OBSERVING REQUEST
University of Arizona Observatories

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

Probing Lyα Emitters at the Epoch of Cosmic Reionization

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Abstract of Scientific Justification

We propose to use MAG2/M2FS to spectroscopically identify a large sample of Lyα emitter (LAE) candidates at $z \geq 6$ selected in part of the COSMOS field. COSMOS covers $\sim$2 deg^2, and has very deep narrow-band images that allow us to efficiently select LAEs at $z \sim 5.7$, 6.5, and 7.0. We will simultaneously observe many other interesting targets including Lyman-break galaxies (LBGs) at $z \geq 6$. With the proposed observations, we expect to confirm >40 LAEs and >80 LBGs at $z \geq 6$. This is a pilot study for our large joint LAE survey program with Arizona, Carnegie, Chile, and China. When this program completes, we will find more than 300 LAEs and 600 LBGs. We will build the largest, well-defined, fundamental sample of LAEs that consists of more than 500 LAEs at $z \geq 6$ over 4.5 deg^2 in several distinct fields, when previous LAEs samples are included. With this unique sample, we will accurately determine the Lyα luminosity function (LFs) at $z \sim 5.7$ and 6.5, and conclusively confirm the strong evolution of the Lyα LF from $z \sim 5.7$ to 6.5, which provide independent evidence that cosmic reionization ends at $z \sim 6$. We will put the strongest constraints on the Lyα LFs at $z \sim 7.0$ and 7.3. These LAEs also carry crucial information about the reionization history. Such information will be measured from the evolution of the Lyα LFs, from the fraction of LAEs among LBGs, from their extended Lyα emission halos, and from the clustering of LAEs. This unique sample will further be used to study the galaxy formation and evolution at their earliest stage, using their secure redshifts and the wealth of multi-wavelength data from HST, Spitzer, and the largest ground-based telescopes.

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	MAG2	f/11	M2FS			2	grey	Jan–Mar	Jan–Apr	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: Optimal dates are the dates earlier than April 15th, so that our field will be on the sky for 6 hours. In addition, we would like to share nights with others to maximize the usage of the nights (in this case, we would like to request 3 nights, and we will use about 20 hours).

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	the COSMOS field	10h 00m	+02d 10m	Main targets: LAEs and LBGs at $z \geq 6$

Approval for Instrument Use from PI: Instrument PI is also a co-I of the proposal.

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

Scientific Justification

(I) Background: high-redshift galaxies at the epoch of cosmic reionization

In recent years, with the advances of instrumentation on HST and large ground-based telescopes, the number of galaxies found at $z \geq 6$ increased dramatically, and high-redshift galaxies started to play an important role on the study of cosmic reionization (Robertson 2010). The majority of them were photometrically selected Lyman-break galaxies (LBGs) or candidates found by the dropout technique. So far more than one thousand LBGs at $z \geq 6$ have been reported; only a tiny fraction of them have been spectroscopically confirmed (e.g. Stark 2011; Jiang 2011; Finkelstein 2013; Ellis 2013). A complementary way to find $z \geq 6$ galaxies is the narrow-band (or Lyα) technique. This technique has a high success rate of spectroscopic confirmation due to the presence of strong line emission in a short wavelength range. Over 200 Lyα emitters (LAEs) at $z \geq 6$ have been spectroscopically identified[1] (e.g. Hu 2010; Ouchi 2010; Kashikawa 2011).

Individual galaxies are usually too faint to provide useful information about the IGM state during the reionization era. However, such information can be drawn from their statistic properties, such as the evolution of the Lyα luminosity function (LF), and the change of the LAE fraction among LBGs (e.g., Kashikawa 2011; Stark 2011; Treu 2012). For example, recent studies have shown that the Lyα LF evolves rapidly from $z \sim 5.7$ to 6.5 (e.g., Hu 2010; Kashikawa 2011). This was explained by the increasing neutral fraction of the IGM that attenuates Lyα emission via the resonant scattering of Lyα photons. It suggests the end of cosmic reionization at these redshifts, which is consistent with the results from the study of luminous $z \geq 6$ quasars (e.g. Fan 2006). As such, one would expect a further decline of the Lyα LF towards $z > 6.5$.

