

**OBSERVING REQUEST**  
**University of Arizona Observatories**

**Year:** 2017

**Term:** Jul–Dec

**Proposal type:** short-term

## Using Polarization to Reveal the Nature of Ly $\alpha$ Nebulae

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Myung Gyoon Lee (SNU)

### Abstract of Scientific Justification

Ly $\alpha$  “blobs” are mysterious, giant ( $\sim 100$  kpc), glowing gas clouds in the distant universe. We discovered that they occupy halos that evolve into galaxy clusters today. The blobs’ gas may be the proto-intracluster medium and their embedded galaxies the progenitors of massive cluster galaxies. Yet we do not know why Ly $\alpha$  blobs glow. Our kinematic measurements were the first to exclude shocks and winds from AGN or starbursts as power sources (Yang et al. 2014), suggesting that photoionizing radiation or resonant scattering of Ly $\alpha$  photons might be responsible. To differentiate between these two possibilities requires polarization mapping, as resonant scattering should lead to large polarization gradients, while photoionization should not produce any polarization. However, with MMT+SPOL, we detect strong polarization (up to 17%) in the Ly $\alpha$  nebula about the radio galaxy B3 J2330+3927, where photoionization was believed to dominate (You et al. 2017). Our preliminary maps of three other blobs of different classes—radio-quiet, radio-loud, AGN-less—are generally consistent with scattering, but their polarization morphologies and gradients vary widely, motivating a larger, more representative survey. Recently, we were awarded a NRF funding to upgrade SPOL’s blue band sensitivity, making numerous lower redshift Ly $\alpha$  blobs accessible for the first time. Here we wish to target an enormous Ly $\alpha$  nebula that we recently discovered at  $z = 2.0$ , which surrounds an ultraluminous QSO. This observation and those for which we will propose in the following cycle will allow us to construct a statistically-meaningful sample to test the consistency of polarization properties among blobs, particularly among those of a single class.

### Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling		Sharing	
								Optimal	Acceptable	Poss.	Adv.
1	MMT	f/9	SPOL	*		2	dark	Dec	Dec	yes	yes

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

If at all possible, block scheduling of this proposal with other successful MMT SPOL proposals is best to avoid excessive transport of the instrument away from its commitments at other telescopes.

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	Jackpot Nebula	08:41:58.470	+39:21:21.00	z=2.046

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**Approval for Instrument Use from PI:** The PI of MMT/SPOL (Paul Smith) is a Co-I of this proposal.

**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
Eunchong Kim	M. G. Lee, Y. Yang		no	yes

## Scientific Justification

**The Puzzling Nature of Ly $\alpha$  Blobs.** Ly $\alpha$  nebulae (aka “Ly $\alpha$  blobs” or LABs) are rare, extended sources at  $z = 2\text{--}6$  with typical Ly $\alpha$  sizes of  $10''$  ( $\sim 100$  kpc) and line luminosities of  $L_{\text{Ly}\alpha} \sim 10^{44}$  erg s $^{-1}$  (e.g., Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Dey et al. 2005; Yang et al. 2009, 2010). They lie in overdense regions of compact, Ly $\alpha$ -emitting galaxies and generally have multiple, embedded sources (Matsuda et al. 2004, Yang et al. 2010, Prescott et al. 2008, 2012). With a blind survey of Ly $\alpha$  blobs and a statistical comparison to a large volume cosmological simulation (Yang et al. 2009, 2010), we discovered that Ly $\alpha$  blobs occupy halos that evolve into those of the richest groups and clusters today. Their embedded galaxies likely merge to form brightest cluster galaxies at  $z \sim 0$ . The Ly $\alpha$ -emitting gas may represent the proto-intracluster medium. Determining the source of the blobs’ Ly $\alpha$  emission is therefore essential to understanding the evolution of large-scale structure and the most massive galaxies.

*What causes these nebulae to glow?* Proposed power sources include superwind outflows driven by embedded AGN or starburst galaxies (Taniguchi & Shioya 2000), as well as cold gas accretion along the filaments (Goerdt et al. 2009). However, our observations with Magellan/MagE, VLT/SINFONI (Yang et al. 2011) and VLT/X-shooter (Yang et al. 2014b) detect only modest outflows ( $< 200$  km s $^{-1}$ ), and no inflows, implying that neither strong winds nor cold gas accretion is the source of Ly $\alpha$  emission. Another possibility is that photoionization by an AGN leads to recombination throughout the nebula (Haiman & Rees et al. 2001). Yet, in our detailed study of eight blobs (Yang et al. 2014b), we found that only two contain a hard ionizing source that could photoionize the surrounding gas, consistent with the low overall fraction of blobs with embedded or nearby AGN (17%; Geach et al. 2009). Another mechanism that could produce the extended Ly $\alpha$  emission is the resonant scattering of Ly $\alpha$  photons produced by central AGN or star-forming galaxies (Hayes et al. 2011; Geach et al. 2016).

