MAPPING THE POLARIZATION OF THE RADIO-LOUD Lyα NEBULA B3 J2330+3927*

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ABSTRACT

Lyα nebulae, or “Lyα blobs,” are extended (up to ~100 kpc), bright ($L_{Lyα} \gtrsim 10^{43}$ erg s$^{-1}$) clouds of Lyα emitting gas that tend to lie in overdense regions at $z \sim 2–5$. The origin of the Lyα emission remains unknown, but recent theoretical work suggests that measuring the polarization might discriminate among powering mechanisms. Here we present the first narrowband imaging polarimetry of a radio-loud Lyα nebula, B3 J2330+3927, at $z = 3.09$, with an embedded active galactic nucleus (AGN). The AGN lies near the blob’s Lyα emission peak, and its radio lobes align roughly with the blob’s major axis. With the SPOL polarimeter on the 6.5 m MMT telescope, we map the total (Lyα + continuum) polarization in a grid of circular apertures of a radius of 0.5 kpc, detecting a significant ($>2\sigma$) polarization fraction $P_{%}$ in nine apertures and achieving strong upper limits (as low as 2%) elsewhere. $P_{%}$ increases from <2% at ~5 kpc from the blob center to 17% at ~15–25 kpc. The detections are distributed asymmetrically, roughly along the nebula’s major axis. The polarization angles $\theta$ are mostly perpendicular to this axis. Comparing the Lyα flux to that of the continuum and conservatively assuming that the continuum is highly polarized (20%-100%) and aligned with the total polarization, we place lower limits on the polarization of the Lyα emission $P_{%}$, ranging from no significant polarization at ~5 kpc from the blob center to ~3%-17% at 10–25 kpc. Like the total polarization, the Lyα polarization detections occur more often along the blob’s major axis.

Key words: galaxies: active – galaxies: high-redshift – galaxies: individual (B3 J2330+3927) – intergalactic medium – polarization

1. INTRODUCTION

Giant (up to ~100 kpc) gaseous, Lyα-emitting nebulae, also known as Lyα “blobs” (Steidel et al. 2000; Matsuda et al. 2004; Dey et al. 2005; Prescott et al. 2008; Yang et al. 2009), are extremely luminous ($L_{Lyα} \gtrsim 10^{43}$ erg s$^{-1}$) and were first discovered in overdense regions of the high-redshift ($z \sim 2–5$) universe (Matsuda et al. 2005; Prescott et al. 2008). Their rarity and clustering are consistent with their occupying massive ($\sim 10^{15} M_\odot$) dark matter halos that then evolve into rich groups or clusters of galaxies today (Yang et al. 2009, 2010). The Lyα blob gas may therefore represent the proto-intracluster medium and the embedded sources of the progenitors of cluster galaxies (Yang et al. 2010; Prescott et al. 2012). Thus, identifying the mysterious source or sources of the extended Lyα emission is essential to understanding the evolution of the large-scale structure and the most massive galaxies.

Observations and theory suggest a range of powering mechanisms, including gravitational cooling radiation (Haiman et al. 2000; Fardal et al. 2001; Faucher-Giguère et al. 2010; Goerdt et al. 2010; Rosdahl & Blaizot 2012), shock heating from starburst-driven winds (Taniguchi & Shioya 2000; Mori et al. 2004), the resonant scattering of Lyα photons produced by star formation (Steidel et al. 2011), and photo-ionizing radiation from active galactic nuclei (AGNs) (Haiman et al. 2000). Even with careful constraints on the Lyα line profile and distribution, discriminating among these models is difficult, in part due to the complex radiative transfer of the resonantly scattered Lyα line and the uncertain internal geometry of each Lyα blob (e.g., Yang et al. 2011, 2014a, 2014b).