Now the main concern is the poorly constrained Lyα LFs at $z \sim 5.7$ and 6.5. There is a large discrepancy (up to a factor of 3) among the LFs derived by different groups (Figure 1). The sample of Kashikawa 2011 covers a small area (0.2 deg^2) but goes very deep (26.5 AB mag). The sample of Hu 2010 covers a larger area but goes much shallower. The sample of Ouchi 2010 covers the highest-density region of LAEs in the SXDS, and its LF is biased (Figure 2). So cosmic variance is likely the main reason for the discrepancy mentioned above (private communications with these groups), and a larger, homogeneous sample is the only solution. In addition, the numbers of LAEs known at $z \geq 7$ are very small: 2 at $z \simeq 7.0$ (Iye 2006; Rhoads 2012), and 2 at $z \simeq 7.3$ (Ono 2012; Shibuya 2012). *Therefore, a larger, well defined sample of spectroscopically confirmed LAEs at these redshifts over a wider area is urgently needed.*

(II) The proposed survey of LAEs at $z \geq 6$

We propose to carry out a deep spectroscopic survey of $z \geq 6$ LAEs in the COSMOS field. This is part of our large LAE program, aiming to build a fundamental sample of LAEs at $z \geq 6$, by conducting deep LAE surveys in several distinct fields including SXDS (covers UDS), COSMOS (covers UltraVISTA), GOODS, and SSA22, etc. These fields are chosen to have existing deep optical narrow-band imaging data (as well as broad-band data) taken by Subaru Suprime-Cam. Suprime-Cam has played a major role in searching for high-redshift LAEs. The majority of the currently known LAEs at $z \geq 6$ were discovered by Suprime-Cam (e.g. Hu 2010; Ouchi 2010; Kashikawa 2011). The above fields have deep imaging data in narrow bands NB816 and NB912 (and/or NB921) that go to 25.5–26 AB mag. Some fields also have deep imaging data in the NB973, NB1006 (and/or NB1010). These bands correspond to the detection of LAEs at $z \sim 5.7$, 6.5, 7.0, and 7.3, respectively. More information about the images is provided in the next section. In addition, these are famous fields, covered by lots of ancillary data, including near-IR images from HST.

The proposed observations for 2015A are a pilot program for our large LAE program mentioned above. In this pilot program, we will observe 2–3 pointings in COSMOS with Magellan/M2FS. M2FS has 256 fibers over a 30' FoV, allowing us to include many interesting objects other than our primary objects. Our major secondary targets are LBGs at $z \geq 6$ (i and z band dropouts). This pilot study alone will not only provide us a large sample of spectroscopically confirmed galaxies at $z \geq 6$, but also validate our target selection and observing strategy, and improve our overall efficiency for future observations. Based on this pilot study, our group will conduct the large LAE survey program in future semesters, using Magellan/M2FS (and possibly the MMT/BINOSPEC) through Arizona, Carnegie, Chile, and China (TAP program).

[1] Here we call galaxies found by the narrow-band technique LAEs and those found by the dropout technique LBGs. This is a widely used definition, however, this LAE/LBG classification only reflects the methodology that we employ to select galaxies.

