OBSERVING REQUEST
University of Arizona Observatories

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

Using Polarization to Reveal the Nature of Lyα Nebulae

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Abstract of Scientific Justification

Lyα "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 Lyα 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 Lyα 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 Lyα 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. **KASI has recently awarded us funding to upgrade SPOL's blue band sensitivity and to enlargen its field-of-view, making numerous lower redshift Lyα blobs accessible for the first time.** Here we wish to target a newly discovered enormous bright Lyα nebula at $z = 2.0$ (Hennawi et al. 2015) that is associated with an ultraluminous QSO quartet system. 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 Optimal	Scheduling Acceptable	Sharing Poss.	Sharing 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	SDSSJ0841+3921	08:41:58.470	+39:21:21.00	z=2.046
2	(Jackpot Nebula)			

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
			no	no

Scientific Justification

The Puzzling Nature of Lyα Blobs. Lyα nebulae (aka "Lyα blobs" or LABs) are rare, extended sources at z = 2–6 with typical Lyα sizes of 10$''$ ($\sim$100 kpc) and line luminosities of $L_{\rm Ly\alpha} \sim 10^{44}$ 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, Lyα-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 Lyα blobs and a statistical comparison to a large volume cosmological simulation (Yang et al. 2009, 2010), we discovered that Lyα 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 Lyα-emitting gas may represent the proto-intracluster medium. Determining the source of the blobs' Lyα 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 ($< 200\,{\rm km\,s^{-1}}$), and no inflows, implying that neither strong winds nor cold gas accretion is the source of Lyα 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 Lyα emission is the resonant scattering of Lyα 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 Lyα 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 so far to target only a handful of blobs at $z \gtrsim 2.6$, limiting our ability to draw statistically-meaningful conclusions. **KASI has recently awarded us funding to upgrade SPOL's blue band sensitivity and enlargen its field-of-view, making the numerous lower redshift (and thus brighter) Lyα blobs accessible for the first time.** As a result, a large and representative survey of Lyα blob polarization is now possible. Thus, we propose to extend our survey to include a newly discovered enormous bright Lyα nebula at $z = 2.0$ (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 Lyα photons at points throughout the cloud. These *in-situ* produced Lyα photons are not resonantly scattered and have no preferential orientation with respect to the neutral medium and the observers, thus the nebula's Lyα 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 Lyα photons will be scattered by the nebula, sometimes into our sightline (Figure 1). Then the escaping Lyα 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°) toward the observer.

The Steward–KASI Polarimetric Survey of Giant Lyα 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 Lyα nebulae with various AGN, radio, and host galaxy properties. We have now measured polarization around four Lyα 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.).

Despite having a small sample so far, our key results are 1) the ubiquitous detection of significant polarization fraction ($P_{\rm tot}$), 2) the wide range in $P_{\rm tot}$, and 3) the diversity of polarization patterns (Figure 2).

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 *patchy*; significant polarization is detected only to the southeast of its Lyα peak, with all the vectors perpendicular to that direction. Among these three objects, $P_{\rm tot}$ also varies significantly, from nearly unpolarized (1.9%±0.9% within a 8$''$ diameter aperture) in B3 J2330+3927 to $\sim$4% in LABd05 to $\sim$12% in SSA22-LAB1. Note that even though 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, we expected that strong UV radiation from the AGN accretion disk would photoionize much of the surrounding gas and thus produce little or no polarization. Instead we observed high local polarization fractions (up to $\sim$17%) within the nebula. Furthermore, the polarization gradient is roughly consistent with a model in which Lyα photons produced by the central AGN are resonantly scattered (You et al. 2017). Now we have detected up to $\sim$13% local polarization fractions in LABd05, where an obscured AGN is ionizing the surrounding gas cloud. Therefore, it appears that the resonant scattering plays crucial role in producing Lyα halos even where photoionization is clearly present. To understand the relative contribution of the two mechanisms and ultimately constrain the physical conditions of the Lyα-emitting gas (e.g., ionization state, optical depth), state-of-the-art radiative transfer (RT) 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, Korea.

