OBSERVING REQUEST
University of Arizona Observatories

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

Spectroscopic Identification of a Large Sample of Bright Lyman-α Emitter Candidates at $z \simeq 3.7$

P.I.: Eiichi Egami (SO; *eegami@as.arizona.edu*; 520-621-3161)

CoI(s): Fengwu Sun⋆ (Peking University/SO), Linhua Jiang (Peking University)

Abstract of Scientific Justification

In recent years, we have witnessed the growing number of star-forming galaxies known at high redshift. These objects provide clues to the galaxy formation and evolution in early epochs. Despite the progress made so far, current galaxy samples are still limited by small area coverage and the small number of spectroscopic redshifts. Here we propose to use MMT Hectospec to spectroscopically identify a large sample of candidate Lyman-α Emitters (LAEs) at $z \simeq 3.7$ and candidate Lyman-break galaxies (LBGs) at $3.5 < z < 5$, selected in the Subaru-XMM Deep Survey (SXDS) field. SXDS has very deep broad and narrow-band imaging data that allow us to efficiently select high-redshift LAEs and LBGs. With the proposed observations, we expect to confirm more than 100 LAEs and > 50 LBGs. This will be the largest sample of spectroscopically confirmed LAEs at $z \sim 3.7$. The unique sample will be used to measure a variety of galaxy properties. We will derive a robust Lyα luminosity function (LF) at $z \sim 3.7$, and study the evolution of the Lyα LF from $z \sim 2.1$ to ~ 7.0 by comparing to the LFs at other redshifts. The Hectospec spectra will enable us to study the properties of Lyα emission lines, extreme LAEs, and the (anti)correlation between UV continuum and Lyα EW, etc. The stacking of LAE narrow-band images will be used to detect Lyα halos around LAEs that are due to the resonant scattering of Lyα photons, which allows us to study how Lyα photons escape from young galaxies This unique sample will also be used to study galaxy properties such as size, morphology, age, stellar mass, etc., using the secure redshifts and the wealth of multi-wavelength data from HST and Spitzer.

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		Hectospec			1	grey	Oct–Nov	Oct–Dec	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: None.

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	SXDS	02h18m	–05d	$NB570 < 25$

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

(I) Background: high-redshift LAEs

In recent years, the number of star-forming galaxies known at high redshift has grown rapidly, owing to new generation instruments on HST and large ground-based telescopes (see e.g. Stark 2016 ARAA for references). These objects provide critical information for us to understand the formation and evolution of galaxies in the distant universe. Two major methods have been applied to search for high-redshift star-forming galaxies, the Lyman-break technique and the narrow-band (or Lyα) technique (here we define LBGs as galaxies found by the Lyman-break technique, and define LAEs as those found by the narrow-band technique). In particular, the narrow-band technique has been very efficient to find high-redshift galaxies due to its high success rate of spectroscopic confirmation. Several dark atmospheric windows with little OH skylines in the optical are often used to detect distant LAEs at $z \simeq 2.1$, 3.1, 3.7, 4.5, 4.8, 5.7, 6.5, and 7.0. So far a large number of LAE candidates at these redshifts have been reported, and some of them have been spectroscopically confirmed (e.g. Rhoads et al. 2000, 2003; Hu et al. 2002, 2010; Kashikawa et al. 2006, 2011; Gawiser et al. 2007; Ouchi et al. 2008, 2010; Wang et al. 2009; Zheng et al. 2013). All these Lyα surveys were made with ground-based instruments owing to their large field-of-views (FOVs) and relatively low sky-background in OH-dark windows.

Despite the progress that has been made so far, there is a lack of large and homogeneous samples of spectroscopically confirmed LAEs at several redshift slices like $z \sim 3.1$ and 3.7. Existing LAE samples have a few issues. First of all, many of them are photometrically selected galaxies. For example, the largest $z = 3.7$ LAE sample was reported by Ouchi et al. (2008); but only ~ 25 LAEs in that sample have spectroscopic redshifts. Spectroscopic observations not only remove contaminants, but also provide secure redshifts that are important for deriving reliable physical properties. Second, the current spectroscopic samples of LAEs usually cover very small area (order of ~ 100 arcmin^2). Statistical studies are heavily limited by cosmic variance. For example, the normalizations of Lyα LFs at $z \sim 4.5$ can be different by a factor of 3 in two different small fields (Zheng et al. 2013). Finally, current LAE samples at different redshifts were obtained using quite different selection criteria based on different datasets by different research groups, which may introduce large systematical uncertainties. An homogeneous sample selected by a consistent method is critical for studying the cosmic evolution of LAEs.