To differentiate between the two latter possibilities requires polarization mapping of the extended Ly $\alpha$  emission, as resonant scattering should lead to large polarization gradients, while the photoionization model produces no polarization. However, our results from our successful MMT+SPOL survey (You et al. 2017; E. Kim et al. in prep.) are varied; blobs with or without AGN, and that are radio-loud or radio-quiet, all have polarization maps roughly consistent with resonant scattering, but with different polarization morphologies, gradients and overall degree of polarization. Because of the limited blue sensitivity of SPOL, we have been able to cover so far only a handful of cases at  $z \gtrsim 2.6$ , which are not enough to draw a firm conclusion.

**Recently, we were awarded a NRF funding to upgrade SPOL’s blue band sensitivity, making the numerous lower redshift (and thus brighter) Ly $\alpha$  blobs accessible for the first time.** As a result, a large, statistically-meaningful and representative survey of Ly $\alpha$  blob polarization is now possible with the planned upgrades. Thus, we propose to extend our survey to include a newly discovered enormous bright Ly $\alpha$  nebula (Hennawi et al. 2015) that is associated with an ultraluminous QSO quartet system.

**Polarimetry: A New Angle on the Problem.** Polarimetric observations can discriminate between photoionization and resonant scattering. If embedded sources photoionize the entire nebula, then hydrogen recombination leads to the production of Ly $\alpha$  photons at points throughout the cloud. These *in-situ* produced Ly $\alpha$  photons are not resonantly scattered and have no preferential orientation with respect to the neutral medium and the observers, thus the nebula’s Ly $\alpha$  emission will be only slightly polarized, if at all. On the other hand, if there is only photoionization and recombination close to an embedded source, the Ly $\alpha$  photons will be scattered by the nebula, sometimes into our sightline (Figure 1). Then the escaping Ly $\alpha$  emission will be polarized, and the polarization strength will increase with the projected distance from the embedded source because photons at larger radii scatter by larger angles (closer to  $90^\circ$ ) toward the observer.

**Steward–KASI Polarimetric Survey of Giant Ly $\alpha$  Nebulae; Diverse Polarization Patterns.** Polarimetry of low surface brightness nebulae is notoriously difficult; the robust measurement of spatially extended emission at a fraction of the sky background requires careful and accurate calibration using an instrument that imparts little to no polarization signature on the data. Nevertheless, the unique capabilities of MMT/SPOL have made it possible to carry out the first polarimetric survey of giant Ly $\alpha$  nebulae with various AGN, radio, and host galaxy properties. We have now measured polarization around four Ly $\alpha$  blobs; one with a radio galaxy (B3 J2330+3927; Figure 2; You et al. 2017), one with no radio source or known AGN (FLS-LAB1), one with a radio-loud QSO (SSA22-Sb3-LAB1), and one with a radio-quiet obscured AGN

(LABd05; Figure 2; E. Kim et al. in prep.).

The key results from our on-going survey so far are (1) the diversity of polarization patterns and the wide range of the polarization degree of entire nebulae ( $P_{\text{tot}}$ ) even among the small sample and (2) the ubiquitous detection of significant polarizations among all sample.

Unlike the *concentric pattern* found in SSA22-LAB1 (Hayes et al. 2011), B3 J2330+3927 shows a *cylindrical pattern* aligned with the radio-jet direction such that significant polarization is detected only along the blob's major axis and at angles perpendicular to that axis, with the polarization fraction increasing at larger radii from the blob center. LABd05's polarization map is more or less *patchy*: the polarizations were detected only at the SE part of its Ly $\alpha$  peak and all perpendicular to that direction. Among these three objects, the total polarization degrees also vary significantly: nearly unpolarized ( $1.9\% \pm 0.9\%$  for  $8''$  diameter) in B3 J2330+3927,  $P_{\text{tot}} \sim 3.8\%$  in LABd05, to highest degree of 12% in SSA22-LAB1. Note that even though significant polarization up to  $\sim 17\%$  is detected locally within B3 J2330+3927, the total polarization can be very low, demonstrating that spatially resolved imaging polarimetry is essential to probe the polarization properties of the nebula.

