CHARTING THE TIMELINE OF REIONIZATION WITH A Lyα SPECTROSCOPIC STUDY

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Abstract. Reionization was the last major phase transition of the intergalactic medium (IGM), and scrutinizing the detailed evolution of the IGM is a key frontier in observational cosmology. Thanks to the resonant nature of Lyα scattering with neutral hydrogen, Lyα emission can be utilized as a presently accessible probe of reionization. I aim to put observational constraints on the time evolution of the neutral hydrogen fraction in the intergalactic medium (IGM) by providing an unbiased measure of the Lyα equivalent-width (EW) distribution during the epoch of reionization using a comprehensive ground-based Lyα spectroscopic dataset. With the measure of the Lyα EW distribution at different redshifts, combined with the theoretical predictions of the ionizing conditions of the IGM, I will unveil the detailed timeline of reionization. Furthermore, the constrained ionizing status of the IGM provides key information on the required ionizing photon budget from galaxies, which is estimated from the cosmic star formation rate density by assuming an escape fraction of ionizing photons in the galaxies. With the future galaxy survey data from the *James Webb Space Telescope (JWST)*, the primary result of my proposed study will reveal the interactive evolution of the IGM and galaxies in the early universe.

1. Introduction: Reionization and Galaxies in the Early Universe

Galaxies in the early universe are inherently coupled with the process of reionization, when the intergalactic medium (IGM) became transparent. The prevailing theory is that galaxies in the early universe were the primary sources of supplying ionizing photons (e.g., Finkelstein et al. 2012a, 2015; Robertson et al. 2013, 2015), with faint galaxies below the detection limit of current observations contributing a significant portion of the ionizing photons (Finkelstein 2016; Livermore et al. 2017). However, constraining the cosmic star formation rate density during the epoch of reionization, which can be converted to an ionizing photon budget, is still highly controversial due to the current observational limit as well as a less constrained ionizing photon escape fraction in the galaxies (e.g., Bouwens et al. 2015; Finkelstein et al. 2015).

Understanding the duration of reionization by tracing the neutral hydrogen fraction in the IGM provides a key constraint on how much ionizing photons from the distant galaxies were required to explain the timeline of reionization. High-energy Ionizing photon production from galaxies is tied to star formation in the galaxies, thus charting the detailed time line of reionization provides a strong constraint on star formation and galaxy evolution in the early universe.

I will pursue my proposed research on tracing the time evolution of the neutral hydrogen fraction in the IGM during the epoch of reionization by using Lyα emission as an immediate accessible probe of reioinzation. **My proposed study aligns with the science implementation of NASA's Cosmic Origins Program (see *"This program seeks to understand how the universe has evolved since***

the Big Bang ...") **as well as NASA's strategic objective of the Astrophysics Division (see *"Explore the origin and evolution of the galaxies ..."*) in Chapter 4.4 of the NASA SMD 2014 Science Plan**. Furthermore, the *James Webb Space Telescope (JWST)*, the NASA's premier observatory, will be performing a more extensive Lyα survey with its near-infrared (NIR) spectrographs into the reionization epoch, allowing me to extend my current research into the even more distant and earlier universe with higher statistical confidence.

2. Background: Lyα emission as a probe of reionization

Reionization is the last major phase transition of the IGM, and scrutinizing the detailed evolution of the IGM is a key frontier in observational cosmology, which also provides key information for studying the dominant source of the ionizing photons, galaxies in the early universe. Wilkinson Microwave Anisotropy Probe (WMAP) and Planck observations constrain the midpoint of reionization to be $z \sim 8-9$ (Larson et al. 2011, Planck Collaboration et al. 2016), and quasar observations at high redshift suggest that it ended at $z \sim 6$ (e.g., McGreer et al. 2015). Complementary measurements of the end of reionization based on the Lyα emitter (LAE) luminosity function at $z \sim 6$ agree with those from the CMB and quasar observations (e.g., Malhotra & Rhoads 2004; Ota et al. 2017; Ouchi et al. 2018; Zheng et al. 2017). However, robust studies of the IGM during reionization are still limited, as it is, for example, difficult to map the neutral fraction of the IGM during reionization with quasar spectroscopy due to the lack of a large population of quasars at $z > 7$. Although 21cm intensity mapping with square kilometer array will directly probe the neutral hydrogen in the IGM, it is yet years away from operation.

