OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term⋆

Mapping the Most Massive Overdensity Through HI: Bok/90Prime Imaging of a Galaxy Overdensity at z = 2.3

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Abstract of Scientific Justification

By examining the recent and complete data release of SDSS-III over a volume of 1Gpc^3, we have identified the most extreme overdensities of Lyα absorbers at $z = 2.32 \pm 0.03$, which then can be probed with our custom narrowband filter NB403. Some of these systems are associated with a high concentration of quasars at the same redshift. These overdensities are likely to represent the most biased regions, which are embedded into the most massive large-scale structures in the universe at the peak of galaxy formation ($z = 2 - 3$). Our simulations, KPNO-4m and Bok observations in 2014 suggest a strong correlation between the 1-D high optical depth Lyα absorbers, which arise from the IGM, and true 3-D mass overdensities over scales of 10-30 h^{-1} Mpc. We now have discovered two of the largest 1-D absorber overdensities at $z > 2$ and within 20 h^{-1} Mpc found to date, from entire and most recent data release of SDSS-III. With Bok/90Prime, we propose here to carry out deep narrowband (NB403) + broadband (Bw) imaging to find Lyman-α emitting galaxies (LAEs) in these systems. These observations will build a crucial sample of the galaxy overdensities traced by groups of large intergalactic Lyα absorbers, and further reveal the star formation activity in these rarest galaxy environments.

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	Bok	PF	90Prime			4	dark	Oct- Dec	Nov-Dec	yes	yes

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	J0230-0040	02:30:48.0	-00:40:12.0	$z = 2.32$
2	J0823+5210	08:23:26.4	+52:10:48.0	$z = 2.32$

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 for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Zheng Cai	Xiaohui Fan		no	yes

Scientific Justification

Large-scale Filamentary Structure around the Protocluster at early Universe

Theories of structure formation predict that galaxy formation preferentially occurs along large-scale filamentary or sheet-like mass overdense regions in the early Universe and the intersections of such filaments or sheets evolve into dense clusters of galaxies at the later epoch (Governato et al. 1998; Kauffmann et al. 1999; Cen & Ostriker 2000; Benson et al. 2001). Recent deep observations of star-forming galaxies at high redshift, such as Lyman break galaxies (LBGs) or Lyα emitters (LAEs), have revealed their inhomogeneous spatial distribution over several tens to a hundred Mpc (Steidel et al. 1998, 2000). One needs a wide field camera with ~ 1 deg^2 to fully reveal the large-scale filamentary or sheet-like mass overdensities (Matsuda et al. 2005; Lee et al. 2014).

Previously, a large overdensity of LBGs and LAEs was discovered at $z = 3.1$ in the SSA22 overdense field at scale of 10' $\times$ 10' field of view, and it was regarded as a protocluster of galaxies (Steidel et al. 2000). Matsuda et al. (2005) carried out wide-field and deep narrow-band imaging observations of in this SSA22 proto-cluster with Subaru/Suprime Camera with large field of view. Indeed, Matsuda et al. (2005) discovered a belt-like region of high surface density of LAEs with the length of more than ~ 70 Mpc (45') and the width of about 10 Mpc in comoving scale, consistent with the prediction of the structure formation model. However, the number of previous confirmed large-scale structures that have sufficiently large volume coverage is still too small to allow for robust comparisons to hierarchical structure formation models (Matsuda et al. 2005; Chiang et al. 2013; Lee et al. 2014). The Bok/90 prime with a large field of view of 1 deg^2 provides us a great opportunity to conduct studies to to fully cover and reveal sheet-like or filamentary structures associated with massive large-scale structure at tens to hundred of Mpcs.

Our team have developed a novel technique in the past two years for identifying the extreme tail of the matter density distribution. We use the presence of large optical depth from IGM HI absorption at large scale observed in the spectra of high-redshift quasars as tracers of proto-clusters and highly overdense regions. This method allows us to cover significantly larger volume and is less biased since HI density is closely correlated with dark matter and galaxy density field over large scale. This technique enables the discovery of the most extreme galaxy environment in the early universe.

The relation between Lyα optical depth and 3-D mass overdensity can be naturally interpreted. At galaxy and cluster scales ($\lesssim$1Mpc), hydrodynamical processes associated with the galaxy photoionization and feedback are important. At larger scales, however, hydrodynamical effects are no longer important and HI gas density and dark matter density closely trace each other (McDonald et al. 2003, Cai et al. 2015 in prep.). Frye et al. (2008) presented a unusual intergalactic Lyα absorption in the spectrum of a galaxy at z=4.9. The Lyα optical depth is remarkably high within a large 20 h^{-1} Mpc (comoving) region compared with that seen towards other sight lines at similar redshifts. This absorption feature indeed pinpoints a large reservoir of HI in the IGM, which in turn trace a large galaxy overdensity (Matsuda et al. 2010).