(III) Science enabled by the survey

With the proposed observations, we expect to find >40 LAEs at $z \sim 5.7$ and 6.5, and >80 LBGs at $z \geq 6$. When our large survey program completes, we will find more than 300 LAEs at $z \sim 5.7$ and 6.5, and a few LAEs at $z \sim 7$ and 7.3. This will largely increase (more than double) the number of known LAEs at these redshifts. In addition, we will identify >600 LBGs at $z \geq 6$. Compared to previous LAE samples, our sample will be more homogeneous in terms of target selection and spectroscopic identification; it will have a much higher completeness. We will re-analyze the LAE samples reported by Hu 2010, Ouchi 2010, and Kashikawa 2011. Their LAEs were also selected in Subaru Suprime-Cam images, so we are able to apply the same selection criteria for these samples. This means that the previous LAE samples and our new sample can be calibrated uniformly to make a fundamental sample with more than 500 LAEs at $z \geq 6$. This sample will be used to study the earliest galaxy formation and evolution and cosmic reionization.

We will accurately determine the Lyα LFs at $z \sim 5.7$ and 6.5. The large sample over ~4.5 deg^2 will significantly reduce cosmic variance and improve the measurement of LFs. More importantly, all the imaging data were taken by the same instrument and reduced by our own pipeline, and all the LAE candidates were selected in the same way. Therefore, this sample is well defined, with the minimum uncertainties from systematics. We will solve the discrepancy among the Lyα LFs (at $z \sim 5.7$ and 6.5) derived by different groups, and for the first time, conclusively confirm the strong evolution of the Lyα LF from $z \sim 5.7$ to 6.5. This evolution provides an independent piece of evidence that cosmic reionization ends at $z \sim 6$.

We will put the strongest constraints on the Lyα LFs at $z \sim 7.0$ and 7.3. LAEs at $z \geq 7$ are rare and faint. The current Lyα LFs at $z \sim 7.0$ and 7.3 are constrained by 1–2 LAEs at each redshift. Although larger samples with several photometrically selected LAEs have been reported (Ota 2010; Konno 2014), none of them have been spectroscopically confirmed. On the other hand, the results from these studies suggested a rapid evolution of the Lyα LF from $z \sim 6.5$ to 7 and beyond. We expect to identify 3–5 LAEs at $z \sim 7.0$ and 7.3. This will significantly improve the measurements of the Lyα LFs at the two redshifts, which will confirm the rapid evolution of the Lyα LF from $z \sim 6.5$ towards 7.3.

Our unique sample of LAEs and the derived Lyα LFs will allow us to explore cosmic reionization using several methods. The first one has been mentioned above, i.e., the evolution of the Lyα LF from $z \sim 5.7$ to > 7. The second one is the fraction of objects with strong Lyα emission among LBGs. This fraction is expected to decrease towards higher redshifts ($z \geq 6$), as the neutral IGM fraction gets higher. Such change of the fraction has been found in several small LBG samples (e.g. Stark 2011; Treu 2012; Bian 2014). We expect to identify more than 600 LBGs. This will be the largest uniform sample of LBGs at $z \geq 6$ that can be used to study the fraction of LBGs with strong Lyα emission. We will provide the best constrains on the evolution of this fraction, which will be used to derive the state of the IGM at this redshift.

The third method is to detect Lyα emission halos around LAEs. Because of the resonant scattering of Lyα photons by neutral hydrogen, Lyα emission could form large diffuse Lyα halos around high-redshift galaxies. However, such halos have not been detected by stacking ~ 40 LAEs at $z \sim 5.7$ and ~ 40 LAEs at $z \sim 6.5$ (Jiang 2013). We will likely for the first time detect such halos by stacking > 300 LAEs at $z \sim 5.7$, and > 100 LAEs at $z \sim 6.5$. The size and intensity of the Lyα halos will be used to estimate the density and ionizing state of the IGM. The fourth method is to measure the clustering of LAEs. The IGM is partially ionized (before it is fully ionized) in the reionization process. This patchy reionization will cause additional clustering of LAEs. This additional clustering is believed to be a powerful probe of reionization (e.g. McQuinn 2007; Jensen 2014). However, it has not been detected yet (e.g. Kashikawa 2011), because it requires a large sample with a few hundred of LAEs. We expect to detect this clustering with our large LAE sample. The above results will be directly compared with our cosmological simulations.