A presently accessible method for studying the IGM in the reionization era is to observe Lyα emission from continuum-selected galaxies with follow-up spectroscopy. The fraction of continuum-selected Lyman break galaxies (LBGs) with strong Lyα detected in emission spectroscopically (known as the "Lyα fraction") was found to increase from $z = 3$ to $z = 6$ (Stark et al. 2010). It was thus to be expected that the Lyα fraction at $z \sim 7$ would be at least as high as at $z = 6$. However, initial studies have found an apparent deficit of strong Lyα emission at $z > 6.5$ (e.g., Fontana et al. 2010; Pentericci et al. 2011, 2018). The dust content of galaxies has been found to decrease with increasing redshift (Finkelstein et al. 2012, Bouwens et al. 2014), thus the increased fraction of strong Lyα emission from $z = 3 \rightarrow 6$ is likely due to decreasing dust attenuation in galaxies. Therefore, the perceived drop in Lyα emission at $z > 6$ is unlikely to be due to dust, and may imply that the neutral hydrogen fraction in the IGM increases significantly from $z \sim 6 \rightarrow 7$, although other galaxy evolutionary features and the uncertainty of the Lyman continuum escape fraction need to be taken into account (e.g., Dijkstra 2014; Kimm et al. 2017; Mason et al. 2018; Rosdahl et al. 2018).

Despite this tantalizing evidence, measuring the Lyα fraction depends on the sensitivity of the observed spectra and the completeness of the detected LAEs. For instance, selection criteria without longer wavelength continuum detection would lead to a bias toward faint galaxies with strong Lyα emission (see discussion in De Barros et al. 2017). Avoiding the selection bias toward faint galaxies with strong Lyα emission, De Barros et al. (2017) reported a Lyα fraction at $z \sim 6$ lower than the values previously reported in the literature from a large sample of LAEs. Also, from the analysis of 100 LAEs from the Multi-Unit Spectroscopic Explorer (MUSE)

Wide survey (Herenz et al. 2017), Caruana et al. (2018) showed that the choice of a rest-frame equivalent-width (EW) cut seems to be impactful on the measured Lyα fraction, finding no dependence of the Lyα fraction on redshift at $3 < z < 6$ with no EW threshold (commonly 25Å in the literature).

All things considered, while many previous studies have used the Lyα fraction as a measure of the evolution of Lyα emission, it is a somewhat less constraining measure, since it often does not fully account for the continuum luminosity of LAEs as well as it assumes that all non-detection objects among the observed galaxies are at that redshift, which is not necessarily to be true without spectroscopic confirmation. **To provide the unbiased tracer of neutral hydrogen in the IGM using Lyα emission, here I propose to use the Lyα EW distribution during the epoch of reionization as a probe of the IGM neutral hydrogen fraction by applying the newly-introduced methodology in my recent publication (Jung et al. 2018), which accounts for data incompleteness (e.g., observing conditions, galaxy UV continuum luminosity, and galaxy photometric redshift probability), to a comprehensive spectroscopic dataset of Lyα emission.**

3. Ground-based Spectroscopic Data for Lyα Emission during the Epoch of Reionization

To search for Lyα emission from galaxies in the reionization era, I have performed deep spectroscopic observations of candidate galaxies from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS). I use the galaxy sample from Finkelstein et al. (2015), which consists of ~ 1000 candidate $z > 6$ galaxies in the CANDELS GOODS-S and GOODS-N fields, as well as the Hubble Ultra Deep Field. A unique aspect of my program is that, compared to other studies which use