The Plan: Targeting Bright, Lower-Redshift Lyα 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 the Jackpot nebula at $z = 2.0$ (Hennawi et al. 2015), which lies in a massive overdensity around four QSOs. Next semester, we will propose to observe the bright blob (MAMMOTH-1) that has an obscured AGN (Cai et al. 2017) and that we discovered last year. These newly discovered Lyα nebulae are among the biggest (300–500 kpc) and most Lyα luminous ($2 - 14 \times 10^{44}$ erg s^{-1}) blobs ever found, allowing us to map their polarization properties very efficiently. These observations will complete the first polarimetric survey of high-redshift, giant Lyα 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

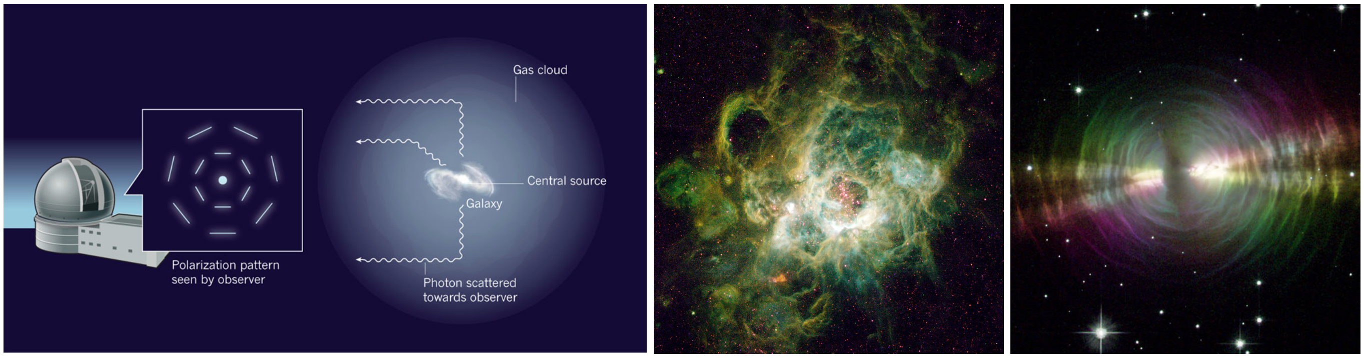

Figure 1: **(Left)** Illustration for Lyα imaging polarimetric observation. Lyα photons produced by an embedded source (in this picture, the galaxy) are resonantly scattered in the surrounding gas cloud. The photons observed furthest from the source have scattered perpendicular to their initial direction 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 Lyα photons originated. **(Middle and Right)** Two images suggesting two possible causes of extended Lyα 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.

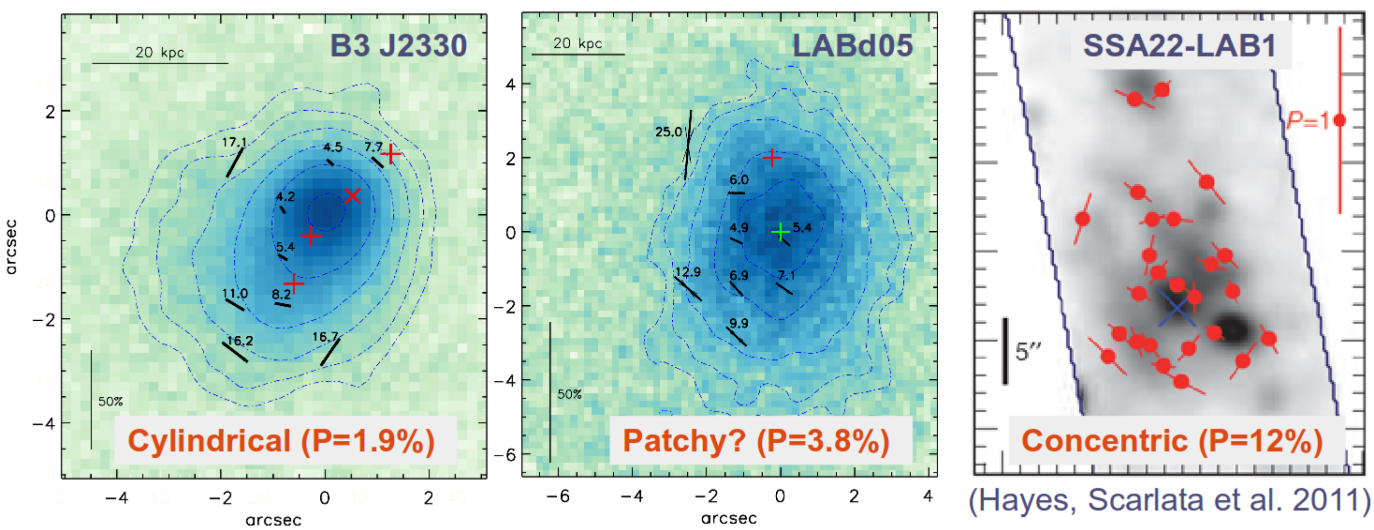

Figure 2: **Diverse Polarization Patterns in Lyα Nebulae. (Left)** MMT/SPOL Polarization measurements of the radio galaxy, B3 J2330+3927 (You et al. 2017). The $>2\sigma$ polarization detections measured are shown as black vectors. The length and direction of the vector represents the polarization fraction 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 Lyα 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 Lyα peak, respectively. The polarization pattern is patchy, the detections lie only to the southeast of the Lyα peak. **(Right)** Concentric polarization pattern in SSA22-LAB1 (Hayes et al. 2011). The proposed extension of our polarimetric survey to lower redshift, brighter Lyα 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 Lyα 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.

