikes at $z > 6.5$ to constrain the IGM evolution and the timeline of reionization.

If the $z = 6.7$ Lyβ transmission spike is a real transmission feature associated with a highly ionized region in the IGM, a transmission spike is expected to present in the Lyα forest at $z = 6.7$. Figure 2 shows the VLT/X-Shooter spectrum of this $z = 6.7$ Lyβ transmission spike in the Lyβ forest (the upper panel) and the spectrum of the same redshift window in the Lyα forest (the lower panel), which is highly contaminated by a sky OH emission line. Deep imaging from HST is needed to target ULAS J1120+0641 to verify the nature of the $z = 6.7$ transmission spike at its Lyα wavelength.

A $z = 6.7$ highly ionized region can be characterized with the FQ937N imaging

The Lyα wavelength of the $z = 6.7$ Lyβ transmission spike falls into the FQ937N filter in WFC3/UVIS, allowing us to directly search any Lyα flux associated with the $z = 6.7$ transmission spike. <u>We request 22-orbit WFC3/UVIS imaging of the $z = 6.7$ transmission spike with the FQ937N filter.</u> With the proposed program, we will be able to:

<u>**(1)** Study the nature of the $z = 6.7$ transmission spike.</u> From the existing VLT/X-Shooter spectrum (Figure 2), the observed flux of the $z = 6.7$ Lyβ transmission spike is 1.8×10^{-18} $\rm erg\,s^{-1}\,cm^{-2}$, and the observed total optical depth is 4.3, including a pure Lyβ

optical depth at $z = 6.7$ and a foreground Lyα optical depth of ~ 3.3 at $z = 5.5$ (Yang et al., 2020a). Assuming that the $z = 6.7$ Lyβ transmission spike is associated with a highly ionized region at $z = 6.7$ in the IGM, the expected line flux of the corresponding $z = 6.7$ Lyα transmission spike is 5.7×10^{-18} $\mathrm{erg\,s^{-1}\,cm^{-2}}$, after correcting the foreground Lyα forest absorption and applying a conversion factor of 2.25 between the Lyα optical depth and the Lyβ optical depth at the same redshift (Fan et al., 2006a). The proposed depth of this program will be able to achieve a 3σ detection for the expected Lyα flux of 5.7×10^{-18} $\mathrm{erg\,s^{-1}\,cm^{-2}}$, thus to reveal the time at which one of the first highly ionized regions appear in the IGM, constraining the timeline of reionization.

And **(2)** measure the Lyα optical depth at $z = 6.7$ and constrain the IGM evolution at $z = 6.7$. The proposed program will also measure the effective Lyα optical depth at $z = 6.7$ over the entire FQ937N filter, and Figure 3 shows the Lyα effective optical depth measurements in Yang et al. (2020a) and the expected effective Lyα optical depth of 5.2 measured from this program, assuming only the $z = 6.7$ transmission spike contributes to the flux inside the FQ937N filter and the flux density is zero elsewhere inside the FQ937N filter. An effective Lyα optical depth of 5.2 is much lower than the extrapolated Lyα effective optical depth relation from previous study (Yang et al., 2020a). This will yield critical evidence of the IGM evolution at $z = 6.7$, placing a robust constraint on the inhomogeneity of reionization models such that these reionization models need to illustrate the existence of such a transparent patch at $z = 6.7$.

When and how did the IGM start to become highly ionized?

Investigating the nature of the $z = 6.7$ transmission spike gives us the first opportunity to verify whether highly ionized regions in the IGM can appear as early as 300 Myr before the nominal end of reionization at $z = 5.3$ (Bosman et al., 2021), constraining the timeline of reionization and the inhomogeneity of reionization models. Furthermore, this program will provide a new pathway for future studies on $z > 6.5$ transmission spikes. These rare transmission spikes at $z > 6.5$ will be critical to understand the IGM evolution at $6 < z < 7$, especially when comparing the distribution of confirmed transmission spikes with prediction from radiative transfer simulations (e. g., Chardin et al., 2018; Garaldi et al., 2019). This will advance the key science goal of HST to reveal the structure of the universe and to understand the intergalactic space during reionization.