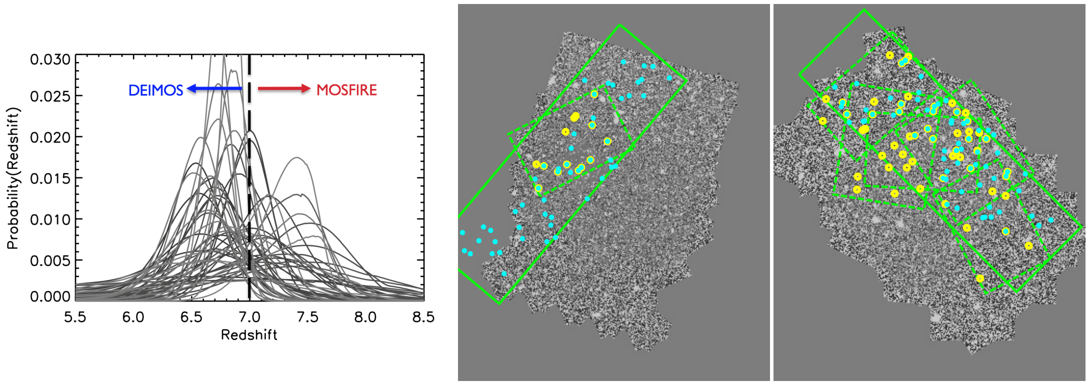

FIGURE 1. (Left) the redshift probability distribution functions of $z_{phot} \sim 7$ galaxies. Even though the maximum probabilities are arount at $z \approx 7$, those galaxies may be located at any redshift between $z = 6$ and $z = 8$. Either one of DEIMOS and MOSFIRE can cover the entire redshift range, thus it is critical to utilize both instruments. (Right) mask designs of spectroscopic observational survey in the GOODS-S (left) and GOODS-N (right) fields. Observed areas are marked by green rectangles; larger one is DEIMOS (5'x16.7'), and smaller dashed one is MOSFIRE (6'x4'). Cyan and yellow circles are observed galaxies with DIEMOS and MOSFIRE, respectively.

only optical or NIR spectrographs, I have data from both the DEIMOS (optical) and MOSFIRE (NIR) spectrographs on the Keck 10-meter telescopes. This is *required* for strong constraints on the observability of Lyα emission, as the broad range of the photometric redshift probability distributions of candidate galaxies results in a significant chance of the true redshift being anywhere in the range $6 < z < 8$ (see the left panel in Figure 1). **Therefore, spectroscopic follow-up with both DEIMOS and MOSFIRE is necessary for ensuring comprehensive wavelength coverage of Lyα emission at $z \sim 6-8$, and is thus crucial to probing into the rapid evolution of reionization.**

The entire observing program of this study is a total of 18 nights of spectroscopic integration for 183 galaxies at $z > 5$: for 118 galaxies with Keck/DEIMOS (PI: R. Livermore) and 84 galaxies with Keck/MOSFIRE (PI: S. Finkelstein) (the majority coming through the NASA/Keck allocation). Spectroscopic observation details are shown in Figure 1 (right).

In addition to all of the obtained observational data (green rectangles), I am in the VANDELS collaboration team (Co-PI's L. Pentericci and R. McLure; Co-I Finkelstein), which provides a deep VIMOS survey of the CANDELS CDFS and UDS fields, so that I will utilize the deep optical spectroscopic dataset of > 200 LAEs at $z \sim 3-5$ on GOODS-S from the VANDELS survey (Pentericci et al. 2018a). This is necessary for providing the reference measure of the Lyα EW distribution from the fully-ionized universe. Plus, Pentericci et al. (2018b) published the CANDELSz7 survey data, which provides the most extensive Lyα survey dataset (> 50 LAEs) at $z \sim 6-7$. In collaboration with Dr. L. Pentericci, I will utilize the CANDELSz7 dataset, combined with my DEIMOS dataset, to measure the Lyα EW distribution at $z \sim 6-7$. Lastly, my MOSFIRE dataset is the most comprehensive dataset for Lyα search at $z > 7$. ***In summary, my dataset, which is already in-hand at*** $4 \lesssim z \lesssim 8$***, represents the most complete spectroscopic survey ever for galaxies in/after the reionization epoch.***

4. Unbiased Measure of the Lyα Equivalent-width Distribution as a Probe of Reionization

While some previous studies have used the Lyα fraction as a measure of the evolution of Lyα emission, it is a somewhat less constraining measure since it often does not, at least in its base form, account for data incompleteness such as the galaxy continuum luminosity and the photometric redshift probability distribution. For this reason, I implement a more detailed analysis of my dataset, where I place constraints on the evolution of the Lyα EW distribution, using detailed simulations to include the effects of incompleteness. This distribution function has been well studied at $0.3 < z < 6$, and has been found to have the form of an exponential distribution, dN/dEW $\propto$ exp(-EW/W_0), with a characteristic EW e-folding scale (W_0) of $\sim$ 60Å over the epoch $0.3 < z < 3$ (e.g., Gronwall et al. 2007; Guaita et al. 2010, Ciardullo et al. 2012, Wold et al. 2014, 2017); and possibly higher at higher redshift (Ouchi et al. 2008, Hu et al. 2010, Kashikawa et al. 2011, Zheng et al. 2014, Hashimoto et al. 2017). Particularly, in the epoch of reionization, the neutral hydrogen atoms in the IGM are expected to diminish these EWs, lowering the e-folding scale (W_0) of the observed Lyα EW distribution (e.g., Bolton et al. 2013, Mason et al. 2018). This gives us our research question: at what confidence can new observations rule out the e-folding scale (W_0) of $\sim$ 60Å at $z > 6$?