Confirm a Massive Overdensity Traced by Three HI absorption at $z = 2.32 \pm 0.02$.

During 2014, we have discovered two pilot fields at $z = 2.32 \pm 0.02$, selected from the inital survey which covering 3000 deg^2, and small redshift interval of $\Delta z = 2.32 \pm 0.04$ to match our custom narrowband filter. This initial survey volume is about 0.17 (h^{-1} Gpc)^3. The two fields contain a group of five IGM Lyα absorption systems within $\lesssim$ 30 Mpc on the sky (Figure 1). In addition, this absorption system is associated with multiple quasars in nearby 30 Mpc at the same redshift.

We have carried out narrowband (NB403) and broadband (Bw) imaging on one field using the KPNO-4m/MOSAIC in 2014A, and have dicovered a significant overdensity of 80 Lyα emitters (LAEs) at the bright end ($\mathrm{mag}_{\mathrm{NB403}} < 23.8$) over the whole field. The number of bright LAEs is a factor of $4 - 5 \times$ higher than that in random fields over a $40\,\mathrm{Mpc}$ scale (Ciardullo et al. 2012), and the LAE overdensity is even higher in the density peak of this large-scale structure. Further, we discover one giant and luminous LAB with $\mathrm{mag}_{\mathrm{AB}} \sim 19$ and size $\gtrsim$ (200 kpc)^2 (Figure 2). This LAB is more luminous than any LAB discovered from large narrobwand survey over 10 deg^2 (Yang et al. 2008).

In 2014A, we have also conducted LBT/LBC multicolor imaging with U, V, and i filters to probe LBGs

with $z = 2.3 \pm 0.3$ in this field. Although LBG selection only select galaxies in a wide redshift range, we still detect an overdensity of LBG galaxies in the LAE density peak region ($20\mathrm{Mpc} \times 10\ \mathrm{Mpc}$). This detection strongly indicates the density peak of this structure contains a galaxy overdensity of > 10 at $z = 2.32 \pm 0.02$. Our LBT/MODS spectroscopy have targeted 15 bright LAEs in a small area of 50 arcmin^2 in the structure, and successfully confirm the Lyα emission of 14 LAEs associated with this large-scale structure. *This overdensity is the most massive large-scale structure yet discovered at $z > 2$, and we call this structure as BOSS1441+4000.*

Bok/90Prime is Ideal for Fully Quantify and Map the Most Massive Large Scale Overdensity

In 2015B, **we propose Bok/90Prime deep narrowband + broadband imaging** to probe the LAEs in two of the most extreme HI absorber groups drawn from the complete SDSS-III Lyα forest database at $z = 2.32 \pm 0.03$. We will conduct deep observations on two overdense fields, to fully quantify and characterize the overdensities. In order to achieve this goal, we need to detect LAEs down to $\sim L^*$ at S/N ~ 5, and use the LAEs to map and measure the overdensity. Simultaneously, these observations should also detect extended Lyα blobs, probing the connection between them and galaxy overdensities. We will use our custom *NB403* narrowband filter and the Bw broadband filter to select LAEs and Lyα blobs. In order to quantify the galaxy overdensity associated with these two field, we need to detect LAEs down to $\sim L^*$ at S/N ~ 5. At z$\sim$2.3, this corresponds to a Lya flux level of $F_{Ly\alpha} \sim 4.0 \times 10^{-17}$ erg cm^{-2} s^{-1} (mag$_{\mathrm{AB}}$=24.5). The B broadband images need to reach mag$_{\mathrm{AB}} = 25.5$ to establish the continuum.

The 90Prime camera on Bok telescope is ideal for this program. First, the projected separation of the IGM HI absorption and quasars in each field is $\lesssim$ 40' (Fig. 2), which perfectly fit 90 prime large field of view of 1deg^2. Second, our custom narrowband filters, which are necessary to enhance the Lyα emission relative to the broadband-measured continuum, can be easily loaded into the instrument. Third, the 2.3m primary mirror and very high efficiency of the 90 prime in the Bw band makes LAE detection $z \sim 2$ relatively efficient. For one field, we only need a 13-hour NB403 narrowband and a 1.5-2hr B broadband to reach $\sim L^*$ LAEs at z $\sim$ 2. The main goals of this Bok/90Prime observations are:

(a) Find the nature of the QSO group fields, using LAEs to quantify the overdensity and the relative bias of LAEs and QSOs as tracers.