Our observations will enable several secondary science objectives other than the discovery of > 600 luminous LBGs. The deep fields are famous fields with a large amount of ancillary data. In particular, these fields are (partly) covered by deep near-IR and mid-IR imaging data, such as UDS, UltraVISTA, HST CANDELS, and Spitzer Warm Mission Exploration programs, etc. For example, the combination of the optical and infrared data allow us to perform SED modeling and derive detailed physical properties of these galaxies, including age, metallicity, stellar mass, star-formation history, etc.

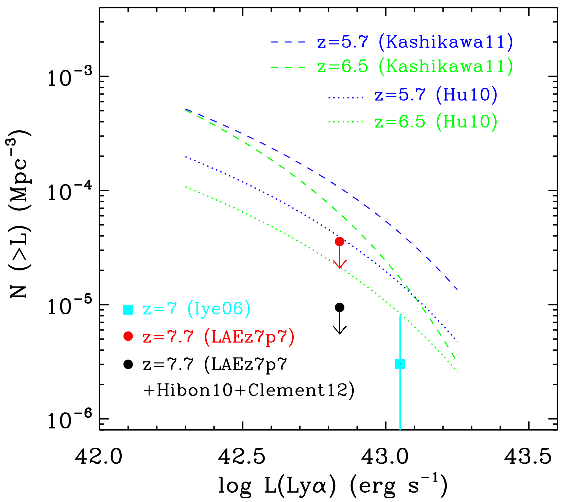

Figure 1: Lyα LF of high-redshift LAEs. The figure shows a strong evolution of the Lyα LF at the bright end from $z \simeq 5.7$ to 7.7. The blue and green lines represent the LFs at $z \simeq 5.7$ and 6.5, respectively (Hu 2010; Kashikawa 2011). There is a large discrepancy between the two studies, mainly due to cosmic variance, and our LAE survey program will solve this issue. The cyan square shows the LF at $z \simeq 7$ derived from one $z = 6.96$ LAE (Iye 2006). Our program will improve the measurement of LF at $z \simeq 7$.

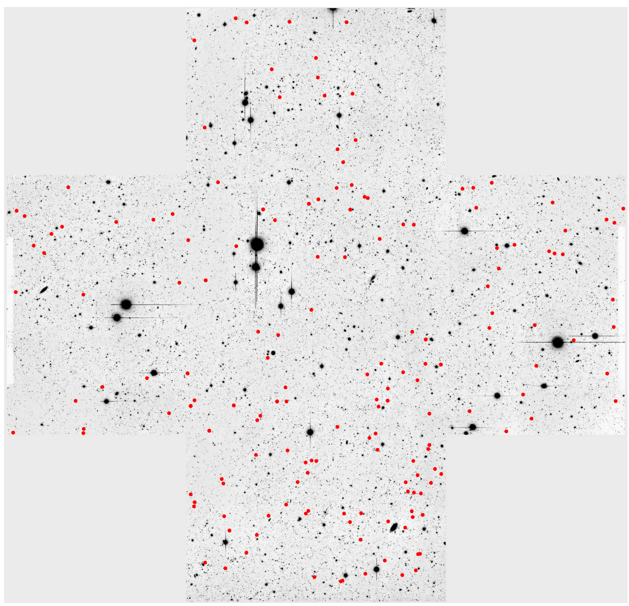

Figure 2: The SXDS field showing uneven distribution of LAEs. The total area is about 1.3 deg^2. The UDS field is in the central. The red circles represent LAE candidates at $z \sim 5.7$. There are significant overdense regions and void regions. Ouchi (2010) only observed the south part of the field, where the LAE density is 5 times higher than the density in the central part. This shows that it is critical to search a much larger area for LAEs to minimize bias from cosmic variance and galaxy clustering. It is the goal of our program.

