OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–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 (50-100 kpc), glowing gas clouds in the distant Universe. We discovered that they occupy halos that evolve into rich galaxy groups and clusters today. The blobs' gas may be the proto-intracluster medium and the blobs' embedded galaxies the progenitors of massive cluster galaxies. Yet we do not know why Lyα blobs glow. Our recent Lyα and Hα line measurements with the VLT are the first to exclude shocks and winds from AGN or from starbursts as sources of the extended Lyα emission. Instead, these measurements, coupled with AGN diagnostics, suggest that photoionizing radiation from AGN might be responsible. Another possible explanation is the resonant scattering of Lyα photons originating from star-forming galaxies or weaker AGN. The next test of the importance of photoionizing AGN as a power source is the polarization of the Lyα emission, yet only two such measurements exist to date. One Lyα blob (SSA22-LAB1) without any evidence of an AGN appears to be strongly polarized (up to 18%), suggesting that resonant scattering plays a major role. On the other hand, with MMT/SPOL, we detect high polarization (up to 20%) in a radio-loud Lyα nebula B3 J2330+3927 where photo-ionization should dominate! Thus the current polarization measurements are contradictory. To further test the potential of Lyα polarimetry in determining the importance of scattering vs. photoionization, we propose to target a recently discovered Lyα halo associated with an optically-luminous, but radio-quiet QSO.

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	Oct	Sep-Nov	no	no

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 $\star$ appended to the proposal type indicates a continuation proposal; a $\star$ 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	LBQS 0049+0045	00:52:02.40	+01:01:29.3	z=2.27

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 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

The Puzzling Nature of Lyα Blobs. Lyα nebulae (aka "Lyα blobs" or LABs) are rare, extended sources at z = 2–5 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; Prescott et al. 2008, 2012; Yang et al. 2010). With a blind survey of Lyα blobs and a statistical comparison to a large volume cosmological simulation (Yang et al. 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 $z \sim 0$, and the blob 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? Speculation includes 1000 km s^{-1} shock and wind excitation arising from AGN or from intense bursts of star formation (Taniguchi & Shioya 2000), as well as radiation from cold gas accretion along filaments (Haiman, Spaans & Quataert 2000; Fardal et al. 2001). However, our recent work with VLT/SINFONI (Yang et al. 2011) and VLT/X-shooter (Yang et al. 2014) finds only modest outflows and that the covering factor of any inflows must be $< 13\%$, excluding both strong winds and cold gas accretion as blob emission drivers.

An alternate explanation for the extended Lyα emission is that photoionization by an AGN leads to recombination throughout the nebula (Haiman & Rees 2001). A fraction (17%) of blobs have embedded or nearby AGN (Geach et al. 2009). Furthermore, our work on blob optical emission lines reveals that two of eight Lyα blobs without X-ray evidence for AGN actually contain a hard ionizing source (i.e., AGN) that may photoionize the surrounding gas. Yet there remain Lyα blobs without any AGN signatures in multi-wavelength data, i.e., without any clear means of global photoionization, suggesting instead that the blob's extended Lyα emission arises when photons produced by an embedded star forming galaxy or weak AGN are resonantly scattered (Steidel et al. 2011; Hayes et al. 2011).

Polarimetry is required to show the degree to which photoionization or resonant scattering plays a role in the Lyα emission. **With MMT/SPOL, we have now made the first detection of Lyα polarization in a radio-loud Lyα blob (B3 J2330+3927) and only the second detection from any kind of Lyα nebula (Fig. 1; C. You et al. in prep.).** The polarization strength and gradient are roughly consistent with a model in which Lyα photons produced in the central AGN are resonantly scattered (Dijkstra & Loeb 2008). To better understand the nature of Lyα blobs, we propose here to map the polarization of a radio-quiet, AGN-associated blob, LBQS 0049+0045, to complement our existing observations of B3 J2330+3927 and a radio-quiet, AGN-less blob, FLS-LAB1.

