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

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. In the large scale structures at high redshifts, the galaxies have an inhomogeneous spatial distribution, and the filamentry structures could spread over several tens to a hundred Mpc. By examining the absorption spectra of ∼100,000 quasar sight-lines at over a volume of 0.5 Gpc^3 in the SDSS-III, we have identified one overdensities traced by group of Lyα absorption systems at $z = 2.32 \pm 0.02$. Our KPNO-4m/MOSAIC have suggested a significant overdensity of bright Lyα emitting galaxies (LAEs) with $L > 2 \times L^*$ over an area of 30 × 30 arcmin^2. Our follow-up LBT/LBC, and LBT/MODS observations have spectroscopically confirmed this massive large-scale structure. With Bok/90Prime, we propose here to carry out deep narrowband (NB403) + broadband (Bw) imaging to probe LAEs down to L^* in these systems over a larger scale of 1 deg^2. These observations will fully map the 2-D filamentary structure; and confirm the inhomogeneous and sheet-like distribution of galaxies over the large-scale of $\sim$ 100 Mpc scale associated with the most extreme overdensity we have confirmed in 2014. Simultaneously, this observations will also enable us to search for Lyα blobs in a larger scale of hundred of Mpcs in this overdense field, and define the connection between blobs and galaxy overdensities at large scale.

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			3	dark	Apr-Apr	Mar-May	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	J1440+4000	14:45:50	+40:00:02	$z = 2.32$

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, one 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 narrow-band imaging for this SSA22 protocluster using 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 total 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 the large 1 deg^2 field of view and optimized blue sensitivity provide us a great opportunity to conduct studies to fully cover and reveal the sheet-like filamentary structures associated with massive large-scale structure at tens to hundred of Mpcs.

Confirm a Massive Overdensity Traced by Group of Lyα absorption at $z = 2.32 \pm 0.02$.

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 Lyα absorption at large scale observed in the spectra of high-redshift quasars as tracers of proto-clusters and highly overdense regions. Our large-scale cosmological simulation have shown a strong correlation between matter overdensity and intergalactic Lyα absorption. This correlation has a broad peak over the scale of 10-30 comoving Mpc. We also have demonstrated that most of the structures that traced by largest 1-D IGM Lyα absorption systems represent a 4-5σ mass overdensity in 20 h^{-1} Mpc scale, corresponding to a galaxy overdensity of 4σ over this large scale (Cai et al. 2014, ready to submit).

Druing 2013 and 2014, by utilizing the large library of quasar spectra available from the SDSS-III, we have discovered one field at $z = 2.32 \pm 0.02$, selected from early SDSS-III 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 selected field contains 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 seven quasars in nearby 30 Mpc at the same redshift.

We have carried out narrowband (NB403) and broadband (Bw) imaging on this field using the KPNO-4m/MOSAIC in 2013A and 2014A. Although weather condition in both year is not ideal, we have dicovered a significant overdensity of 80 Lyα emitters (LAEs) at the bright end (mag$_{\rm NB403} < 23.8$, $L \gtrsim 2 \times L^*$) 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). Further, we discover one giant and luminous Lyα-bolb (LAB) with mag$_{\rm AB} \sim 19$ and size $\gtrsim$ (200 kpc)^2. This LAB is a factor of 2 $\times$ more luminous than any LAB discovered from large narrobwand survey over 10 deg^2 (Yang et al. 2008).

In 2014A, we have 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 this field. Also, the LBG distribution is highly inhomogenous at ~ 20 Mpc, which can be reflected from the current data (see Figure 2). 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, and successful 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 $z \sim 2$, and we call this structure as BOSS1441+4000*.

This structure has a much larger galaxy overdensity compared with that in SSA22 field, and the filamentary structure should be fully revealed over an area of $\gtrsim 45'$. From Figure 2, one sub-region has a high concentration of LAEs appears to lie at the east of the current coverage. Also, there is one large IGM absorption systems locate outside the current MOSAIC field of view of 30' × 30' (see Figure 2), 25% of 90Prime's FOV. The apparent geometry of the structure mapped by the existing data suggests that this structure need to be mapped with larger area, beyond the extent of the current coverage.