This program will additionally characterize the high-redshift galaxies which are responsible for ionizing a $z = 6.7$ highly ionized region, traced by the transmission spike, using the FQ937N imaging. This program will be able to search Lyα emission with 3σ down to a luminosity of $\sim 3 \times 10^{42}$ $\mathrm{erg\,s^{-1}}$ at $z = 6.7$. An existing HST broad-band imaging program GO-13039 and three approved JWST GTO programs (1205, 1222, 1243) will allow the selection of high-redshift galaxies in the same field of this program. These programs provide a complementary dataset to study the spatial correlation between the $z = 6.7$ transmission spike and high-redshift galaxies through Lyα emission, enabling a direct measurement of the ionizing photon escape fraction (Kakiichi et al., 2018). This will investigate the contribution of high-redshift galaxies to the ionizing photon budget during reionization.

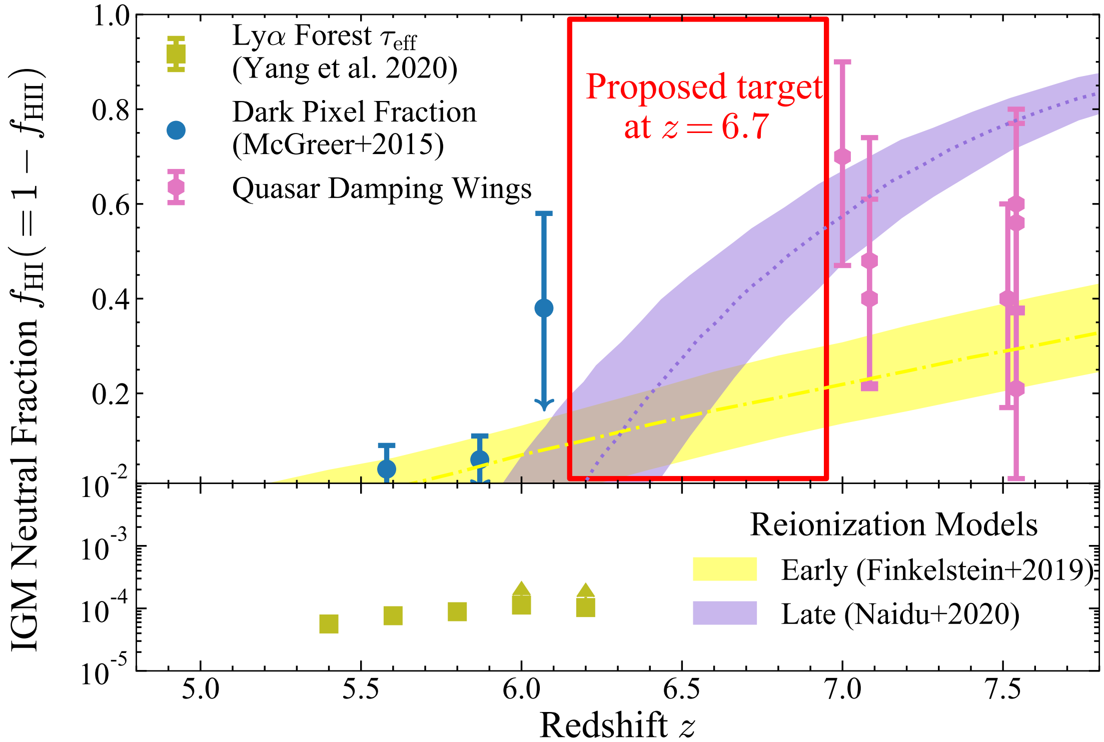

Figure 1: Recent measurements on the IGM neutral fraction ($f_{\rm HI} = 1 - f_{\rm HII}$) from high-redshift quasars. At $z < 6$, measurements from Gunn-Peterson optical depth in Lyα forests (yellow green squares, Yang et al., 2020a) and "dark" fraction of Lyα and Lyβ forests (blue circles, McGreer et al., 2015) indicate the IGM is highly ionized. At $z > 7$, the IGM fraction derived from damping wing absorption feature embedded in quasar spectra is significantly neutral (pink hexagons, Greig et al., 2017; Bañados et al., 2018; Davies et al., 2018; Greig et al., 2019; Wang et al., 2020; Yang et al., 2020b). There are few available constraints on $f_{\rm HI}$ at $6 < z < 7$ (shown by the red rectangle), leading to different reionization models. The early reionization model led by faint galaxies in yellow (Finkelstein et al., 2019), and the late reionization model led by bright galaxies in purple (Naidu et al., 2020) can predict an IGM neutral fraction differing by 36% at $z = 7$. At $6 < z < 7$, it is likely that the IGM undergoes a rapid evolution such that it transits from a significantly neutral IGM at $z > 7$ into a highly ionized IGM at $z < 6$. We propose to observe a transmission spike identified in the Lyβ forest at $z = 6.7$, possibly tracing a highly ionized region much earlier before the end of reionization, to understand the IGM rapid evolution during reionization, and to further distinguish different reionization models.