For the blob that extends around the radio galaxy B3 J2330+3927, at first we expected that strong UV radiation from the AGN accretion disk would photoionize much of the surrounding gas and thus to detect little or no polarization. However, we observed high polarization strengths (up to  $\sim 17\%$ ) and a polarization gradient roughly consistent with the model in which Ly $\alpha$  photons produced by the central AGN are resonantly scattered (You et al. 2017). Furthermore, we also detected  $\sim 13\%$  of polarization from LABd05 where an obscured AGN is ionizing the surrounding gas cloud. Therefore, it appears that the resonant scattering plays crucial role in producing the Ly $\alpha$  halos even in the systems where the photoionization is clearly present. In order to understand the relative contribution of the two mechanisms and ultimately to constrain the physical conditions of the Ly $\alpha$ -emitting gas (e.g., ionization state, optical depth), state-of-the-art radiative transfer and polarization modeling of these systems are essential. Currently, we are working with RT experts: Prof. Mark Dijkstra at U Oslo and Prof. Hee-Won Lee at Sejong University.

**The Plan: Targeting Bright, Lower-Redshift Ly $\alpha$  Blobs with an Upgraded SPOL.** Our current sample suggests some similarities in polarization among blobs with radio-quiet, radio-loud, and non-AGN embedded sources, but there are also differences. We do not know how typical these results are, as our blob sample is too small to be representative. Furthermore, we are unable to draw statistically-meaningful conclusions about the consistency of polarization properties among blobs of a *single* class. For example, do all radio-galaxies exhibit cylindrical patterns around their radio-jet? Therefore, we are using the SPOL upgrade funding to replace the current off-the-shelf Nikkor lens with a blue-sensitive counterpart and to increase the instrument's field-of-view. These changes will allow us to target blobs at lower redshifts ( $1.7 < z < 2.5$ ), where the majority of the  $\sim 30$  known (and all the brightest) blobs reside. Thus, in this cycle, we propose to target an enormous blob known as Jackpot nebula that we recently discovered at  $z = 2.0$  (Hennawi et al. 2015); it lies in a massive overdensity around four QSOs and AGNs. Next semester, we will propose for a bright blob (MAMMOTH-1) with an obscured AGN (Cai et al. 2017) to complete the extended survey. These newly discovered Ly $\alpha$  nebulae are among the biggest (300–500 kpc) and most Ly $\alpha$  luminous ( $2 - 14 \times 10^{44} \text{ erg s}^{-1}$ ) blobs ever found, allowing us to map their polarization properties very efficiently. These observations will conclude our first polarimetric survey of high-redshift giant Ly $\alpha$  nebulae.

**References** • Dey, A., et al. 2005, ApJ, 629, 654 • Dijkstra, M., Haiman, Z., & Spaans, M. 2006, ApJ, 649, 37 • Dijkstra, M., & Loeb, A. 2009, arXiv:0902.2999 • Fardal, M. A., et al. 2001, ApJ, 562, 605 • Francis, P. J., et al. 2001, ApJ, 554, 1001 • Geach, J. E., et al. 2009, ApJ, 700, 1 • Geach, J. E., et al. 2016, arXiv:1608.02941 • Haiman, Z., & Rees, M. J. 2001, ApJ, 556, 87 • Hayes, M., Scarlata, C., & Siana, B. 2011, Nature, 476, 304 • Hennawi, J. F. et al. 2015, Science, 348, 779 • Keel, W. C., et al. 1999, AJ, 118, 2547 • Matsuda, Y., et al. 2009, MNRAS, 400, L66 • Matsuda, Y., et al. 2006, ApJ, 640, L123 • Matsuda, Y., et al. 2011, MNRAS, 410, L13 • Prescott, M.K.M. et al. 2011, ApJ, 730, L25 • Prescott, M.K.M. et al. 2012, ApJ, 752, 86 • Bower, R., Nature 476, 288289 (18 August 2011) • Steidel, C. C., et al. 2000, ApJ, 532, 170 • Steidel, C. C., et al. 2011, ApJ, 736, 160 • Taniguchi, Y. & Shioya, Y. 2000, ApJ, 532, L13 • Yang, Y., et al. 2009, ApJ, 693, 1579 • Yang, Y., et al. 2010, ApJ, 719, 1654 • Yang, Y., et al. 2011, ApJ, 735, 87 • Yang, Y., et al. 2014, ApJ, 793, 114