Measuring the polarization of the Lyα line can shed new light on the problem. Recent radiative transfer simulations predict the polarization of the Lyα line in a number of different scenarios. For example, backscattered Lyα flux from galaxies surrounded by a superwind-driven outflow is expected to produce a Lyα polarization fraction $P_{%}$, which rises with the radius to as much as ~40% where the neutral hydrogen column density $N_{HI}$ drops below $10^{19}$ cm$^{-2}$ (Dijkstra & Loeb 2008). A similar $P_{%}$ integrated over the line profile may arise from cooling radiation from a collapsing proto-galaxy (Dijkstra & Loeb 2008; see also Trebitsch et al. 2016), but with inverted wavelength dependence when the line is spectrally resolved. Resonant scattering in the diffuse intergalactic medium typically results in a lower $P_{%}$ (~7%), which depends on the flux of the ionizing background (Loeb & Rybicki 1999; Rybicki & Loeb 1999; Dijkstra & Loeb 2008). These models, which all currently assume spherical symmetry, continue to grow more sophisticated (e.g., Trebitsch et al. 2016). Their

* The observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.
improving, detailed predictions, when combined with the new availability of polarimeters on the largest telescopes, provide a unique opportunity to isolate the mechanism that powers \(Ly\alpha\) blobs by mapping the polarization.

Polarization work on \(Ly\alpha\) blobs has been limited. To date, only two \(Ly\alpha\) blobs have been observed with narrowband imaging polarimetry. One, SSA22–LAB1, shows concentric polarization rings, reaching \(\sim 10\%\) at \(\Delta \sim 0.000\) kpc from the blob center and rising to \(\sim 20\%\) at \(\Delta \sim 0.005\) kpc (Hayes et al. 2011)—which suggests a central powering source for this \(Ly\alpha\) blob (see also Beck et al. 2016). In the other blob, LABd05, Prescott et al. (2011) do not detect polarization within a single, large (radius \(\sim 3.3\) kpc) aperture, obtaining an upper limit of \(2.6\% \pm 2.8\%\); deeper and spatially resolved observations are required to test this result (E. Kim et al. 2016, in preparation). These past studies assume that the polarization arises solely from \(Ly\alpha\), given that the \(Ly\alpha\) line dominates the continuum emission, at least at large radii. Both \(Ly\alpha\) nebulae are radio-quiet. Spectro-polarimetry of a radio-loud \(Ly\alpha\) nebula, TXS 0211–122, at \(z = 2.3\) reveals polarization of the \(Ly\alpha\) line: \(16.4\% \pm 4.6\%\) on one side of the nebula (Humphrey et al. 2013). In this case, spatial information is limited, inhibiting the interpretation of the results.

Looking to the literature on radio galaxies, which can be surrounded by line emission nebulae similar in \(Ly\alpha\) luminosity and spatial extent to blobs (see McCarthy 1993 and references therein), does not improve our understanding of how \(Ly\alpha\) polarization is distributed across the sky. Existing polarization measurements of radio galaxies, seeking to explain the alignment effect—the strong correlation between their radio and optical continuum morphologies (McCarthy et al. 1987)—tend to focus on the continuum (Vernet et al. 2001). Constraints on \(Ly\alpha\) polarization are few, particularly over the tens of kpc scales typical of \(Ly\alpha\) blobs. Using spectro-polarimetry, Cimatti et al. (1998) find that the \(Ly\alpha\) line is unpolarized in two radio galaxies. Lyo around another radio galaxy, 4C 41.1, is polarized at a low level (\(1.12\% \pm 0.26\%\)), while its continuum emission is unpolarized (Dey et al. 1997).

The similarity in morphology and energy between extended \(Ly\alpha\) nebulae with radio-loud and radio-quiet AGNs suggests an unexplored connection between their powering mechanisms (Dey et al. 1997; Villar-Martín et al. 2003). Here we present the first \(Ly\alpha\) imaging polarimetry measurement for a blob with an embedded radio galaxy. We use the SPOL imaging spectro-polarimeter on the 6.5 m MMT telescope to map B3 J2330+3927, a radio-loud \(Ly\alpha\) blob at \(z = 3.087\). Its embedded radio galaxy is one of the 1103 radio sources from the Third Bologna Catalog (Ficarra et al. 1985; Vigotti et al. 1989). The associated \(Ly\alpha\) nebula was discovered by De Breuck et al. (2003) through a long-slit spectroscopy and observed in detail by Matsuda et al. (2009). SPOL is a clean instrument, designed to reduce any instrument polarization by integrating over 16 different waveplate positions. At the redshift of our source, SPOL’s high stability and sensitivity on the MMT enable measurement of a few percent polarization on scales of \(\sim 0.005\) kpc, even at the low surface brightnesses characteristic of \(Ly\alpha\) blobs.