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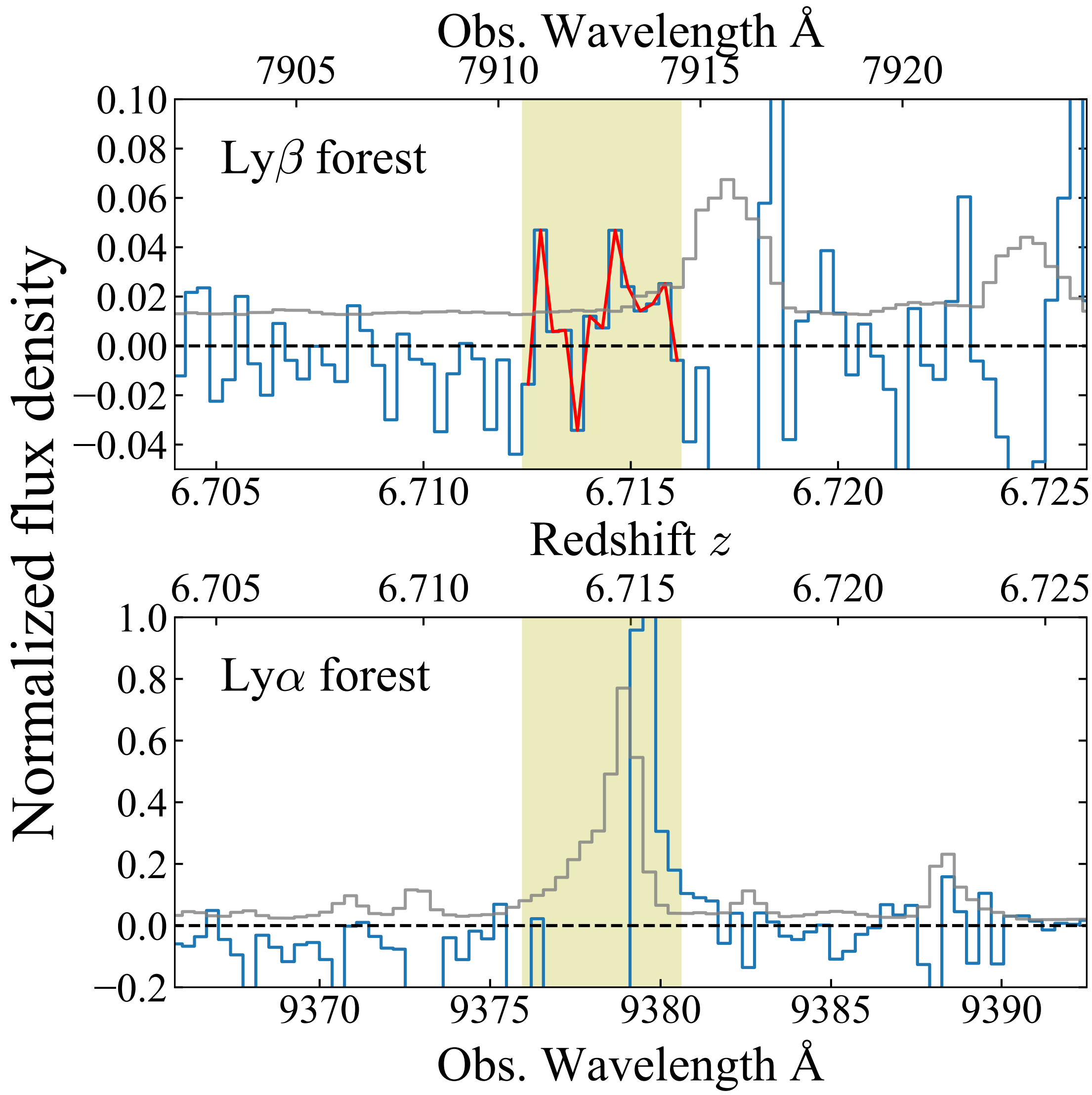