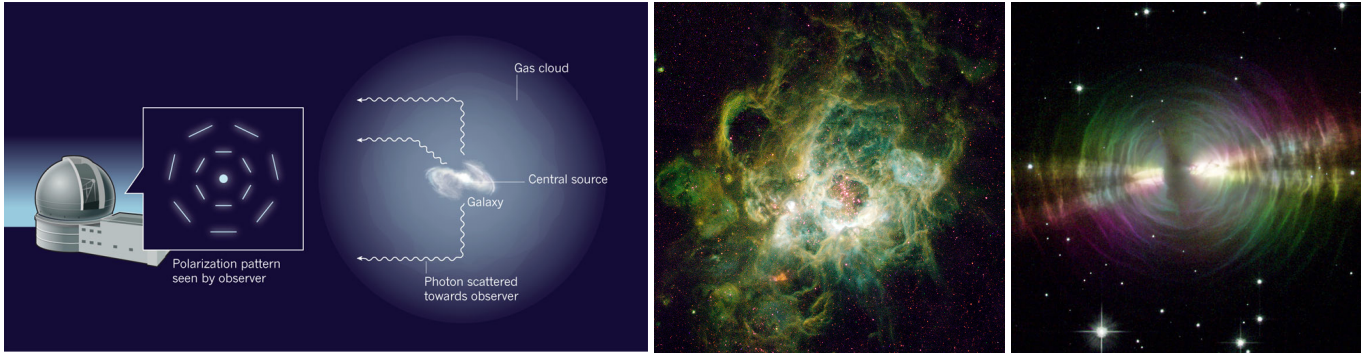


Figure 1: **(Left)** Illustration for  $\text{Ly}\alpha$  imaging polarimetric observation.  $\text{Ly}\alpha$  photons produced by an embedded source (in this picture, the galaxy) are resonantly scattered in the surrounding gas cloud. The photons observed furthest from the source have scattered perpendicular to their initial direction and are strongly polarized. The observers will see a polarization pattern of concentric rings centered on the source (Dijkstra & Loeb et al. 2008, image credit: R. Bower 2011). In other words, polarimetric mapping tell us where the observed  $\text{Ly}\alpha$  photons originated. **(Middle and Right)** Two images suggesting two possible causes of extended  $\text{Ly}\alpha$  emission in blobs: photoionizing radiation from intensely star forming regions (represented by the HII region in the middle panel) and resonant scattering (represented by dust-scattered emission from the Egg Nebula in right panel). Note that, as outlined in the left panel, scattering should produce coherent, concentric rings of polarization, which increase in strength with radius.