This paper is the first of several to map the polarization of giant \(Ly\alpha\) nebulae at high redshift. In this paper, we present the map of our first target and establish our methodology. Subsequent papers will analyze the full blob sample and compare the results to those of physical models. This paper is organized as follows. In Section 2, we describe the details of our observations. In Section 3, we discuss the data reduction for the polarization measurement and the calibration sources. In Section 4, we present our polarization map and discuss possible sources of error. In Section 5, we summarize our conclusions.

2. THE OBSERVATIONS

2.1. The Target

B3 J2330+3927 is a high-redshift (\(z = 3.087\)) radio galaxy at R.A. = \(23^h30^m8^s\) and decl. = \(39^\circ27^\prime12^\prime\) that is embedded in a giant \(Ly\alpha\) halo that extends over \(\sim 130\) kpc. This nebula is one of the brightest known, with \(L_{\alpha Ly\alpha} = 2.5 \times 10^{44}\) erg s\(^{-1}\) (Matsuda et al. 2009). The CO emission and H\textsc{i} absorption reveal a massive gas and dust reservoir associated with the radio galaxy (De Breuck et al. 2003; Ivison et al. 2012). VLBA and VLA data show a one-sided jet driven by a Type II AGN (Pérez-Torres & De Breuck 2005). The galaxy environment of this \(Ly\alpha\) blob is overdense: a combination of broad and narrowband observations (Matsuda et al. 2009) reveals 127 compact \(Ly\alpha\) emitter candidates and another giant (~100 kpc) but radio-quiet \(Ly\alpha\) blob within the \(31^\prime \times 24^\prime\) \((58 \times 44\) comoving Mpc\(^3\)) field. This wealth of ancillary data, the redshift, and a bright point source at R.A. = \(23^h30^m25^s\) and decl. = \(39^\circ27^\prime08^\prime\) useful for image registering and alignment make B3 J2330+3927 an attractive target.

2.2. The Instrument

On UT 2012 September 18–20, we used the 6.5 m MMT telescope on Mount Hopkins, Arizona, to observe B3 J2330+3927 with the SPOL CCD imaging/spectro-polarimeter in its imaging polarimetry mode (Schmidt et al. 1999b). We used a narrowband filter (\(\Delta 583\)) on loan from Kitt Peak National Observatory that is centered at 4980 A and has a FWHM of 54 A. The detector is a thinned, anti-reflection-coated 1200 \(\times\) 800 STA CCD with a pixel scale of 0.019 pixel\(^{-1}\) and a quantum efficiency of \(\sim 0.85\) in the filter bandpass. We obtained a total of 8.6 hr exposure time on B3 J2330+3927. For the calibration of the instrument, we observed unpolarized and polarized standard stars each night. We also observed CRL 2688 (the “Egg Nebula”) as an extended polarized source to investigate any unforeseen systematic effects across the 19" \(\times\) 19" field of view.

In SPOL, the telescope is fed through a half-wave plate and then to a Wollaston prism. The Wollaston prism is located in the optical path between a transmissive collimator and a plane mirror that substitutes for a diffraction grating when imaging polarimetry is desired. The narrowband filter is placed in the collimated beam between the collimator and the Wollaston prism. The half-wave plate retards one orthogonal component of the light and thus changes the polarization angle of the incoming light. The Wollaston prism splits the two orthogonal polarizations so the two polarizations are imaged separately—in our case, in separate “panels” in one “image.” The difference between these two panels indicates the strength of the polarization.