Figure 2: *The upper panel* – The VLT/X-Shooter spectrum (blue) of the $z = 6.7$ transmission spike (red) in the Lyβ forest of ULAS J1120+0641; *The lower panel* – The VLT/X-Shooter spectrum in the corresponding redshift window of the $z = 6.7$ transmission spike (yellow green shaded region) in the Lyα forest. The y-axis shows the transmitted flux (i.e., the observed flux density normalized by the continuum flux density), and the spectral uncertainty is in grey in both panels. The Lyα window of the $z = 6.7$ Lyβ transmission spike is highly contaminated by a sky OH emission line. We propose for deep HST WFC3/UVIS imaging to confirm the nature of the $z = 6.7$ transmission spike with the FQ937N filter, and to search Lyα emission from galaxies in the same field that are likely responsible for ionizing the region traced by the transmission spike.

Bosman, S. E. I., Davies, F. B., Becker, G. D., et al. 2021, arXiv:2108.03699

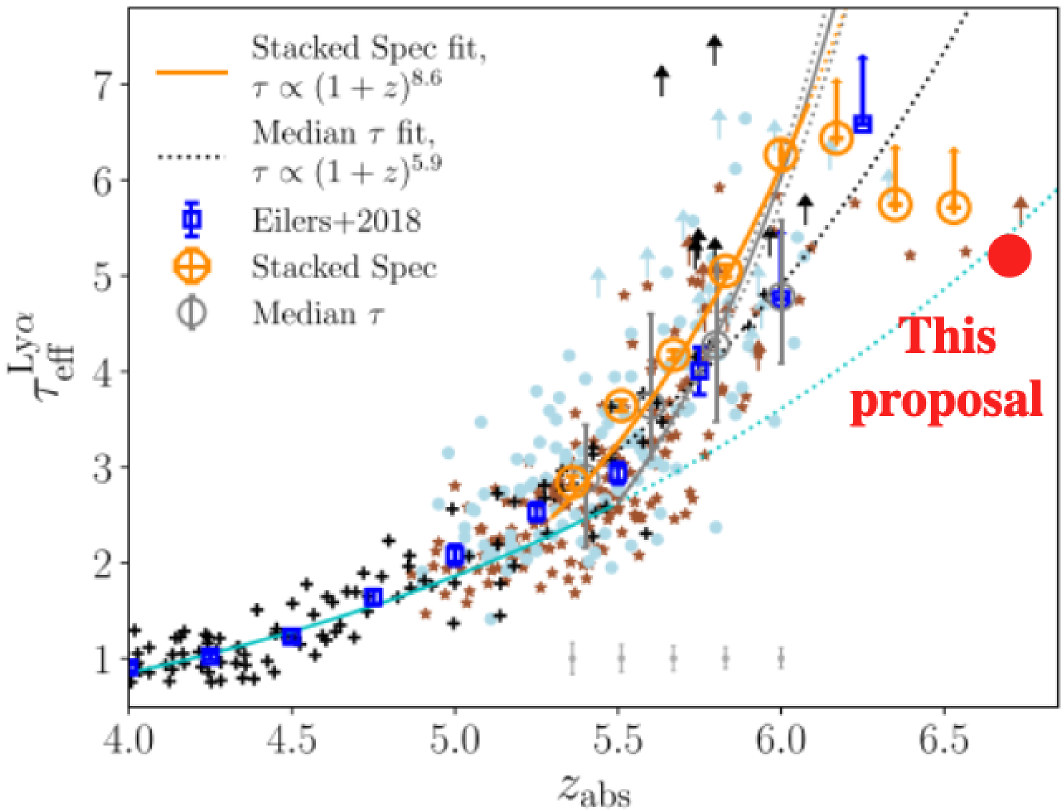

Figure 3: Measurements of Lyα effective optical depth (points) and fitted Lyα effective optical depth redshift evolutions (lines) from Yang et al. (2020a). We will verify the nature of the $z = 6.7$ transmission spike and measure its optical depth in the Lyα forest with the proposed WFC3/UVIS imaging. The expected Lyα optical depth obtained by this program is denoted by the red circle, assuming only the $z = 6.7$ transmission spike contributes to the flux inside the FQ937N filter and the flux density is zero elsewhere. The expected Lyα effective optical depth of the $z = 6.7$ transmission spike is much lower than the predicted value from Yang et al. (2020a) (the orange line). With the proposed program, we will be able to verify the nature of the transmission spike and to confirm the timing of one of the first highly ionized patches appearing in the IGM.

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