(b) Use LAEs to probe the star formation activity and luminosity function in these QSO extreme overdensities.

(c) Study the photo-ionization effects of QSOs on the distribution and equivalent widths (EW) of LAEs (Cantalupo et al. 2012).

(d) Search for Lyα blobs and define the connection between blobs and extreme galaxy overdensities.

(e) Study the intergalactic HI absorptions in this overdense field (right panel of Fig.1) and use the HI optical depth to constrain the strength of QSO/galaxy photo-ionizations.

References.

Adelberger et al. 2003, ApJ, 584, 45;

Erb et al. 2011, ApJ, 740, L31;

Frye et al. 2008, ApJ, 685, L5;

Guaita et al. 2010, ApJ, 733, 114;

Kollmeier et al. 2003, ApJ, 594, 75;

Matsuda et al. 2010, MNRAS, 403, L54;

McDonald et al. 2002, ApJ, 580, 42;

Reddy et al. 2009, ApJ, 692, 778;

Steidel et al. 2005, ApJ, 626, 44;

Yang et al. 2009, ApJ, 693, 1579

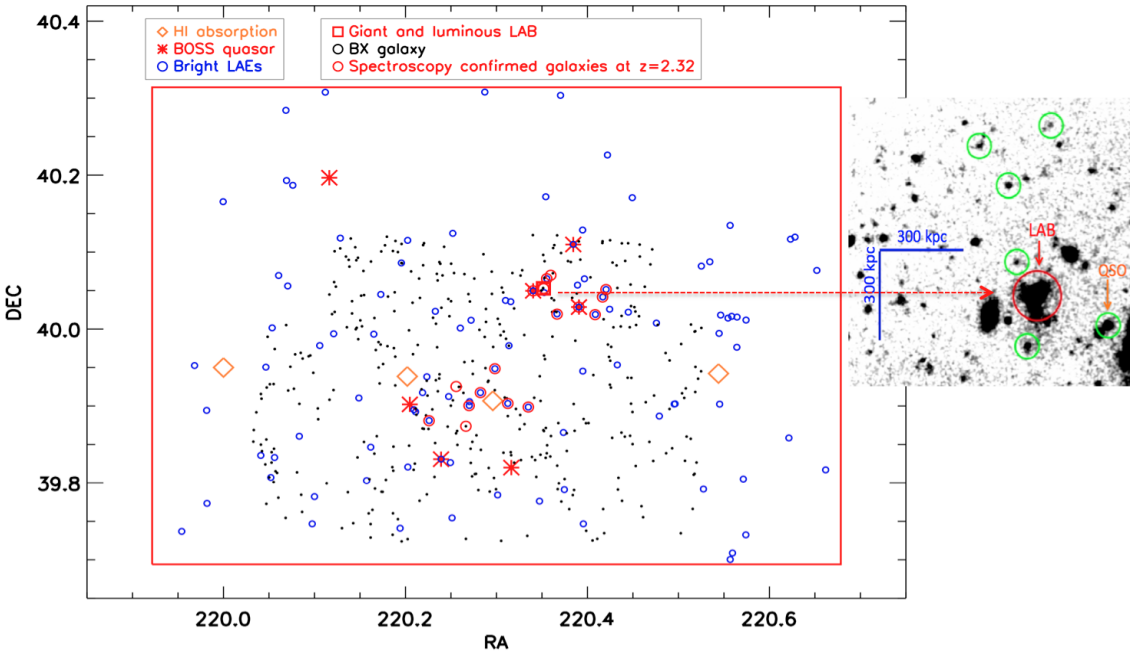

Figure 1: The field we observed in 2014. The positions of the rare group of intergalactic Lyα absorptions (orange diamonds) and quasar group (red asterisks) within 20 h^{-1} co-Mpc at $z = 2.32 \pm 0.02$. At 30 Mpc, this field has the highest number of strong IGM absorbers and quasars in the early SDSS-III data release in 2013. The number of LAEs in KPNO-4m/MOSAIC field (red rectangle) is a factor of $4\times$ higher than that in random fields. Our LBT/MODS spectroscopy have targeted 15 LAEs with $\mathrm{mag}_{\mathrm{NB403}} < 23.8$ with two masks in small area of 50 arcmin^2, and confirmed 14 of them (red circles), including one giant luminous LAB (right inset image). In 2015B, we propose to observe two fields traced by that more extreme group of Lyα absorption systems selected from entire SDSS-III database.