Polarimetry: A New Angle on the Problem. Polarization of the Lyα line helps to discriminate among photoionization versus resonant scattering models for the blob's extended Lyα emission (Dijkstra & Loeb 2008). If an embedded or nearby AGN photoionizes the nebula, then hydrogen recombination dominates, and the observed Lyα emission arises from the extended gas itself. In this case, the Lyα photons are detected from their formation site and do not scatter, producing little or no polarization. If, on the other hand, the cloud is not photoionized globally, and photons from the embedded source can scatter to some degree, the escaping Lyα emission will be polarized, with the polarization fraction increasing with radius and oriented in concentric circles about the central source. The true situation is likely to include some combination of photoionization and resonant scattering.

Polarimetry of low surface brightness nebulae is notoriously difficult; robust measurement of spatially extended emission at a fraction of the sky background requires careful and accurate calibration using an instrument that itself imprints little to no polarization on the data. A claimed VLT detection of a ring of highly polarized Lyα emission $4''$–$8''$ from the center of SSA22-LAB1 (Hayes et al. 2011), a Lyα blob at z = 3.09, suggests that the Lyα photons are produced centrally and then scattered at large radii by neutral gas. Yet this polarization detection and its interpretation are controversial. Hayes et al. (2011) had to carefully select the spatial binning of their data to obtain a 3σ to 4σ measurement. Their calibration data (including their flat field exposures) were not taken contemporaneously with their observations. Their polarization standards

were point sources and did not provide a check on their ability to accurately measure the polarized flux from a faint, spatially extended source. **These are all deficiencies remedied by MMT/SPOL and our experimental design** (see Experimental Design & Technical Description).

MMT/SPOL Lyα Polarization Survey. To explore the potential of Lyα polarimetry as a new tool, we have undertaken a MMT/SPOL survey for the brightest Lyα nebulae with diverse radio and AGN properties (Table 1). For the first blob observed, B3 J2330+3927, the Lyα flux and polarization trace the morphology of the central radio source and its radio-lobe (Fig. 1). The high degree of polarization (up to $\sim$20%) is surprising given that a radio-loud AGN is expected to photoionize the surrounding gas. If this polarization strength turns out to be common among the nebulae associated with significant ionizing radiation, the conclusions of Hayes et al. (2011) may no longer be valid. Therefore, obtaining Lyα polarization maps for blobs with strong AGN provides the means to test the connection between AGN strength and degree of polarization.

The Plan. SPOL on the MMT is an exquisitely clean system for making polarization measurements. As verified during our previous runs at the MMT, the instrumental polarization remains less than $< 0.1\%$. The accuracy of our measurements will not be limited by the instrument, but rather by the photon (Poisson) noise from the source.

To obtain reliable measurements of Lyα polarization within a reasonable time investment ($\sim$2 nights), the surface brightness of the target should be higher than $\sim 10^{-17}$ erg s^{-1} cm^{-2} arcsec^{-2}. Here we propose to obtain MMT/SPOL observations of a recently discovered Lyα nebula that extends over 460 kpc around an optically-luminous, but radio-quiet QSO (Fig. 2; Cantalupo et al. 2014). This observation, when coupled with our existing observations of the radio-loud, AGN-associated B3 J2330+3927 and the radio-quiet, AGN-less blob, FLS-LAB1, will provide new insights into the power sources of Lyα nebulae.