References

Curtis-Lake, et al. 2012, MNRAS, 422, 1425
Ellis, et al. 2013, ApJL, 763, 7
Fan, et al. 2006, ARAA, 44, 415
Finkelstein, et al. Nature, 502, 524
Hu, et al. 2010, ApJ, 725, 394
Iye, et al. 2006, Nature, 443, 186
Jensen, et al. 2014, arXiv: 1406.1358
Jiang, et al. 2011, ApJ, 743, 65
Jiang, et al. 2013, ApJ, 773, 153
Kashikawa, et al. 2011, ApJ, 734, 119
Kimm, et al. 2014, arXiv:1405.0552
Konno, et al. 2014, arXiv:1404.6066
McQuinn, et al. 2007, MNRAS, 381, 75
Ono, et al. 2012, 744, 83
Ota, et al. 2010, ApJ, 722, 803
Ouchi, et al. 2010, ApJ, 723, 869
Rhoads, et al. 2012, ApJL, 752, 28
Robertson, et al. 2010, Nature, 468, 49
Shibuya, et al. 2012, ApJ, 752, 114
Stark, et al. 2011, ApJ, 728, 2
Treu, et al. 2012, ApJ, 747, 27

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)***

(I) Overall program

As we mentioned earlier, we plan to carry out a deep spectroscopic survey of high-redshift LAEs in several distinct fields, including SXDS, COSMOS, GOODS, SSA22, etc. We expect to find more than 300 new LAEs and 600 new LBGs. We will build the largest, well-defined, fundamental sample of LAEs at $z \geq 6$, which will consist of more than 500 LAEs at $z \sim 5.7$, 6.5, 7.0, and 7.3, when previous LAEs samples are included. This unique sample will allow us to study the galaxy formation and evolution at their earliest stage. These galaxies also carry crucial information about the reionization history.

The proposed observations are a pilot study for the above large survey program. In this pilot study, we will observe 2–3 pointings in COSMOS with Magellan/M2FS. This will not only provide us a sample of spectroscopically confirmed galaxies, but also validate our target selection and observing strategy, and improve our overall efficiency for future observations. This is a joint program with Arizona (Xiaohui Fan, Linhua Jiang), Carnegie (Yue Shen), Chile (Zhenya Zheng), and China (TAP program; Luis Ho). In the next two years, we plan to obtain 3–4 nights from each of the partners.

(II) Imaging data and target selection

As we mentioned in the previous section, our fields all have very deep narrow-band imaging data from Subaru Suprime-Cam that go to ~ 26 AB mag. Suprime-Cam has a large FoV ($27' \times 35'$) and high throughput in the optical. Our fields also have deep broad-band images in the B, V, R (or r), I (or i), z, and Y (or y) bands from Suprime-Cam. The typical depth is 27–28 AB mag (3σ in 2" diameter) in the $BVRI$ bands, and 26–27 AB mag in the z and Y bands. The band coverage and depth slightly vary across the fields. We have reduced Suprime-Cam images for these fields using our own pipeline (Jiang 2013).

The selection of high-redshift LAE and LBG candidates is straightforward, as it has been demonstrated in great details in the literature. Since we have plenty of fibers, we would like to increase completeness by including some less promising candidates. We will use roughly half of the fibers ($\sim$120) for $z \geq 6$ LAEs and LBGs, about ~ 80 fibers for other interesting targets such as lower-redshift (e.g. $z \sim 4.5$, 4.8) LAEs and very faint AGNs, and the rest fibers for sky and alignment/standard stars.

(III Telescope and instrument

We propose to use MAG2/M2FS to spectroscopically identify our targets. M2FS is a PI instrument, and PI is our proposal co-I. In terms of overall throughput, M2FS is comparable to IMACS at $\lambda > 8000$Å. We are purchasing a new pair of gratings for M2FS that are optimized for the wavelength range at > 8000Å, so that the throughput will be increased by up to a factor of two. More importantly, M2FS, with a large FoV, can cover many targets. Fiber conflict can be safely ignored, as the M2FS fibers can be as close as 12" (center to center). In addition, our tests on current M2FS images show that there is very little scattering light (can be properly modeled) and that we can perform very good sky subtraction. We choose to use low-resolution mode ($R \sim 2000$) which is sufficient to identify our galaxies.