Linear polarization measurements with SPOL are accomplished by stepping a wheel holding a semi-aichromatic half-wave plate through two sequences that are aimed at measuring Stokes parameters \(Q\) and \(U\), respectively. A \(Q\)-sequence yields two images \((Q^+\) and \(Q^-)\): the first \((Q^+)\) consisting of two beams (panels) of four exposures at four orthogonal position angles of the waveplate \((0^\circ, 90^\circ, 180^\circ, 270^\circ)\) and the second
taken at angles offset by 45° from the first (45°, 135°, 225°, 315°). The U-sequence follows the same progression (U− and U+) as the Q-sequence, but the waveplate position angles are offset by 22.5° from those of the Q-sequence. The redundancy in the data-taking sequences ensures that effects caused by imperfections in the waveplate and the waveplate’s positioning in the optical path are minimized. As a result, the instrumental polarization of SPOL is consistently <0.1% and is verified by our measurements of unpolarized standards during the nights that we observed B3 J2330+3927 (Section 3.3.1). We do not include this negligible polarization in the subsequent analysis of the data. In addition, the dual-beam design of SPOL eliminates the possibility of measuring spurious polarization arising from variable seeing and sky transparency during observing sequences.

For B3 J2330+3927, we took exposures of 300 s per waveplate position angle, so we completed both Q and U sequences in 80 min. In total, we obtained six full polarization sequences. We optimized the MMT optics between each measurement, except when the seeing remained ideal and the weather conditions did not change. The seeing was ~1″0 during most of the observations, rising to ~1″5 for the two sequences taken at the end of each of the two nights. We used the positions of the Lyα blob center (R.A. = 23h30m24.9, decl. = 39°27′12″) and of a bright point source (R.A. = 23h30m25.10, decl. = 39°27′05″4; ~8″ to the southeast of the blob center) to register and align our images, as the field was dithered slightly between polarization sequences to minimize the effects of any poorly calibrated pixels. We measured the polarization efficiency of the system (ρeff = 0.973) by inserting a Nicol prism before the aperture plate and waveplate in the light path within the instrument. This efficiency is consistent with other measurements acquired over more than two decades for SPOL at 4980 Å when it is used as a spectro-polarimeter.

3. THE DATA REDUCTION

3.1. Pre-processing

To prepare the images for polarization measurement, we perform overscan correction, bias subtraction, flat fielding, and cosmic-ray removal. For flat fielding, we obtained domeflats with all the polarization optics (the Wollaston prism and half-wave plate) and constructed a partial skyflat by median-combining the science images with the central Lyα blob blocked out. The domeflats show a significant gradient across the image that the science exposures and partial skyflat do not. To correct the domeflats, we fit the gradient with a 2D first-order polynomial and divide it out. We apply the resulting “flattened” domeflat to the partial skyflat and the science images. There are no significant gradients in the resulting images.

We use the L.A.Cosmic package (van Dokkum 2001) to remove cosmic rays from our images. We examine the cosmic ray masks by eye to confirm that a real signal from the nebula remains.

3.2. Polarization Calculation

As described in 2.2, from a full Q–U sequence we obtain a total of four images (Q−, Q+, U−, U+), each with two panels (“up” and “down” beams). Here we explain the calculation of the polarization parameters from those images.

With the notation

\[ q \equiv \frac{Q}{I} \quad \text{and} \quad u \equiv \frac{U}{I}. \]  

\(q\) and \(u\) can be determined using the following formulae:

\[ q = \frac{Q}{I_Q} = \frac{1}{2} \left[ \left( \frac{Q^+ - Q^-}{Q^+ + Q^-} \right)_{\text{up}} + \left( \frac{Q^+ - Q^-}{Q^+ + Q^-} \right)_{\text{down}} \right] \]  

\[ u = \frac{U}{I_U} = \frac{1}{2} \left[ \left( \frac{U^+ - U^-}{U^+ + U^-} \right)_{\text{up}} + \left( \frac{U^+ - U^-}{U^+ + U^-} \right)_{\text{down}} \right]. \]

where \(I_Q\) and \(I_U\) are the total intensities measured from the Q and U sequences, respectively:

\[ I_Q = \{ (Q^+ + Q^-)_{\text{up}} + (Q^+ + Q^-)_{\text{down}} \}/2 \]

\[ I_U = \{ (U^+ + U^-)_{\text{up}} + (U^+ + U^-)_{\text{down}} \}/2 \]

\[ I = \frac{1}{2} (I_Q + I_U). \]

Ideally, \(Q^+_{\text{up}}\) is the same as \(Q^+_{\text{down}}\) and \(Q^-_{\text{down}}\) is the same as \(Q^-_{\text{up}}\). The same applies to the U images.

