OBSERVING REQUEST
University of Arizona Observatories

Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term

Probing the Gaseous Universe at the Post-Reionization Epoch

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Abstract of Scientific Justification

The cosmic reionization has been suggested to be complete at $z \sim 6$ but with a possible tail to $z \sim 5.5$. The evolution of the Universe at this post-reionization epoch is still unclear. Luminous quasars are excellent tracers to reveal the details of how the universe has evolved: when used as background sources, they allow us to constrain the state of the diffuse gas on galactic and intergalactic scales via the quasar absorption line technique. However, due to the lack of known luminous quasars at $5 < z < 5.7$, little progress has been done made thus far. Our group has now established a sample of luminous quasars at $5 < z < 5.8$. Using these luminous quasars, we aim at addressing two main topics: (1) the state of the intergalactic medium (IGM) at the post-reionization; and (2) the evolution of the damped Lyα systems (DLAs), the possible progenitors of today's disk galaxies. We will use the 'dark gaps' method to measure the upper limit on the volume-weighted IGM neutral hydrogen fraction, which is the a model-independent constraint without assumptions of physical conditions in IGM and quasar's UV continuum. We will also carry out a high redshift DLA survey at redshift range of $z \sim 5 - 5.5$, the highest redshift range where DLA could be easily detected. Only few DLAs at $z \sim 5$ have been discovered before. Based on the DLA fraction (40%) from previous surveys, ~ 10 new DLAs can be expected in our whole sample. New discoveries of DLAs at $z \sim 5 - 5.5$ will place strong constraints on neutral gas and metallicity evolution in normal galaxies at high redshift. In this proposal, we request 3 MMT/Red nights to obtain high resolution spectra of 13 luminous quasars among our quasar sample in the fall sky.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling: Optimal	Scheduling: Acceptable	Sharing: Poss.	Sharing: Adv.
1	MMT	f/9	Red			3	grey/dark	Oct–Nov	Sep–Nov	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*:

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	J001232.88+363216.10	3.137	36.53781	redshift=5.55, z=19.30 mag
2	J003414.35+375954.00	8.55978	37.99833	redshift=5.67, z=19.99 mag
3	J005656.04+224112.16	14.23352	22.68671	redshift=5.64, z=19.88 mag
4	J010806.60+071120.67	17.0275	7.18908	redshift=5.53, z=19.57 mag
5	J011614.30+053817.69	19.0596	5.63825	redshift=5.33, z=19.22 mag
6	J012053.93+214706.20	20.22469	21.78506	redshift=5.46, z=19.95 mag
7	J015533.28+041506.74	28.88865	4.25187	redshift=5.37, z=19.26 mag
8	J015745.45+300110.68	29.43937	30.01963	redshift=5.74, z=19.16 mag
9	J021624.16+230409.46	34.10065	23.0693	redshift=5.26, z=19.32 mag
10	J074749.18+115352.45	116.9549	11.8979	redshift=5.26, z=18.27 mag
11	J231738.25+224409.63	349.40938	22.73601	redshift=5.59, z=19.15 mag
12	J232939.30+300350.78	352.41376	30.06411	redshift=5.24, z=18.92 mag
13	J235824.04+063437.49	359.60017	6.57708	redshift=5.32, z=19.53 mag

Approval for Instrument Use from PI: ______________________

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Observations of the Gunn-Peterson effect using absorption spectra of quasars at $z \gtrsim 5.7$ have established $z \sim 6$ as the end of cosmic reionization, when the intergalactic medium (IGM) is rapidly transforming from largely neutral to completely ionized (Fan et al. 2006). Becker et al. (2015) find evidence for UV background fluctuations at $z \sim 5.7$ in excess of predictions from a single mean-free-path model, which indicates that reionization is not fully complete at that redshift. McGreer et al. (2015) also suggest that reionization is just completing at $z \sim 6$, possibly with a tail to $z \sim 5.5$. However, the details of the gas evolution at the post-reionization epoch remains largely unknown.

Absorption spectra of high redshift luminous quasars provide key probe to the intergalactic medium (IGM). However, at high redshift, quasars are very rare. At $5 < z < 6$, about ∼200 quasars are known; most of them are too faint to be used for the study of IGM (AB mag $\gtrsim$20. Our group recently constructed a sample of luminous quasars at redshift range of $5 < z <$5.8 (Wang et al. 2016; Yang et al. 2017). We plan to obtain high resolution spectra of these newly discovered ultra-luminous quasars to investigate the evolution of HI gas at $z \gtrsim 5$ in both intergalactic and galactic scales. Two main goals of this project are to probe (1) the state of the IGM at the post-reionization; and (2) the evolution of DLAs, the possible progenitors of today's disk galaxies.