Bok/90Prime Required to Fully Quantify and Map the Most Massive Large Scale Overdensity

In 2014A, we have confirmed one massive large-scale strcutre in an area of $30' \times 30'$. We reached this field down to bright LAEs with $L \gtrsim 2 \times L^*$. In 2015A, **we propose Bok/90Prime deep narrowband + broadband imaging** to fully probe the LAEs down to L^* in much larger area of 1 deg^2, and fully map the filamentary structure at scales of $\sim$ 100 Mpc associated with the most extreme overdensity we have confirmed in 2014A.

We will conduct deep observations on this field, 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 $\sim$ 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 over large scale. We will use our custom *NB403* narrowband filter and the Bw broadband filter to select LAEs and Lyα blobs. The B broadband images need to reach mag$_{\rm AB} = 25.5$ to establish the continuum.

The 90Prime camera on Bok telescope is ideal for this program. First, the projected separation of the IGM Lyα absorption systems and quasars is $\sim$ 40'. There are two IGM Lyα absorption systems locate outside the current MOSAIC probe. The Bok/90Prime perfectly fit the overall geometry of the structure suggested by IGM absorption and current LAE distribution. 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 90Prime in the B band makes LAE detection $z \sim 2$ relatively efficient. We need a 18-hour NB403 narrowband and a 2-hr B broadband to reach $\sim L^*$ LAEs at z $\sim$ 2. The main goals of this Bok/90Prime observations are:

(a) Fully reveal the large-scale filamentary overdensities over a 1 deg^2 area using LAEs down to L^*. This probe is crucial for us to evaluate the size of this large-scale structure; and confirm the large-scale inhomogenous distribution of galaxies and sheet-like mass overdensities up to hundred of Mpcs associated with a massive large-scale structure, which will be directly used to compare with cosmological simulation.

(b) Probe LAEs deeper down to L^*, and study the relation between spatial distribution of LAEs and the intergalactic Lyα absorption systems ditributed in a large area of $\sim$ 1 deg^2, and also use the Lyα optical depth to constrain the local strength of QSO/galaxy photo-ionizations.

(c) Search for Lyα blobs in a larger scale of hundred of Mpcs in this overdense field, and define the connection between blobs and galaxy overdensities.

(d) Use LAEs to probe the Lyα-based star formation activity and luminosity function in these large-scale structure traced by group of IGM Lyα absorption systems.

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; Kuiper et al. 2010, MNRAS, 405, 969; Kollmeier et al. 2003, ApJ, 594, 75; Matsuda et al. 2005, AJ, 128, 569-584; 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