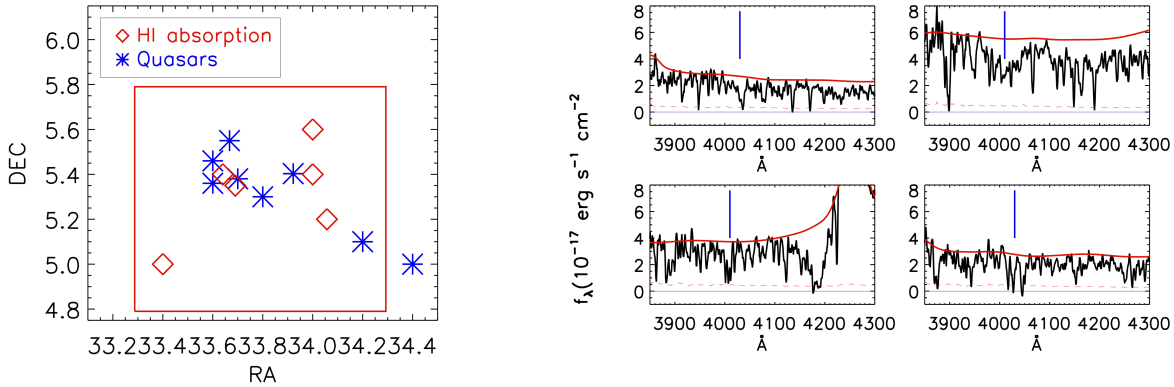

Figure 2: (Left): One field we propose to observe in 2015B with Bok/90Prime. The extremely high density of deep IGM absorptions (red diamonds) at $z = 2.31 \pm 0.02$ and quasars at the same redshift range of $z = 2.31 \pm 0.02$ (blue asterisks) make this field unique in the complete SDSS-III data release. Over a 15 h^{-1} Mpc scale, the optical depth of these deep IGM Lyα absorbers (red diamonds) is $> 4\times$ higher than the mean optical depth at $z = 2.3$. The red square shows the 90Prime field of view. (Right): The spectra of four deep IGM Lyα absorption (red diamonds in the left panel) in this field. In each spectrum, blue bars indicate the position of these IGM absorption at $z = 2.31 \pm 0.02$ and are covered by our custom NB403 filter. In 2015B, with Bw and *NB403* filters, we expect to identify hundreds of LAEs down to L^* in this and another similar field.

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)***

The main goal of the observations is to characterize galaxy overdensity traced by rarest group of IGM Lyα absorption. In 2015B, we will conduct deep observations on two overdense fields, to fully quantify and characterize the overdensities. In order to achieve this goal, we need to detect LAEs down to $\sim L^*$ at S/N ~ 5, and use the LAEs to map and measure the overdensity. Simultaneously, these observations should also detect extended Lyα blobs, probing the connection between them and galaxy overdensities. We will use our custom *NB403* narrowband filter and the Bw broadband filter to select LAEs and Lyα blobs.

Target selection:

The deep IGM Lyα forest absorbers are selected from SDSS-III survey. To match our custom narrowband filter, we select the deep IGM absorption with the redshift range of $z = 2.32 \pm 0.03$. The deep Lyα absorbers are selected by picking regions where the transmit flux ($T_{\rm flux}$) over 20 Å (15 h^{-1} Mpc) is smaller than 0.5, corresponding to an effective optical depth of 0.6, a factor of 3 $\times$ higher than the mean optical depth at $z = 2.3$. From the absorption profile, we have ruled out the DLAs which also causing wide absorptions, and only select the deep Lyα absorbers due to the IGM overdensity over a large scale of $\sim 20 - 30$ Mpc.

Then, we pick the fields with the highest density of deep IGM absorbers. In 2014, our observations have confirmed a significant overdensity of bright LAEs associated with a group of IGM HI absorbers (Fig.1). In 2015B, from the complete SDSS-III data release, we have selected two fields with a higher density of deep IGM absorbers compared with the field we observed in 2014. These two fields have 4-5 deep IGM absorbers at the scale of 30 Mpc at $z = 2.31 \pm 0.02$. Fig.2 shows that one field in 2015B is also associated with a large quasar group at the same redshift of $z = 2.31 \pm 0.02$.

LAEs Selection:

To identify LAE candidates requires the subtraction of the continuum emission within the *NB403* passband. Thus, we use *NB403* narrowband and Bw broadband to select LAEs at $z = 2.32 \pm 0.02$. We use the color selection technique with $Bw - NB403 > 0.86$, which will select EW $>$ 66Å LAEs (rest frame EW$>$20Å).