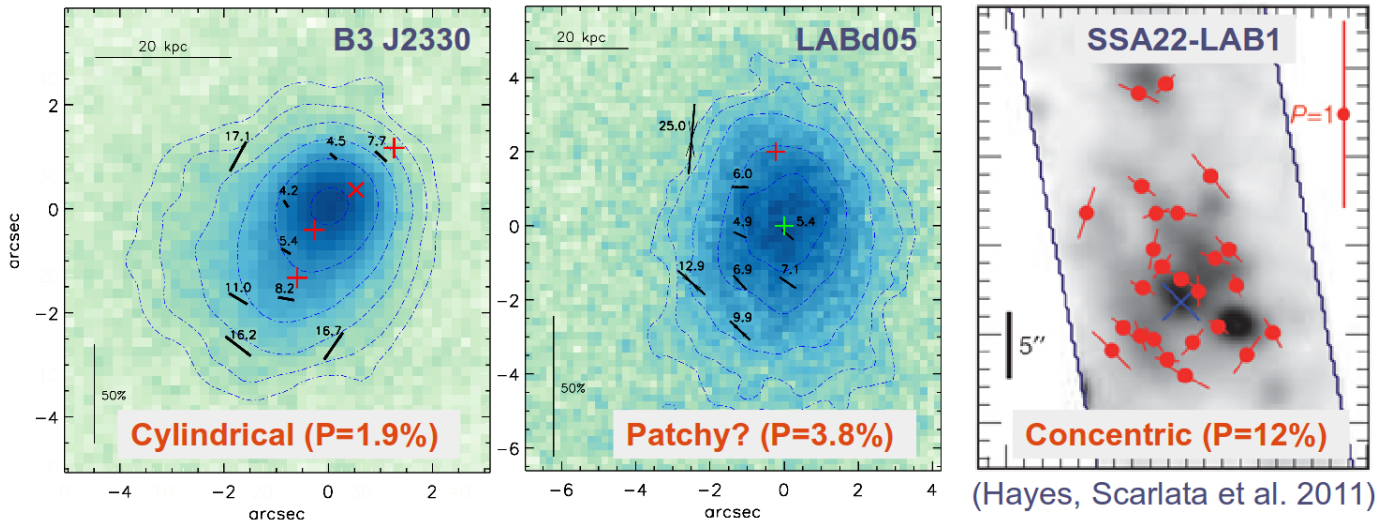


Figure 2: **Diverse Polarization Patterns in  $\text{Ly}\alpha$  Nebulae.** **(Left)** MMT/SPOL Polarization measurements of the radio galaxy, B3 J2330+3927 (You et al. 2017). The  $>2\sigma$  polarization detections measured are shown as black vectors. The length and direction of the vector represents the polarization fraction and direction, respectively. Significant polarizations are detected only along the blob's major axis (also the radio lobe axis) and have angles perpendicular to that axis, with the polarization strength increasing with radius from the center. **(Middle)** Preliminary  $\text{Ly}\alpha$  polarization map for the LABd05, the radio-quiet blob with an obscured AGN (E. Kim et al. in prep.). The red and green crosses represent the location of the known obscured AGN and the  $\text{Ly}\alpha$  peak, respectively. Polarization patterns are patchy: only detected at the SE of the  $\text{Ly}\alpha$  peak. **(Right)** Concentric polarization pattern in SSA22-LAB1 (Hayes et al. 2011). The proposed extension of our polarimetric survey to lower redshift, brighter  $\text{Ly}\alpha$  nebulae will allow us to isolate the importance of photoionization versus scattering by increasing our sample size to include several blobs of each radio, AGN, and host galaxy class (Table 1).

**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)*

With MMT/SPOL, we propose to obtain a polarization map for the newly discovered Jackpot nebula, which has the highest diffuse Ly $\alpha$  luminosity to date (Hennawi et al. 2015). We will use SPOL in imaging mode with a narrow band filter for our targets. The required narrowband filter (3700/110) will be borrowed from CTIO or purchased depending on the schedule.

We estimate the observing times based on our previous experience with MMT/SPOL assuming that after the planned SPOL upgrade (See “Other Information” section), the throughput at 4000Å would be as good as the current sensitivity at  $\sim 5000\text{\AA}$ . During our MMT/SPOL run in September 2012, we obtained the first polarization map of the extended Ly $\alpha$  emission around the radio galaxy B3 2330+3927, which has  $\sim 2\times$  lower surface brightness than Jackpot. With  $\sim 12$  hours of science exposure time and  $\sim 2$  hours of calibrations + overhead, we were able to measure the polarization down to  $\sim 3\%$  ( $2\sigma$ ) over most of the Ly $\alpha$  nebula (Fig. 2). In the case of the Jackpot nebula, we will need at least two pointings to cover the enormous spatial extent (250 kpc;  $\sim 30''$ ). Therefore, we expect to obtain polarization map for the nebula within the same amount of observing time. Since Ly $\alpha$  blobs are faint, low surface brightness objects, the high efficiency of SPOL and the large aperture of the MMT are essential for detecting polarization and constraining its geometry.

Calibrations are critical for the reliable measurement of polarization angle and strength. We will observe polarization standards to calibrate the polarization position angle (to get an absolute PA on the sky) and unpolarized standards to verify the very low ( $< 0.1\%$ ) instrumental polarization that is one of SPOL’s major advantages. Calibration through a Nicol prism (internal to the instrument) will determine the efficiency of SPOL’s semi-achromatic waveplate in the filter bandpass. These necessary on-sky calibrations will take an hour per night. Therefore, we request 2 dark nights for the Jackpot nebula.

Table 1: Survey Plan: Blobs with Existing or Proposed Ly $\alpha$  Polarization Measurements

Name	Radio-jet?	AGN?	Reference
SSA22-LAB1	radio-quiet	unknown	Hayes et al. (2011), <b>Fig. 2</b>
B3 J2330+3927 4C41.17	radio-loud radio-loud	radio galaxy radio galaxy	MMT/SPOL (C. You et al. 2017; <b>Fig. 2</b> ) MMT/SPOL (E. Kim et al., in prep.)
LABd05 FLS-LAB1 MAMMOTH-1	radio-quiet radio-quiet radio-quiet	obscured AGN cold-accretion? obscured AGN	MMT/SPOL (E. Kim et al., in prep., <b>Fig. 2</b> ) MMT/SPOL (E. Kim et al., in prep.) to be proposed in 2018A
SSA22-Sb3-LAB1 Jackpot Nebula	radio-loud radio-quiet	QSO QSO + 3 AGNs	MMT/SPOL (E. Kim et al., in prep.) MMT/SPOL ( <b>this proposal</b> )

Note: Most of these nebulae have a dominant AGN source, but they also contain multiple small (sub- $L_*$ ) galaxies within them.