(II) Proposed observations

We propose to use MMT Hectospec (one pointing) to carry out deep spectroscopic observations to identify a large sample of LAEs at $z \sim 3.7$ selected in the SXDS field. This is part of our large program aiming to build a homogeneous LAE sample at $z \sim 3.1$, 3.7, and 4.8. Our collaborators have obtained a large sample of $z \sim 3.1$ LAEs in SXDS last year (Figure 1). With the proposed observations, we expect to obtain a large sample of $z \sim 3.7$ LAEs in SXDS. We also plan to use one Hectospec night in 2018A to obtain a large sample of $z = 4.8$ LAEs in the COSMOS field. Together with existing samples (or samples from other ongoing programs), we will be able to study the evolution of LAEs from $z \sim 2.1$ up to $z \sim 7.0$.

We want to point out that MMT Hectospec is sensitive enough to detect bright LAEs at $z \sim 3.7$. Hectospec reaches its peak sensitivity at 4500–7200 Å, which corresponds to the detection of LAEs at $z \sim 3-5$ (based on their Lyα emission lines). Last year our collaborators used deep Hectospec observations (8 hours on one pointing) and obtained a sample of more than 100 LAEs at $z \sim 3.1$ down to NB503$\sim$25 AB mag (see details in the next section). This demonstrates that we will be able to detect LAEs at $z = 3.7$ and 4.8 down to a similar depth. It is because of the similar instrument throughput and similar sky background (OH-dark regions) at these wavelengths.

(III) Science enabled by the observations

With the proposed observations, we will obtain a large sample of more than 100 luminous LAEs at $z \simeq 3.7$ over a large area of ~ 0.78 deg^2. This will be the largest spectroscopically confirmed sample at this redshift (the other large sample is from Lee et al. 2014 and Dey et al. 2016 that contains a giant protocluster in the Bootes field). Our sample will be used to study a variety of galaxy properties at $z = 3.7$. First of all, we will measure a robust Lyα LF at $z = 3.7$. Owing to the large number of galaxies in a large field, the uncertainty from cosmic variance is only $\sim 25\%$ (Trenti et al. 2008), significantly smaller than those in previous studies. Note that our sample will be highly complete, because we have 300 fibers that allow us to include less promising candidates (using very relaxed selection criteria). We will then put the $z = 3.7$ Lyα LF in the context of cosmic LAE evolution from $z \sim 7.0$ to ~ 2.1, by incorporating the results at $z \sim 2.1$ and 4.5 from the literature and the results at $z \sim 3.1$, 4.8, 5.7, 6.5, and 7.0 from our collaborators or our future observations.

From the Hectospec spectra, we will measure the Lyα emission line flux and equivalent width (EW), and their distributions. These allow us to study extreme LAEs, the (anti)correlation between continuum and Lyα EW, etc. It is still controversial whether there exist LAEs with very strong Lyα EW (e.g. > 240Å), or what is the fraction of these extreme LAEs. It is also controversial whether there exists an (anti)correlation between UV continuum and Lyα EW (e.g. Shapley et al. Reddy et al. 2008; Nilsson et al. 2009). Our sample will answer these questions for galaxies at $z \sim 3.7$. The Hectospec spectra will simultaneously cover CIV 1549Å and HeII 1640Å emission lines, which can be used to constrain the fraction of AGN in these narrow-band selected targets.

In addition, we will detect Lyα emission halos around LAEs that are due to the resonant scattering of Lyα photons by neutral hydrogen. This is done by stacking a large number of LAEs in narrow-band images. Such halos were first reported by Steidel et al. (2011), but later studies based on photometrically selected LAE samples have shown quite diverse results: either strong halos or non-halos (e.g. Matsuda et al. 2012; Feldmeier et al. 2013). We will likely solve this by stacking more than 100 spectroscopically confirmed LAEs. The size and intensity of the Lyα halos will be used to understand the status of IGM and CGM, and how Lyα photons escape from these young galaxies.