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 ∼5000Å. During our MMT/SPOL run in September 2012, we obtained the first polarization map of the extended Lyα emission around the radio galaxy B3 2330+3927, which has $\sim 2\times$ lower surface brightness than Jackpot. With ∼12 hours of science exposure time and ∼2 hours of calibrations + overhead, we were able to measure the polarization down to ∼3% (2σ) over most of the Lyα 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 Lyα 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 Lyα Polarization Measurements

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

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 Lyα 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 Lyα halos not only in giant Lyα nebulae but also in fainter Lyα halos around high-z star-forming galaxies. So far, we have been awarded 15 nights with the MMT (5.5 nights were weathered out and two are scheduled in June). 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 Lyα blob (Jackpot nebula) associated with a QSO quartet.

Given that the time investments are significant due to the low surface brightness of these nebulae and that our target sample is large, we are also seeking MMT time through KASI, where Y. Yang, a Steward Ph.D. recipient and former student of the PI, is on the faculty.

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**)*

- $\star$ **Using Polarization to Discover the Nature of Lyα Nebulae.** (2012B, 3 nights)
  Chang You, Ann Zabludoff, Buell Jannuzi, Paul Smith, Yujin Yang
  We obtained the data for B3 J2330+3927 and partially for SSA22-LAB1. **Although she has left our program, Chang You, who was supervised by the PI, continued to work on her paper, "Mapping the Polarization of the Radio-Loud Lyα B3J2330+3927," which has been published in ApJ.**
- $\star$ **Using Polarization to Discover the Nature of Lyα Nebulae.** (2013A, 3 nights)
  Chang You, Ann Zabludoff, Buell Jannuzi, Paul Smith, Yujin Yang, Moire Prescott
  The time was completely lost due to strong winds.
- $\star$ **Using Polarization to Discover the Nature of Lyα Nebulae.** (2014A, 2 nights)
  Chang You, Ann Zabludoff, Buell Jannuzi, Paul Smith, Yujin Yang, Moire Prescott
  We obtained data for the radio-quiet non-AGN blob (FLS-LAB1). Data reduction and analysis are in progress, led by Eunchong Kim, who is one of the first Korean graduate students participating in our new partnership with KASI and other GMT partner institutions in Korea.
- $\star$ **Using Polarization to Reveal the Nature of Lyα Nebulae.** (2015B, 2 nights)
  Ann Zabludoff, Chang You, Yujin Yang, Buell Jannuzi, Paul Smith, Moire Prescott
  We obtained the data for the radio-loud, QSO Lyα blob (SSA22-Sb3-LAB1) while one night was lost due to high humidity and poor seeing ($2''$–$3''$).
- $\star$ **Using Polarization to Reveal the Nature of Lyα Nebulae.** (2016A, 1 nights)
  Ann Zabludoff, Yujin Yang, Eunchong Kim, Buell Jannuzi, Paul Smith
  We were also awarded one additional night through the KASI. We obtained the data for the radio-quiet AGN Lyα blob (LABd05) while a half night was lost due to high humidity and storms. Data reduction and analysis is being led by Eunchong Kim.
- $\star$ **Using Polarization to Reveal the Nature of Lyα Nebulae.** (2016B, 2 nights)
  Ann Zabludoff, Yujin Yang, Eunchong Kim, Buell Jannuzi, Paul Smith
  We were also awarded one additional night through KASI. We obtained data for two Lyα 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.

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**)*

Upgrade Plans for SPOL. MMT+SPOL is an exquisite spectro/imaging polarimeter with a minimal ($<$0.1%) instrumental polarization. However, its sensitivity below $\sim$4500Å is relatively poor, preventing high S/N polarization measurements of Lyα emission from sources at $z < 2.7$. To gain the access to these, we are upgrading SPOL in collaboration with KASI. 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. The optical and opto-mechanical designs of the lens have been completed in KASI Space Astronomy Group (W. Jeong and S. Park), and the lens is currently being manufactured at a Japanese company, Genesia. These modifications will be completed by this summer and will allow us to map the polarization of largest and most luminous Lyα blobs at $z \sim 2$ for the first time.

External Funding. Besides the support from KASI, this program and related science are funded by the NSF Astronomy and Astrophysics Research Program through grant AST-0908280 (PI Zabludoff) and from the NASA Astrophysics Data Analysis Program through grant NNX10AD47G (PI Zabludoff).