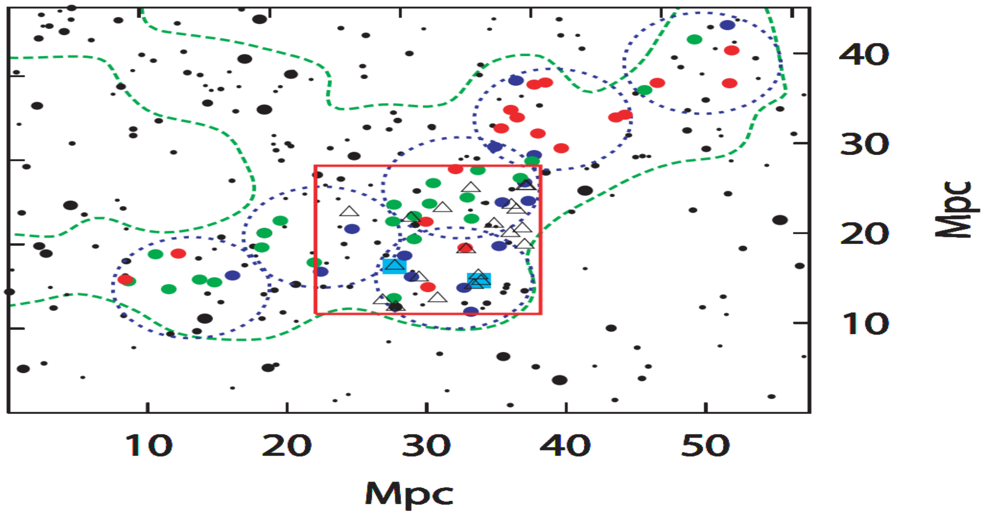

Figure 1: The SSA22 galaxy overdense field. The red box with a small area of 9'×9' shows the original field of view probed by Steidel et al. (2000). Steidel et al. (2000) first discovers this overdense field, by utilizing an overdensity of break galaxies (LBGs) and Lyα-emitting galaxies (LAEs) in this small area. The green line shows the average local surface density of LAEs in this field detected by much larger scale using Subaru/Suprime-Cam (Matsuda et al. 2005) . This Subaru wide-field imaging confirmed that a highly inhomogenous distribution of LAEs and the belt-like filamentary structures associated with SSA22 can be fully revealed at a large scale of > 60 Mpc ($\sim 45'$ at $z \sim 2$).

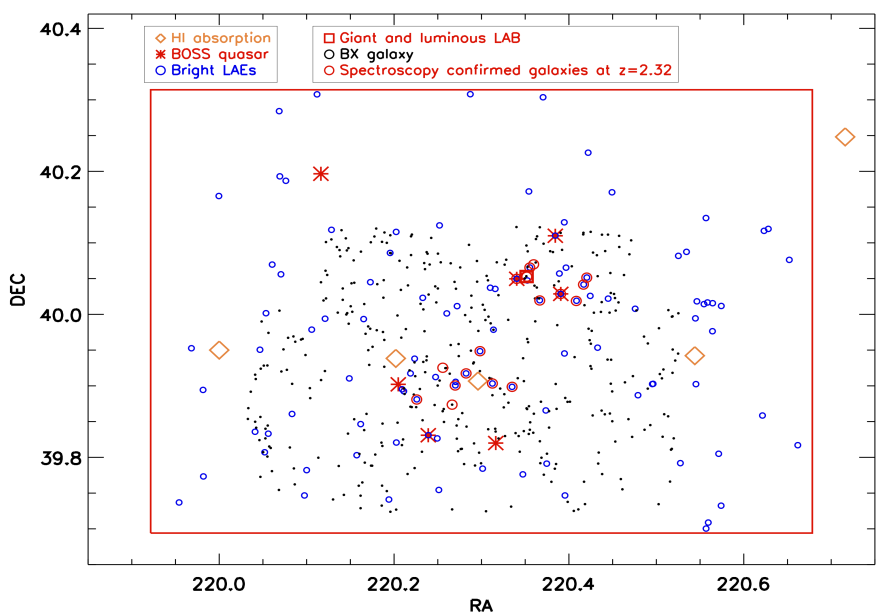

Figure 2: The overdensity we found from a 3,000 deg^2 from SDSS-III/BOSS. This structure is traced by large group of Lyα absorption systems (orange diamonds) and quasars (red asterisks) over 20 h^{-1} comoving Mpc at $z = 2.3$. In KPNO-4m/MOSAIC field of view ($\sim 30' \times 30'$), the number of bright LAEs with $L \gtrsim 2 \times L^*$ is a factor of $4\times$ higher than that in random fields at $z = 2.3$. Our LBT/MODS spectroscopy have targeted 15 LAEs with mag$_{\rm NB403} < 23.8$ with two masks in a small area of 50 arcmin^2, and confirmed 14 of them (red circles), and the LAE density in this small area is $> 10\times$ higher than in random fields. In 2015A, we propose to use Bok/90prime to probe deeper down to $L \sim L^*$ over a much larger 1 deg^2 area, fully reveal the large-scale filamentary structure associated with this massive overdensities.