My first study based on our 4 nights of DEIMOS observations (118 galaxies at $5 < z < 7$) has been published in Jung et al. (2018). I introduced my new scheme to constrain the Lyα EW distribution by considering the sources of incompleteness of my dataset, the photometric redshift probability and observational conditions (e.g., observational depth, wavelength coverage, and sky emission). I simulate the expected number of detections with the various shapes of Lyα EW distributions (Figure 2), and fit the constructed probability distribution of the expected number of detections to the actually observed detections to derive the probability distribution of e-folding scale (W_0) of the Lyα EW distribution. This brings the lease biased measure of the Lyα EW distribution yet. My first result of the measure of the e-folding scale (W_0) of the Lyα EW distribution at $z \sim 6.5$ with DEIMOS rejects the Lyα EW distribution with $W_0 > 36.4$Å (125.3Å) at 1σ (2σ) significance (Figure 3) which provides the additional evidence that the Lyα EW distribution declines at $z > 6$, suggesting an increasing fraction of neutral hydrogen in the IGM at that epoch. Due to the small number of detections from our DEIMOS observation, our current measure is less constraining, but the additional detections from our in-hand MOSFIRE data will be combined in my next publication, providing a robust measure of Lyα EW distribution at even higher redshift ($z \gtrsim 7$).

My new scheme for constraining the EW distribution is very promising as it utilizes all non-detections in the simulation step, and also it is very flexible and applicable to any spectroscopic dataset. Thus, I am already prepared for the further analysis on the additional datasets (our in-hand MOSFIRE data, the VANDELS survey, and the CANDELSz7). In the future during the NASA posdoctoral program, all available deep spectroscopic data will be combined and taken into account in my comprehensive measurement at the Lyα EW distribution. Furthermore, later at the *JWST*'s launch I will be able to extend this study easily and quickly toward even earlier universe.

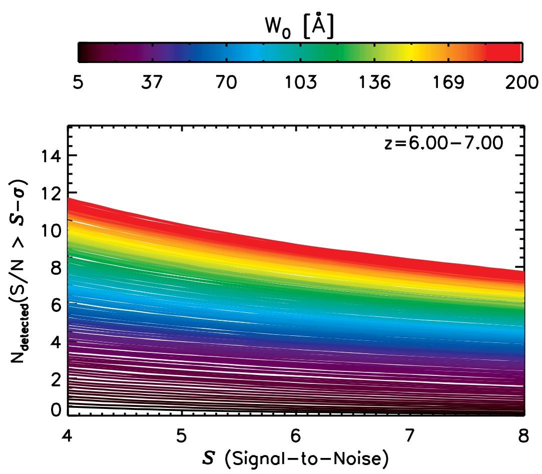

FIGURE 2. The expected number of detections as a function of S/N level ($\mathcal{S}$) with various EW distributions at $z \sim 6.5$. A larger choice of the e-folding scale (W_0) of the Lyα EW distribution (redder color) predicts a larger number of Lyα detections. (Figure 7 in Jung et al. 2018).