The new luminous quasar sample at $z \gtrsim 5$

In the distribution of quasar redshift, there is an obvious gap of known quasars at 5.1 $< z <$ 5.7, due to their similar optical colors to that of late-type stars, especially at $z \sim 5.5$. To fill this gap, we carried out large area surveys of $z \sim 5$ and 5.5 luminous quasars using our new selection methods based on optical, near-IR and mid-IR photometric data (Wang et al. 2016; Yang et al. 2017). Up to date, we have discovered ~ 70 new quasars at $5 < z < 5.8$ with z band magnitude brighter than 20.5 mag. Among them, there are ~ 30 quasars $z > 5.2$ with z band magnitude brighter than 20, which are suitable for the study of absorption features. In this proposal, we propose to 3 MMT/Red nights to observe 13 luminous $5.2 < z < 5.8$ quasars in the fall sky.

The evolution of neutral hydrogen fraction in IGM

The state of IGM provides unique insight into the nature of reionization. Quasar spectra can be directly used to estimate the evolution of neutral hydrogen in IGM, through the redshift evolution of observed flux in Lyα and Lyβ forests. The distribution of dark gaps in quasar spectra provide the only model-independent constraint on the IGM neutral fraction: upper limit of $\bar{x}_{\rm HI}$, the volume-weighted neutral hydrogen fraction (Mesinger et al. 2010). McGreer et al. (2011) used 13 quasars to examined the Lyα and Lyβ forest of high-redshift quasars and found the volume-weighted mean neutral fraction of the IGM at $z \approx 5.9$ to be $x_{HI} \lesssim$ 0.3 (1 σ). McGreer et al. (2015) updated the previous estimation using a larger sample with 22 objects and placed stronger constraint on $\bar{x}_{\rm HI}$ with $\bar{x}_{\rm HI}(< z >= 5.87) < 0.11$ and $\bar{x}_{\rm HI}(< z >= 5.58) < 0.09$ (both 1σ), which suggested that reionization had completed by $z \approx 6$ (See Fig. 1). Our new quasar sample now significantly expand the luminous quasars sample at $z \gtrsim 5$. The high S/N and resolution spectra of these quasars will provide new constraint on the $\bar{x}_{\rm HI}$ estimation. With the observing configuration we proposed, we will only use Lyα forest in this program. Using the same wavelength range for the Lyα forest to McGreer et al. (2015), our quasars at $5.2 < z < 5.8$ will give new measurements of $\bar{x}_{\rm HI}$ at the redshift range of $4.3 < z < 5.7$ (See Fig. 1), at which redshift range there is no similar measurement. Our new measurements will trace the exact evolution of neutral hydrogen in the epoch immediately after reionization, without assumptions about the physical conditions in IGM or quasar UV continuum.

Probing damped Lyα systems (DLAs) at $z \gtrsim 5$

Damped Lyα systems (DLAs) are atomic hydrogen gas clouds measured in absorptions to background quasars with a column density higher than 2×10^{20} cm^{-2}, which are unique laboratories for understanding the conversion of neutral gas into stars at high redshift (Wolfe et al. 2005). DLAs arise from absorption in gas rich galaxies with modest mass and star formation rate, which are beyond direct imaging and spectroscopic detections at high redshift. Both DLA density evolution and metallicity evolution provide strong constraints on galaxy evolution model.

DLAs are the main reservoir of neutral gas (HI) in the universe. Measuring the redshift evolution of DLA will enable the measurement of Ω_{HI}, the mass density of atomic hydrogen gas, and trace the overall evolution of neutral gas. The Ω_{HI} parameter tracks the instantaneous reservoir of cold, neutral gas available for star formation integrated across the entire galaxy population. At $z \sim 0$, the evolution of Ω_{HI} can be measured by using 21-cm emission surveys, while at moderate-to-high redshift, DLA survey is the most effective way to measure Ω_{HI}. Sánchez-Ramírez et al.(2016) combined high-redshift DLA sample with absorption surveys at intermediate redshift and 21-cm emission line surveys of the local universe to study the redshift evolution of Ω_{HI} and suggest a statistically significant evolution from $z \sim 0$ to 5 (See Fig. 2). A higher redshift DLA sample is required to probe the evolution at $z \gtrsim 5$. However, the number of known high-redshift DLAs is very small; only about 10 DLAs have been discovered at $z \gtrsim 4.7$ (Rafelski et al. 2012). At higher redshift ($z > 5.1$), there is no DLA has been detected so far. Since at $z \sim 6$, complete Gunn-Peterson absorption prevents DLA detections completely, $z = 5 - 5.5$ is the highest redshift currently possible to study DLAs. Little is known at DLAs at $z >= 5$ due to the lack of luminous $z \sim 5.5$ quasars in previous surveys.