References

• Cantalupo, S., Arrigoni-Battaia, F., Prochaska, J. X., Hennawi, J. F., & Madau, P. 2014, Nature , 506, 63 • De Breuck, C., et al. 2003, A&A , 401, 911 • 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 • Erb, D. K., et al. 2006, ApJ, 646, 107 • Erb, D. K., et al. 2010, ApJ, 719, 1168 • Fardal, M. A., et al. 2001, ApJ, 562, 605 • Finkelstein, S. L., et al. 2011, ApJ, 729, 140 • Francis, P. J., et al. 2001, ApJ, 554, 1001 • Geach, J. E., et al. 2009, ApJ, 700, 1 • Haiman, Z., & Rees, M. J. 2001, ApJ, 556, 87 • Haiman, Z., Spaans, M., & Quataert, E. 2000, ApJ, 537, L5 • Hainline, K. N., Shapley, A. E., Kornei, K. A., et al. 2009, ApJ, 701, 52 • Hayes, M., Scarlata, C., & Siana, B. 2011, Nature , 476, 304 • Keel, W. C., et al. 1999, AJ , 118, 2547 • Matsuda, Y., Nakamura, Y., Morimoto, N., 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., Smith, P.S., Schmidt, G.D., & Dey, A. 2011, ApJ, 730, L25 • Prescott, Moire K. M. et al. 2012, ApJ, 752, 86 • Rybicki, G. B., & Loeb, A. 1999, ApJ, 520, L79 • Smith, D. J. B. et al. 2008, MNRAS , 389, 799 • Smith, D. J. B. et al. 2009, MNRAS , 393, 309 • 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., Decarli, R., Dannerbauer, H., et al. 2012, ApJ, 744, 178 • Yang, Y., Zabludoff, A., Jahnke, K., & Davé, R. 2014, ApJ , 793, 114

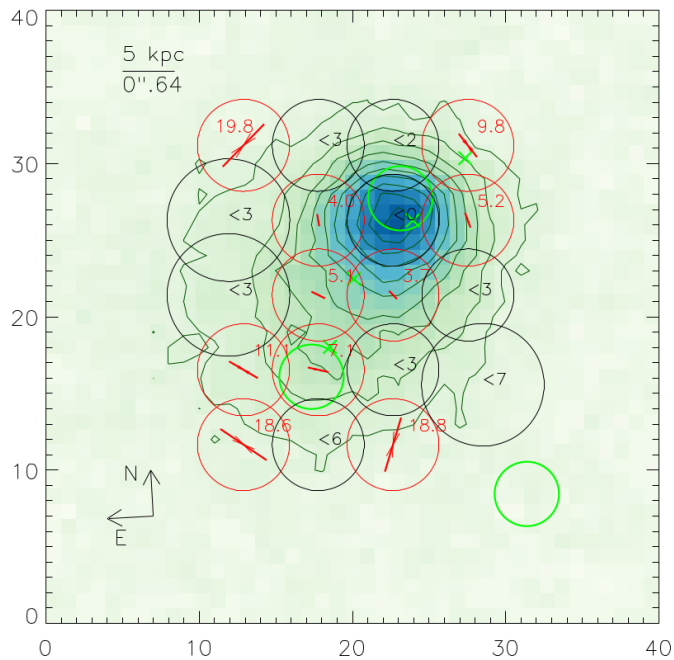

Figure 1: MMT/SPOL polarization measurements overlaid on the Lyα flux map for B3 J2330+3927 (You et al. in prep.). The contours represent flux levels at 5 to 50σ above sky, in intervals of 5σ. The green $\times$ points show the position of the radio knots. The AGN is located at the radio knot near the Lyα peak. Polarization detections significant at greater than 2σ are shown as red vectors. The length and direction of each vector represents the polarization fraction and direction, respectively. The 1σ errors in the polarization fraction and direction are shown on each vector. The polarization fraction is also written in the each aperture. For apertures where the polarization is not detected above 2σ, upper limits are given. Note the strong and radially increasing polarization, as well as the orientation of significant detections along the blob elongation and radio lobe axis.