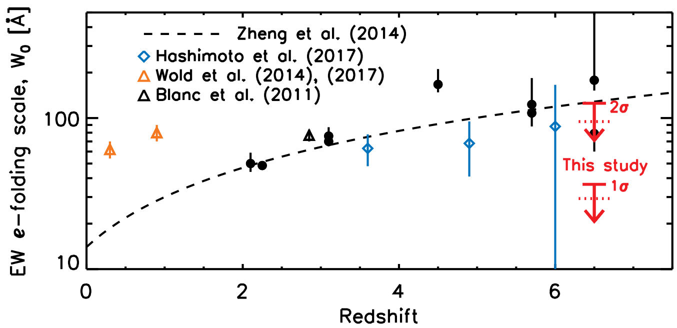

FIGURE 3. (Figure 8 of Jung et al. 2018) the redshift dependence of the Lyα EW e-folding scale (W_0). All data are shown without an IGM absorption correction. The black dashed line describes the best-fit redshift evolution from Zheng et al. (2014), compiling $0 < z < 7$ LAEs from literature: Guaita et al. (2010) at $z = 2.1$, Nilsson et al. (2009) at $z = 2.25$, Gronwall et al. (2007) at $z = 3.1$, Ciardullo et al. (2012) at $z = 3.1$, Ouchi et al. (2008) at $z = 3.1$ and 3.7, Zheng et al. (2014) at $z = 4.5$, Kashikawa et al. (2011) at $z = 5.7$ and 6.5, and Hu et al. (2010) at $z = 5.7$ and 6.5 shown as filled circles. Blue diamonds are the measurements of Hashimoto et al. (2017) using the LAEs ($M_{UV} < -18.5$) from the MUSE HUDF Survey (Bacon et al. 2017), which are consistent with Zheng et al. (2014) at that redshift range. At lower redshift, the W_0 measurements of Wold et al. (2017) at $z \sim 0.3$ and Wold et al. (2014) at $z \sim 0.9$ (orange triangles) suggest a relatively unevolving EW e-folding scale of Lyα across $z \sim 0.3-3.0$, considering the other measurements described above, including Blanc et al. (2011; black triangle) at $z \sim 2.85$. My measure of the Lyα EW distribution at $6.0 < z < 7.0$ rejects the Lyα EW distribution with $W_0 > 36.4$Å (125.3Å) at 1σ (2σ) significance (shown as red downward arrows). This provides additional evidence that the EW distribution of Lyα declines at $z > 6$, suggesting an increasing fraction of neutral hydrogen in the IGM at that epoch.

5. Linking the Measure of the Lyα EW Distribution to Reionization

To concretely constrain the neutral hydrogen fraction in the IGM, we still need a linking bridge to connect the Lyα EW distribution to the neutral hydrogen fraction, where we need input from theoretical works (e.g., Dijkstra et al. 2014; Mason et al. 2018), which predict the expected Lyα EW distribution depending on the IGM neutral fraction (see Figure 4). However, the prediction is dependent on many LAE systematics as well, such as the continuum luminosity, the ISM kinematics, and the stellar mass. The first step which can be done with my dataset is understanding the dependence of the Lyα EW distribution on the continuum luminosity, or UV magnitude ($M_{\rm UV}$). With the most comprehensive dataset (as described earlier), I have an access to the extensive data at $z \sim 3-5$ from the VANDELS survey and will be able to constrain the Lyα EW distribution as a function of $M_{\rm UV}$, for instance between bright ($M_{\rm UV} < -20.25$) and faint ($M_{\rm UV} > -20.25$) populations in the ionized universe at $z < 6$. This will give us the reference measure in the fully-ionized universe for a comparison to the measure of the Lyα EW distribution at $z \sim 6-8$ where the IGM contains neutral hydrogen.

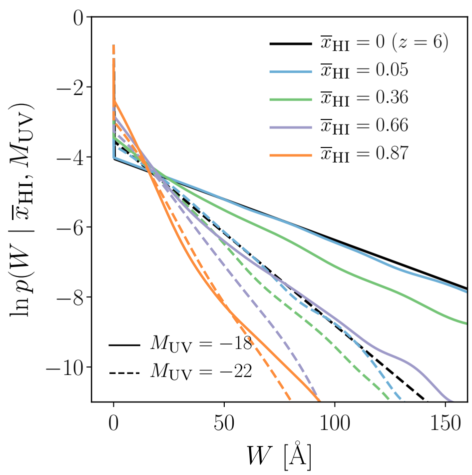

FIGURE 4. (Figure 7 in Mason et al. 2018) Simulated Lyα EW distribution for a range of neutral fractions (colors), for faint (solid line) and bright (dashed line) UV magnitudes.