DLA also provides the only way to trace metallicity evolution in normal galaxies at high redshift. It is difficult to measure the chemical properties of faint star-forming galaxies through emission, while it will be more easily to be determined using absorptions in the spectra of bright background quasars (e.g., Prochaska et al. 2003). The previous studies of metallicities of these known high-redshift DLAs suggest a rapid decline in metallicity of DLAs at $z \sim 5$ (Rafelski et al. 2012, 2014). A higher redshift DLA sample will be able to constrain the model of metal enrichment at the highest available redshift.

The small number of known DLAs at $5 < z < 6$ is mainly due a lack of suitable luminous quasars from previous surveys. From our luminous quasar sample discussed above, we have discovered one DLA system at this redshift. It is a $z \sim 5$ DLA in the spectra of a ultra-luminous quasar, J0306+1853 ($z_{em} = 5.363$; Wang et al. 2015). It is also the most metal-rich DLA found to date at $z \sim 5$. We are now expanding our $z > 5$ DLA search to our entire sample in this MMT program. Based on the fraction of DLAs from XQ-100 survey (about 40%, Berg et al. 2016), $\gtrsim 10$ DLAs are expected in the whole sample. The MMT spectra will be used to identify $z \gtrsim 5$ DLAs, measure HI column density, and estimate Ω_{HI}. Further spectroscopy observations at longer wavelength is needed to measure metallicity of the DLAs discovered in this survey.

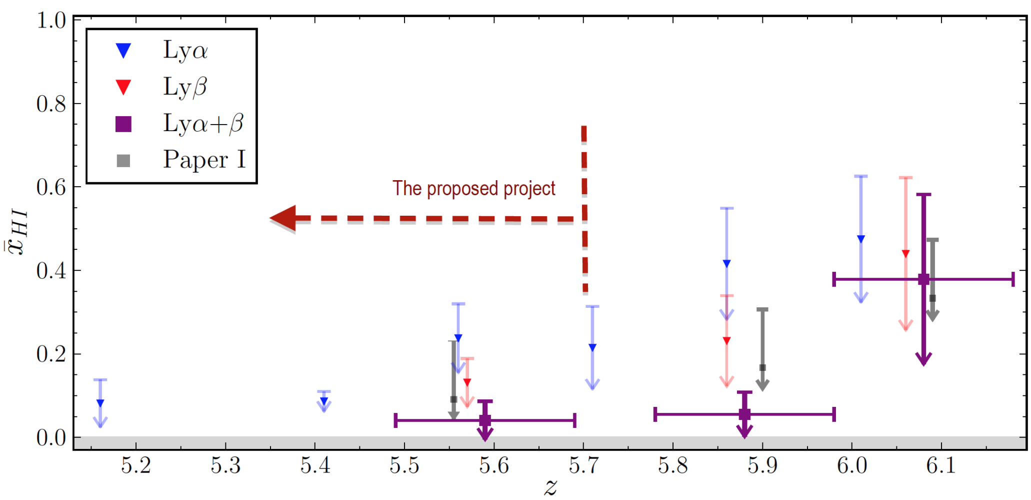

Figure 1: Constraint on the neutral hydrogen fraction using dark gap method. Adapted from McGreer et al. (2015). The Lyα and Lyβ constraints are shown in light blue and light red, respectively, with vertical error bars representing the sightline-to-sightline scatter in the dark fractions estimated from jackknife statistics. The strongest constraints are obtained by combining information from the Lyα and Lyβ forests, denoted by the dark purple points, with horizontal error bars indicating the extent of the redshift bins. The grey upper limits are from the two Keck ESI spectra presented in McGreer et al. (2011) (1σ limits). The dashed line represents the redshift range that this project will focus on.