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)***

In 2014A, we have confirmed one massive large-scale strcutre in an area of $30' \times 30'$. We have reached this field down to bright LAEs with $L \gtrsim 2 \times L^*$. In 2015A, **we propose Bok/90Prime deep narrowband + broadband imaging** to fully probe the LAEs down to L^* in much larger area of 1 deg^2, and fully map the filamentary structure at scales of $\sim$ 100 Mpc associated with the most extreme overdensity we have confirmed in 2014A.

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 $z = 2.32 \pm 0.04$. 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 0.4, corresponding to an effective optical depth of 0.7, a factor of 4 $\times$ 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 2013 and 2014, our observations have confirmed a significant overdensity of bright LAEs associated with the group of IGM Lyα absorbers (Figure 2).

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} ($\rm mag_{AB}$ = 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.

Our KPNO-4m/MOSAIC observations has detected 80 LAEs with $L \gtrsim 2 \times L^*$ in the center 30'$\times$30 area We expect our proposed Bok-90Prime with 1 deg^2 will detect $>$ 300 LAEs down to $L \sim L^*$ to fully map the large-scale structure.

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 3-night to observe one field with extremely rare group of large HI absorption and quasars. From our previous experiences (one night in 2013A and Yang et al. 2010), we need a 18-hour *NB403* narrowband integration per field with seeing $< 1.3''$ to reach a Lyα flux level of $F_{Ly\alpha} \sim 4.0 \times 10^{-17}$ erg cm^{-2} s^{-1} ($\rm mag_{AB}$=24.5). For establishing the continuum, we require a $\sim$ 2-hr integration for B broadband to get $\rm mag_{AB}$ $\sim$ 25.5 at 5σ level to meet our color selection criterion $B - NB$ >0.86. Assuming a 20% of time loss due to the overhead and weather, we request a 3-night.

We request dark time, as the narrowband filter *NB403* ($\lambda_c = 4030$ Å, and FWHM=45 Å) 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**)*

This field was selected using a group of Lyα absorption systems and quasars at $z = 2.32 \pm 0.04$, and was first discovered by our KPNO-4m/MOSAIC project in 2013 and 2014.

In 2014A, a 1-night LBT/LBC and 1.5-night LBT/MODS follow-up observations are awarded in 2014A, data successfully taken. The LBG candidates in this field are selected. The LBG overdensity are clearly detected and coincides with LAE density peaks. LAE candidates are selected based on their broadband color (LBT/LBC) and narrowband brightness (KPNO-4m/MOSAIC). 1.5-night LBT/MODS observation was successful. 15 LAEs are targets with two masks, and we successfully confirmed 14 LAEs. Also, we detect redshifts for multiple LBGs 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 Lyα-blob in our overdense field. Two papers are preparing based on this LBT/LBC+ LBT/MODS observations.

The 2015A Bok/90Prime will be a crucial probe for this large scale structure. This proposed Bok observations will fully map the large-scale structure over 100 Mpc associated with this massive structure. The 2015A Bok/90Prime observation proposed here will form the core dataset for Zheng Cai's thesis at Steward. The successful Bok observations could confirm the largest galaxy structures people found to date, and we do not need additional Bok observations in the future for this large-scale structure.

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:

⋆ 2-night on MMT/blue channel on 2013A, only observed for 0.8-night because of the bad weather. Four systems are observed. Two systems of intergalactic Lyα absorptions are confirmed. One paper is prepared (Cai et al. 2014 ready to submit)

⋆ 1.5-night LBT/MODS observations on 2013A, only observed for 2.5-hour on one mask because of the bad weather. Also, the MODS spectrograph suffered some distortion problems (stars are in elliptical shape, even at the center of the CCD, more severe in the edge). The data are shallow.

⋆ A 1-night LBT/LBC was awarded in 2014A, observations successfully. Interesting results are obtained that 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 are clearly detected and coincides with LAE density peaks (Figure 2). 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 are targets with two masks, and we successfully confirmed 14 LAEs. Also, we detect redshifts for multiple LBGs 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 luminous Lyα-blob in our overdense field. Two papers are preparing based on this LBT/LBC+ LBT/MODS observations.