6. Additional Key Outcome – Testing Photometric Redshifts with Spectroscopic Redshifts

As spectroscopic confirmation of galaxies at $z \gtrsim 6$ is observationally expensive, photometric redshift selection provides a powerful means to construct extensive high-redshift galaxy catalogs based on multi-wavelength imaging survey data (e.g., Stark et al. 2009; Papovich et al. 2011; Bouwens et al. 2015; Finkelstein et al. 2015). However, photometric redshift measurements alone cannot completely remove the possibility that high-redshift candidate galaxies can be low-redshift interlopers. Thus statistical studies using photometric redshifts could be biased if there are uncovered systematic effects in photometric redshifts. Interestingly, a recent spectroscopic confirmation of Lyα emission from the *HST* Faint Infrared Grism Survey (FIGS) (PI: S. Malhotra; Pirzkal et al. 2017) finds a Lyα emission line at z =7.452 which is different from the photometric redshift at the 2σ level (Larson et al. 2018). Furthermore, in my DEIMOS analysis, some of the Lyα emission lines that I have found would lie at the wings of the photometric redshift distributions, implying that perhaps the photometric redshift uncertainties are underestimated. Also, as essentially every quantity I derive (luminosity, stellar mass, star-formation rate) is dependent on the redshift accuracy, improving these estimates of the uncertainties is crucial. However, a comprehensive analysis on the accuracy of the photometric redshift measurements, specifically a calibration of these probability distribution functions, at $z \gtrsim 6$ is lacking. What is needed is a large number of spectroscopic redshifts, which is what my MOSFIRE dataset contains. For example, a preliminary result of Lyα search from my MOSFIRE data shows > 10 Lyα detections at $z \gtrsim 7$ (Figure 5). By performing this analysis with my dataset, which will be part of my proposed research, I will contribute to future studies with both *HST* and *JWST* by optimizing future selection techniques.

7. Program Timeline

I am already involved in the proposed project. My previous publication (Jung et al. 2018) introduces my new scheme for constraining the Lyα EW distribution with the result of our DEIMOS data, and the fully-reduced MOSFIRE dataset is ready to be incorporated in the next publication.

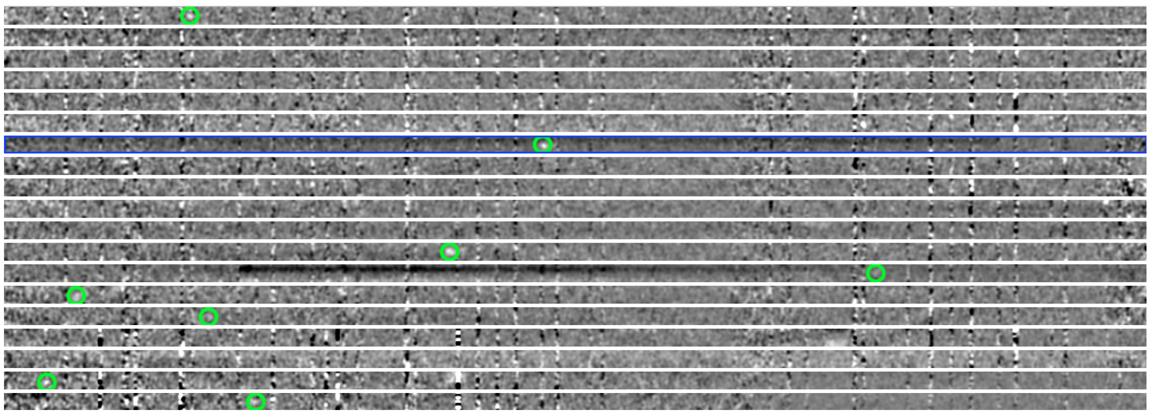

FIGURE 5. (Preliminary) Example MOSFIRE 2D spectra of 19 objects with $>$ 10hrs exposure. Visual inspection over the spectra suggests at least $>$ 5 Lyα detections at $z > 7$ (green circles).