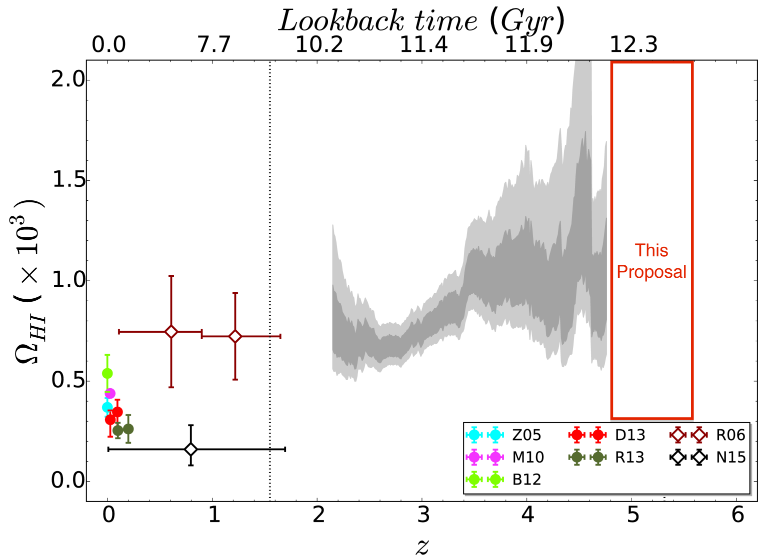

Figure 2: Evolution of the atomic HI gas in galaxies over the cosmic time from Sánchez-Ramírez et al.(2016). Data from 21-cm emission line surveys (circles) and from QSO absorption systems (squares) are plotted. Empty points represents Ω_{HI}^{DLA} and filled Ω_{HI}. Vertical lines are the redshift limits of the combined sample. The Ω_{HI}^{DLA} curve derived from the combined sample (68 and 95 percent confidence intervals) are shown in the shaded regions.

Reference:

Berg, T. A. M., et al. 2016, arXiv:1609.05968;
Becker G. D. et al., 2015, MNRAS, 447,3402;
Fan, X., Carilli, C.L., Keating, B. 2006, ARA&A, 44, 415;
McGreer I. D., Mesinger A., Fan X., 2011, MNRAS, 1096;
McGreer, I. D., Mesinger, A., & D'Odorico, V. 2015, MNRAS,447, 499;
Mesinger A., 2010, MNRAS, 407, 1328;
Prochaska, J. X. et al., 2003, ApJL, 595, L9;
Rafelski, M. et al. 2014, ApJL, 782, L29;
Rafelski, M. et al. 2012, ApJ, 755, 89;
Sánchez-Ramírez, R. et al. 2016, MNRAS 456, 4488;
Wang, F. et al. 2015, ApJL, 807, 9;
Wang, F., Wu, X.-B., Fan, X., et al. 2016, ApJ, 819, 24;
Wolfe, A. M. et al., 2005, ARA&A, 43, 861;
Yang, J. et al., 2017, AJ in press;

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Configuration and exposure time: In this project, we will obtain high resolution optical spectroscopy of 13 luminous quasars using MMT/Red. Using the data, we will measure the upper limit of $\bar{x}_{\rm HI}$ based on the 'dark gaps' method. We will also identify new DLAs and estimate the column density of atomic hydrogen by fitting the Voigt profile to study the evolution of neutral hydrogen. As the fraction of DLAs from XQ-100 survey (Berg et al. 2016), $\sim$ 4 DLAs will be expected among these 13 quasars.

Considering the resolution and stability of instruments, we choose longslit mode with Grating 1200/9000. The Grating 1200 will provide required resolution (R $\sim$ 5000). The spectrual coverage of this grating is 800 $\AA$. Due to this coverage, we will only use Lyα forest to measure $\bar{x}_{\rm HI}$. The wavelength range of Lyα forest is usually set as: starting at 1+z_{min} = (1+z_{em})(1040 $\AA$/λ_α) to the end at $z_{QSO} - 1$. The blue edge is chose to avoid effects from Lyβ and OVI emission and Lyβ forest. The red edge is taken to be $\sim$ 40 Mpc from the quasar redshift to avoid the bias from quasar environment. Here, based on the wavelength coverage of Grating 1200/9000, the spectrum will cover Lyα forest in the range of $z = 4.44 (z = 5.04)$ to $z = 5.1 (z = 5.7)$ for a quasar at $z = 5.2 (z = 5.8)$. It fully covers our focus, $z \gtrsim 5$, of both $\bar{x}_{\rm HI}$ measurements and DLA survey. Since we have low resolution spectra of these quasars that can be used for continuum fitting, we only need the spectra of Lyα forest.

Based on the previous MMT observation experiences, to reach a minimum S/N for absorption measurement and DLA identification, we need a 2-2.5 hours per quasar exposure time of 8 targets with z band magnitude brighter than 19.5, and 2.5-3 hours per quasar of 5 targets with z band magnitude brighter than 19.5. In total, we require 3 nights to observe all 13 targets.

Lunar phases: Our targets are faint in the whole optical window and much fainter in the wavelength shorter that 7000$\AA$. The moon light will affect our spectroscopy significantly. We have to do such observations in dark or grey nights to ensure the quality of the spectra.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

Our long-term goal is to obtain high resolution spectra of $\sim$ 30 luminous quasars at $5.2 < z < 5.8$ to investigate the gas evolution at the post-reionization epoch. Except this proposal, we still need 3-4 MMT nights for remaining quasars to complete this project.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

This is the first Steward proposal of the PI, who is a new postdoc arriving in Fall 2017 to join X. Fan's research group.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*