Our goal is to achieve 5σ detection for $z = 6.5$ LAE candidates down to NB=26 mag. The on-source integration per pointing is about 6 hours, based on our estimate from our M2FS images. We request two nights to finish 2–3 pointings in COSMOS. The COSMOS field will be on the sky for roughly 6 hours (airmass < 1.6) before April 15. If we can share nights with someone else, we will be able to finish 3 pointings, otherwise we will finish 2 pointings. Our main targets will be at 8200Å and 9200Å, which is not very sensitive to the moon phase. On the other hand, our targets are very faint, so we request dark to grey nights.

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 is a new program to target high-redshift LAE candidates in the COSMOS field. If weather cooperates, we will finish the program with the proposed observations. This is also part of a large joint program with Arizona (Xiaohui Fan, Linhua Jiang), Carnegie (Yue Shen), Chile (Zhenya Zheng), and China (TAP program; Luis Ho). Arizona is leading the program. We plan to request 3–4 nights from each of the partners in the next 2 years. This will complete our large LAE survey program.

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)***

Sep 2012: three nights with the MMT/Red channel. *We lost all the time due to a storm in the end of the monsoon season.*

Sep–Oct 2012: four nights with Bok/90Prime. We lost one night due to bad weather. The rest three nights were used to improve the i and z-band imaging of $z \sim 6$ quasar candidates in the SDSS overlap regions.

Mar–Apr 2013: four nights with Bok/90Prime. We lost one night due to bad weather. Another night was cloudy and was used to improve the i and z band photometry of $z \sim 6$ quasar candidates in the SDSS overlap regions. The rest two nights were used for deep i-band imaging of the UKIDSS DXS fields.

Mar 2013: half night with LBT/LUCI (queue mode). We got 3.5 hour on-source integration for a $z \simeq 7.7$ LAE candidate. A paper based on these data together with the LUCI data taken in 2012 has been published (Jiang, et al. 2013, ApJL, 771, 6).

Apr 2013: half night with LBT/MODS. *AZ lost the whole AZ block due to bad weather.*

Apr 2013: two nights with the MMT/Red channel. The program was used to identify $z \geq 6$ quasar candidates in the UKIDSS DXS fields selected from our Bok data. We met very bad seeing of $2'' \sim 4''$ throughout the run, so we had to observe much brighter backup targets. We confirmed several bright quasars at $z \sim 5$, and two bright quasars at $z \sim 6$ in the SDSS overlap regions.

Jul 2013: two nights with the MMT/SWIRC. *The monsoon season had started, and we did not open the dome.*

Sep 2013: two nights with MAG1/IMACS. *We lost almost the whole run due to bad weather. We only got 2 hour good data.*

Oct 2013: two nights with the MMT/Red channel. The time was used to identify $z \sim 6$ quasars in the SDSS overlap regions. We found three new quasars.

Jan 2014: three nights with Bok/90Prime. The time was used to image the UKIDSS DXS fields.

Feb 2014: three nights with the MMT/Red channel. *We lost all the time due to bad weather.*

Mar–Apr 2014: seven nights with Bok/90Prime. The time was used to improve the i and z band photometry of $z \sim 6$ quasar candidates in the SDSS overlap regions. *A paper based on a total of 7 $z \sim 6$ quasars in the SDSS overlap regions is ready to submit. This paper uses the data taken with Bok and the MMT in the runs mentioned above.*

$\LaTeX\,2_\varepsilon$ UAO Observing Proposal class, 'soprop.cls' v1.3 (2007 Aug 01 [RAJ]).