To successfully accomplish the proposed research goals in two years, being supported by the NASA postdoctoral program, I will write two publications from the proposed project after finishing my dissertation, which provide a full Lyα dataset from the DEIMOS+MOSFIRE observations before the start of my NASA postdoctoral program. The first paper during my NASA postdoctoral program years will explain the dependence of the constrained Lyα EW distribution on galaxy continuum luminosity with the VANDELS survey data, which gives $>$ 200 LAEs at $z \sim 3$ – 5. From this paper, I will deliver a reference measure from the control sample from the ionized universe. In my second paper, combining the extensive Lyα dataset from CANDELSz7 survey ($>$ 50 LAEs at $z \sim 6 - 7$; Pentericci et al. 2018b) to my DEIMOS+MOSFIRE dataset, I will be able to constrain the Lyα EW distribution as a function of the continuum luminosity at $z \sim 6$, 7, and 8 during the epoch of reionization. Finally, in the paper, I will trace the time evolution of the neutral hydrogen fraction in the IGM in the reionization era with the model predictions which consider the other physical factors of LAEs such as the Lyman continuum escape fraction (e.g., Dijkstra et al. 2014, Mason et al. 2018). The detailed timeline is described below.

Year 0: Prior to the NASA postdoctoral program – The MOSFIRE data reduction has been completed, and I will report new Lyα detections at at $z > 7$, including a $z \sim 7.6$ Lyα emitter from the our deepest (> 15hrs) MOSFIRE observations for six candidate galaxies (Figure 6), and I will finish my dissertation with fully-reduced 84 galaxy spectra from MOSFIRE, building the most comprehensive dataset at $z \sim 7{-}8$.

Year 1: Analyze > 200 LAEs at $z \sim 3$– 5 from the VANDELS data and write a paper of the continuum luminosity dependence of the Lyα EW distribution in the ionized universe at $3 < z < 5$. This will bring a reference measurement of the Lyα EW distribution to be compared with the Lyα EW distribution at $z > 7$ when the IGM in the universe is significantly neutral.

Year 2: I will write a paper on the detailed timeline of reionzation at $z \sim 6$–8, combined with the model predictions of reionization on the expected evolutions of the IGM and the Lyα EW distribution (e.g., Dijkstra et al. 2014, Mason et al. 2017), providing a very strong observational constraint for deriving a necessary ionizing photon budget from the dominant ionizing sources, thus galaxies.

At the end/after my postdoc program years, I will be prepared for incorporating the extensive data of Lyα observations in the early universe with *JWST* to chart a full history of reionization. Also, the proposed researh on Lyα emission as a probe of reionization is very timely, as the first HETDEX (Hobby-Eberly Telescope Dark Energy Experiment) data is coming out and expected to provide extensive studies on LAE systematics in near future; HETDEX utilizes the Visible Integral-field Replicable Unit Spectrograph (VIRUS) to provide blind, wide-area, integral field spectroscopic survey, and will provide $\sim$ 1M LAE detections at $1.9 < z < 3.5$. I have my collaborators in the HETDEX science team (e.g., Dr. S. Finkelstein), thus will keep pursuing more comprehensive understanding of Lyα systematics, which is necessary to interpret Lyα emission as a probe of reionization.

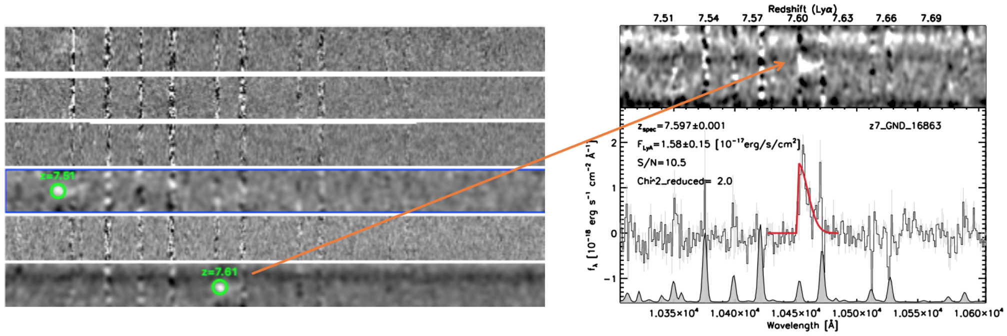

FIGURE 6. (Left) Our MOSFIRE dataset provides the deepest ($>$ 16hrs) NIR spectroscopic data for six candidate galaxies at $z > 7$. The plot shows the fully-reduced and all-mask-combined 2D spectra of the six objects, and we detect two Lyα emission lines at $z = 7.51$ (reported in Finkelstein et al. 2013) and $z = 7.6$ (a new discovery) among the six targets. (Right) 2D and 1D spectrum of the new Lyα detection at $z = 7.6$. The red line shows the asymmetric Gaussian profile of the Lyα line.

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