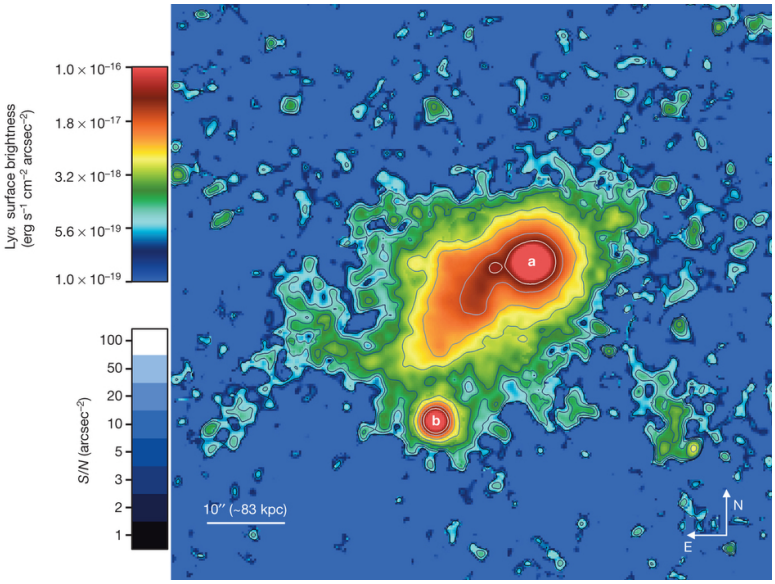

Figure 2: Lyα image of the LBQS 0049+0045 nebula, the target of this proposal.

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 giant Lyα nebula associated with an optically-bright, but radio-quiet QSO (LBQS 0049+0045). We will use SPOL in an imaging mode with a narrowband filter on loan from NOAO as before. We will employ a tilting technique to adjust its central wavelength to match the central wavelength of the redshifted Lyα wavelength ($\sim$3980Å) of LBQS 0049+0045.

We estimate the observing times based on our previous experience. During our MMT/SPOL run in September 2012, we obtained the first polarization map of a radio-loud Lyα blob (B3 2330+3927), which is of similar surface brightness to LBQS 0049+0045. 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% (2σ) for most of the Lyα nebula (see Fig. 1). For the larger LBQS 0049+0045, the SPOL field-of-view will cover the central and brightest part of the nebula, and we will offset to cover fainter regions as time permits. Because 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 fraction. 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 the major advantages of SPOL. Calibration observations through a Nicol prism (internal to the instrument) will determine the efficiency of SPOL's semi-achromatic waveplate in the filter bandpass(es) to be used. These necessary on-sky calibrations will take an hour per night. Therefore, we request 2 dark nights for LBQS 0049+0045.

Table 1: List of Objects with Lyα Polarization Measurements and Our Survey Plan

Name	**Radio-jet?**	**AGN?**	**Reference**
SSA22-LAB1	radio-quiet	unknown	Hayes et al. (2011)
B3 J2330+3927	radio-loud	radio galaxy	MMT/SPOL (C. You et al. in prep.)
FLS-LAB1	radio-quiet	No	MMT/SPOL (analysis in progress)
LBQS 0049+0045	radio-quiet	QSO	MMT/SPOL (**this proposal**)
LABd05	radio-quiet	Yes	MMT/SPOL (future 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**)*

Polarimetry: A New Angle on the Problem.

We are carrying out the first systemic Lyα polarization survey of the brightest Lyα nebulae with various radio and AGN properties to understand the relative importance of resonant scattering and photoionization in illuminating the blob. So far, we have been awarded 5 nights on the MMT (2 were weathered out). Table 1 summarizes the status of our survey and the plan. As shown in Fig. 1, we successfully mapped the polarization of B3 J2330+3927, the first detection of 2-D Lyα polarization from a radio-loud Lyα blob. Preliminary analysis of the radio-quiet, non-AGN blob, FLS-LAB1, also reveals a significant degree of polarization. Here we propose to continue this survey. Given that the time investments are significant due to the low surface brightness of the nebulae, we are also seeking MMT time through KASI, where Y. Yang recently assumed a faculty position.

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**)*

⋆ **Using Polarization to Discover the Nature of Lyα Nebulae.** (2012B, 3 nights)
Chang You, Ann Zabludoff, Buell Jannuzi, Paul Smith, Yujin Yang
We obtained data for B3 J2330+3927 and partially for SSA22-LAB1. We are preparing an ApJ paper "Mapping the Polarization of the Radio-Loud Lyα B3J2330+3927" by C. You et al.

⋆ **Using Polarization to Discover the Nature of Lyα Nebulae.** (2013A, 2 nights)
Chang You, Ann Zabludoff, Buell Jannuzi, Paul Smith, Yujin Yang, Moire Prescott
The time was completely lost due to strong winds.

⋆ **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 the data for the radio-quiet, non-AGN blob (FLS-LAB1). Data reduction and analysis are in progress.