To detect sufficient number of LAEs to measure the galaxy overdensity, we need to reach $\sim$ L* $\sim 1.3 \times 10^{42}$ erg s^{-1} at this redshift (e.g. Guaita et al. 2010, Nilsson et al. 2009). This corresponds to a Lyα flux level $F_{Ly\alpha} \sim 4.0 \times 10^{-17}$ erg cm^{-2} s^{-1} (mag$_{\rm AB}$=24.5) at $z \sim 2.3$, and an unobscured SFR of $\sim 1.5 M_\odot$ yr^{-1}. For continuum measurement, we need to reach $B \sim 25.5$ at the 5σ level to meet our color criterion.

Based on the LAE luminosity function at $z \sim 2$, we expect $\sim 60 \pm 20$ LAEs per 90Prime field of view at the proposed depth *if the field is of average density* (Ciardullo et al. 2012). If the field is an overdense field, we expect to detect a LAE overdensity of at least 3σ level even if the field contains only $2\times$ the average number of LAEs. On the other hand, if the number of LAE is ~ 60 in both fields, we will have shown that the LAEs do not trace by large IGM HI absorption.

At our survey redshift, the only possible interlopers are nearby [O II] λ3727 emitters at z$\approx$0.08. However, such objects rarely have equivalent widths larger than 60Å in the rest frame (Hogg et al. 1998). Therefore, we expect that the contamination of our LAEs by nearby star forming galaxies is minimal.

Exposure time:

We request 4-night to observe two fields with extremely rare group of large HI absorption and quasars. Or, we can be allocated 2-night to obtain a deeper narrowband observations in one of the two fields. From our previous experiences (Yang et al. 2010), we need a 15-hour *NB403* narrowband integration per field with seeing $< 1.4''$ to reach a Lyα flux level of $F_{Ly\alpha} \sim 4.0 \times 10^{-17}$ erg cm^{-2} s^{-1} (mag$_{\rm AB}$=24.5). For establishing the continuum, we require a $\sim$ 2-hr integration for B broadband to get mag$_{\rm AB}$ ~ 25.5 at 5σ level to meet our color selection criterion $B - NB >$0.86.

We request dark time, as the narrowband filter *NB403* ($\lambda_c = 4030$Å, and FWHM=45Å) locates in Bw broadband filter, and are sensitive to moonlight.

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**)*

We use narrowband + broadband imaging to select Lyα emitters (LAEs) to map the overdensity. The whole imaging project coming from non-UAO telescope KPNO-4m, and UAO telescope Bok.

In 2013, we selected the field with highest density of Lyα absorption systems as well as quasars.

In 2014, we use KPNO-4m (1.5-night clear) to map this field using Lyα emittters. The number of LAEs in KPNO-4m/MOSAIC field (red rectangle) is a factor of $4\times$ higher than that in random fields.

In 2014A, our follow-up observations with 1-night LBT/LBC and 1.5-night LBT/MODS were successful, and we got ~ 20 redshifts for the member galaxies associated with the massive overdensity at $z \sim 2$, and we have confirmed that this protocluster is one of the largest overdensities people have found to date at $z \sim 2$, the publications are in preparation.

The 2015B, we selected our targets from entire SDSS-III and most updated SDSS-IV database. The survey volume is a factor of $3\times >$ that in 2013A (the field we have observed in 2014). The Bok/90Prime observations proposed here, combining with our previous observations, will build an crucial sample of the rare mass overdensities traced by large Lyα absorption.

These observations will also continue to form the core dataset for Zheng Cai's thesis.

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**)*

In past two years:

- ⋆ A 1-night LBT/LBC was awarded in 2014A, observations successful. The observations are very well meet our proposed science goals. Because of this data, the LBG candidates associated with a large galaxy overdensity are selected. The LBG overdensity traced by group of quasars and Lyα absorption systems are clearly detected. One paper is preparing.
- ⋆ A 1.5-night LBT/MODS was awarded in 2014A, observation successful. Results are very nice and well meet our science goals. 15 LAEs were targeted with two masks in the density peak of our large-scale structure. We successfully confirmed 14 LAEs. Also, we detect several LBGs' redshifts and a few of them are associated with the large-scale structure. The large-scale strcuture are successfully confirmed. Also, we have confirmed a giant and luminous LABs in our overdense field. Two papers are preparing based on this LBT/LBC+ LBT/MODS observations. One paper is preparing
- ⋆ A 3-night Bok/90Prime was awarded in 2014B. 2 nights were clear and observation successful. We have selected the overdensity of the bright Lyα emitters.