**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 are carrying out the first systematic polarimetric survey of the brightest Ly $\alpha$  nebulae with various radio, AGN, and host galaxy properties. Our work will lead to a better understanding of the relative roles of resonant scattering and photo-ionization in producing the extended Ly $\alpha$  halos not only in giant Ly $\alpha$  nebulae but also in fainter Ly $\alpha$  halos around high- $z$  star-forming galaxies. So far, we have invested  $\sim 10$  MMT nights through the University of Arizona over five years (2012B – 2016B semesters, PI: Chang You, Ann Zabludoff), and two nights through K-GMT Science Program. Table 1 summarizes the status and plan of our imaging survey. As shown in Fig. 2, we successfully measured the polarization of the extended gas around the radio galaxy B3 J2330+3927 and published the first paper of the series (You et al. 2017). Preliminary analysis of the radio-quiet, AGN-less blob (FLS-LAB1), the radio-loud blob (SSA22-Sb3-LAB1), and the blob associated with an obscured AGN (LABd05; E. Kim et al. in prep.) also reveals a significant degree of polarization. Given our upgrade of SPOL for better blue sensitivity (see the “Other Information” section), we request to continue this survey by targeting a newly discovered, luminous Ly $\alpha$  blob (Jackpot nebula) associated with a QSO quartet.

Given that the time investments are significant due to the low surface brightness of these nebulae, we are also seeking MMT time through the University of Arizona. We request two dark nights here. However, the award of a partial time would be still beneficial thanks to our joint effort between two institutions to lead this large survey program.

<b>Previous Use of Steward Facilities</b>
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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**)

★ **Using Polarization to Reveal the Nature of Ly $\alpha$  Nebulae.** (2016A, 1 nights)

*Eunchong Kim, Yujin Yang, Ann Zabludoff, Paul Smith, Buell Jannuzi, Myung Gyoong Lee*

We were also awarded one additional night through the Arizona TAC. We obtained data for the Ly $\alpha$  blob with a radio-quiet AGN (LABd05) while a half night was lost due to high humidity and storms. Data reduction and analysis is being led by Eunchong Kim (see Figure 2).

★ **Using Polarization to Reveal the Nature of Ly $\alpha$  Nebulae.** (2016B, 1 nights)

*Eunchong Kim, Yujin Yang, Ann Zabludoff, Paul Smith, Buell Jannuzi, Myung Gyoong Lee*

We were also awarded two additional nights through the Arizona TAC. We obtained data for two Ly $\alpha$  blobs (SSA22-Sb3-LAB1 and 4C41.17) associated with a radio-loud QSO and a radio-galaxy while one night was lost due to a storm. Data reduction and analysis is being led by Eunchong Kim.

<b>Other Information</b>
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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**)

**Upgrade Plans for SPOL.** MMT+SPOL is an exquisite spectro/imaging polarimeter with a minimal ( $<0.1\%$ ) instrumental polarization. However, its sensitivity below  $\sim 4500\text{\AA}$  is relatively poor, preventing high S/N polarization measurements of Ly $\alpha$  emission from sources at  $z < 2.7$ . To gain the access to these, we are upgrading SPOL in collaboration with the University of Arizona using the support from the PI's National Research Foundation (NRF) grant. We are (1) replacing the current f/1.2 camera lens with a custom-made blue sensitive one, thereby improving the blue throughput by a factor of 5–10, (2) adding an additional aperture to increase the imaging FOV by  $\sim 50\%$ , and (3) purchasing more narrowband filters. These modifications will be completed by the summer 2017 and will allow us to map the polarization of largest and most luminous Ly $\alpha$  blobs at  $z \sim 2$  for the first time. To address previous TAC's concerns about the performance of the new camera lens, we will commission the lens with SPOL at the Bok-2.3m or Kuiper 61-inch telescopes prior to our MMT run. These engineering times will be allocated through the University of Arizona. The optical and opto-mechanical designs of the lens have been completed in KASI Space Astronomy Group, and the lens is currently being manufactured at Genesia in Japan.