In addition to LAEs, we will include a large sample of bright LBG candidates in our observations (note that we have 300 fibers). We will be able to identify: 1) LBGs with strong Lyα emission lines, and 2) very bright LBGs regardless of their Lyα emission strength. We will measure various properties for any confirmed LBGs, like we do for LAEs above. We will constrain the fraction of LBGs with strong Lyα emission (e.g. Stark et al. 2011). The properties of LAEs and LBGs will be used to answer a very important question, what is the relation between LAEs and LBGs, are they two different populations.

SXDS is (partly) covered by deep near-IR and mid-IR imaging data, such as UDS, HST CANDELS, and Spitzer Warm Mission Exploration programs, etc. The combination of the optical and infrared data allow us to derive various physical properties of the galaxies. For example, from HST images, we can measure galaxy size and morphology. By modeling SEDs of the broad-band photometry, we can derive age, stellar mass, star-formation rate, dust extinction, etc. Note that secure redshifts remove one critical free parameter for SED modeling.

References

Dey, et al. 2016, ApJ, 823, 11
Feldmeier, et al. 2013, 776, 75
Gawiser, et al. 2007, ApJ, 671, 278
Hu, et al. 2002, ApJ, 568, 75
Hu, et al. 2010, ApJ, 725, 394
Kashikawa, et al. 2006, ApJ, 648, 7
Kashikawa, et al. 2011, ApJ, 734, 119
Lee, et al. 2014, ApJ, 796, 126
Matsuda, et al. 2012, MNRAS, 425, 878
Nilsson, et al. 2009, MNRAS, 400, 232
Ouchi, et al. 2008, ApJS, 176, 301
Ouchi, et al. 2010, ApJ, 723, 869
Reddy, et al. 2008, ApJS, 175, 48
Rhoads, et al. 2000, ApJ, 545, 85
Rhoads, et al. 2003, AJ, 125, 10006
Shapley, et al. 2003, ApJ, 588, 65
Stark, et al. 2011, ApJ, 728, 2
Stark, et al. 2015, ARAA, 54, 761
Steidel, et al, 2011, ApJ, 736, 160
Trenti, et al. 2008, ApJ, 676, 767
Wang, et al. 2009, ApJ, 706, 762
Zheng, et al. 2013, MNRAS, 431, 3589

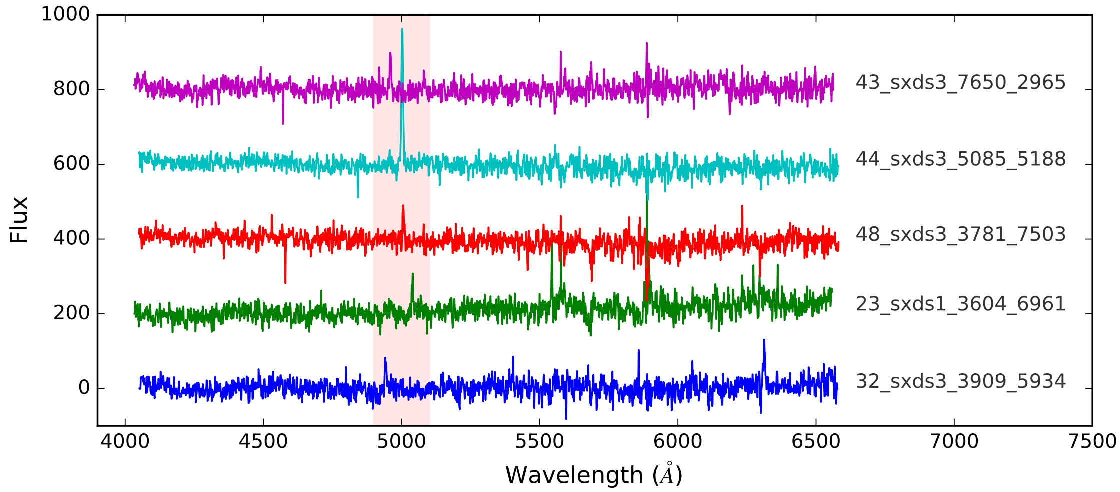

Figure 1: Spectra of five LAEs at $z \sim 3.1$. The spectra were taken using MMT Hectospec by our collaborators last year. The total integration time here is 4 hours. The grating is 600gpm, with a resolution of 2000. The pink shaded region shows the locations of the Lyα emission lines. The brightness of the five LAEs ranges from 23.5 to 25 AB mag in the narrow band. This demonstrates that Hectospec is sensitive to detect LAEs at $z = 3 \sim 4$.

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)***

We propose to use MMT Hectospec to identify a large number of candidate LAEs and LBGs in the SXDS field, SXDS has very deep optical imaging data in a series of broad ($BVRiz$) and narrow (NB503, NB570, NB816, etc.) bands, taken by Subaru Suprime-Cam. The typical depth is 27–28 AB mag (3σ in $2''$ diameter) in the broad bands, and 25–26 AB mag in the narrow bands. The combination of these data allow us to efficiently select candidate LAEs and LBGs.

The selection of high-redshift LAE and LBG candidates is straightforward, as it has been demonstrated in great details in the literature. Basically we use the narrow-band (or Lyα) technique to select LAEs, and the drop-out technique to select LBGs. We have selected about 200 LAE candidates at $z \sim 3.7$ down to NB570=25 mag, and about 100 LBG candidates in the same field. Since we have plenty of fibers, we have included all possible candidates, even less promising candidates (by relaxing selection criteria). Therefore, our final sample will be very complete.

We will use the 600gpm grating with a resolution of 2000, centered at 6300 Å. The resolution is high enough to resolve the [OII] 3727Å doublets, the major contaminants in our LAE sample. The resolution of the 270gpm grating is too low. Based on the results of the LAE sample at $z \sim 3.1$ (Figure 1), with a total of one night integration, we will be able to securely identify our LAE candidates down to NB570=25 mag.

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 stand-alone program. We have not been awarded telescope time from SO before. We request one night here, and we will complete the program with the requested time.

As we mentioned earlier, we also plan to obtain a large sample of LAEs at $z \sim 4.8$ in the COSMOS field. If the proposed observations are successful, we will apply for one Hectospec night in 2018A for $z \sim 4.8$ LAEs.

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**)*

UKIRT/WFCAM 2014B (PI: E. Egami); 140 hours allocated but only 33 hours (24%) of observations were carried out.

UKIRT/WFCAM 2015A (PI: E. Egami); 120 hours allocated but only 46 hours (38%) of observations were carried out.

UKIRT/WFCAM 2015B (PI: E. Egami); 170 hours allocated in total (Priority-1: 80 hours, Priority-2: 90 hours) but only 49 hours (29%) of observations were carried out.

UKIRT/WFCAM 2016A (PI: E. Egami); 160 hours allocated in total (Priority-1: 80 hours, Priority-2: 80 hours) but only 77 hours (48%) of observations were carried out.

UKIRT/WFCAM 2016B (PI: E. Egami); 100 hours allocated in total (Priority-1: 50 hours, Priority-2: 50 hours), but only 17 hours (17%) of observations were carried out.

Status of the Data

UKIRT/WFCAM: All the E-COSMOS data have been fully processed. The E-COSMOS near-infrared source catalog was combined with the HSC-Wide optical catalog to produce a sample of massive high-redshift galaxy candidates. The availability of these images/catalogs as well as the procedure to join the HSC collaboration was presented to the Steward community on March 28, 2017 at the meeting organized by E. Egami.

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**)*

CoI. Mr. Fengwu Sun is an astronomy undergraduate student at Peking University, and will stay at Steward from spring to summer of 2017 as a participant of the Steward–Peking University student exchange program. E. Egami is Mr. Sun's research supervisor during his visit, and this proposal is submitted as part of the proposed collaborative research project between Mr. Sun and E. Egami. If the proposal is accepted, Mr. Sun will work on the target selection and Hectospec fiber configurations for this program during his visit. He is also expected to work with the data once they are obtained.