For each Q–U sequence, we create these \(I, Q, \) and \(U\) images (or \(q\) and \(u\)) and combine them to increase the signal-to-noise ratio (S/N). When combining the sequences, we scale the images to compensate for variations arising from airmass and weather. From these final Stokes images (\(I, Q, U\)), we calculate the polarization fraction \(P_{\text{eq}}\) and angle \(\theta\) using the following formulae:

\[ P_{\text{eq}} = \sqrt{q^2 + u^2} \]

\[ \theta = \frac{1}{2} \arctan \frac{U}{Q}. \]

Because the S/N of our target is low, we calculate \(P_{\text{eq}}\) and \(\theta\) for large aperture sizes (1″2–1″5) over the map. The error associated with the polarization due to photon noise is derived from propagating errors through the above formulae.

3.3. Calibrations

3.3.1. Standard Stars

To calibrate and verify the linear polarization measurements with SPOL, we observed both polarized and unpolarized standard stars (Schmidt et al. 1992a) each night. These observations are summarized in Figure 1. For the unpolarized stars, G191-22B and BD+28 4211, the instrumental polarization \((Q/I \text{ and } U/I)\) at the MMT is indeed <0.1% (top left panel), as previously found for SPOL at other telescopes. We also used these spectro-photometric standard stars to flux-calibrate the narrowband images.

We observed two interstellar polarized standards, BD+59 389 and Hiltner 960. Given that our narrowband filter is centered at a wavelength (4980 Å) different from those in previous measurements of these standards, we calculate the expected \(P_{\text{eq}}\) and \(\theta\) within our bandpass by interpolating between the previous measurements with an interstellar polarization function (Serkowski 1973, p. 145). Our observations of BD+59 389 are consistent with historical measurements, i.e., our three measurements over two nights agree within ±1.6σ and ±2.0σ of the interpolated \(P_{\text{eq}}\) and \(\theta\) from the literature, respectively.
For Hiltner 960, the observed $\theta$ are also within the $\pm 1.3\sigma$ range, but the $P_\%$ are more discrepant ($\sim 3.1\sigma$) than for BD+59 398, likely due to the variability of Hiltner 960. Note that this error ($\Delta P_\% \approx 0.2\%$) is negligible compared to the uncertainties in measurements of the science target, B3 J2330+3927.

4. RESULTS AND DISCUSSION

4.1. Total Polarization Map

Figure 3 shows our polarization map of B3 J2330+3927 for the light in the narrowband image, i.e., Ly$\alpha$ plus continuum.
centered at 4980 Å with a FWHM of 54 Å. We measure the polarization on a grid of circular apertures with a minimum radius of \( R = 3 \) pixels (i.e., 0″6, 4.4 kpc), comparable to the seeing. We enlarge three apertures far from the \( \text{Ly}\alpha \) peak from \( R = 3 \) pixels to 4 pixels so that they reach a flux S/N similar to those of the other apertures.

We detect significant (≥2σ) polarization in nine apertures and achieve strong upper limits (i.e., \( P_{\%} \) as low as 2%) elsewhere, indicating varying polarization across the blob. There is little or no polarization at the blob center and to the southwest of the nebula. The significant detections are generally distributed along the blob’s major axis, which is also the radio lobe direction. Along that axis, \( P_{\%} \) increases from <2% at ~5 kpc from the blob center to roughly 17% at ~15–25 kpc. The polarization angles tend to be perpendicular to that axis.

To test the significance of our polarization measurements, we show the smoothed-\( \chi \) images for the \( Q \) and \( U \) fluxes in Figure 4. Here the \( \chi_{\text{smooth}} \) of an image \( I \) is defined by

\[
\chi_{\text{smooth}} = \frac{I_{\text{smooth}}}{\sigma_{\text{smooth}}} = \frac{I \ast h(r)}{\sqrt{\sigma_i^2 \ast h^2(r)}},
\]

where \( I_{\text{smooth}} \) is the convolved image with a smoothing kernel \( h(r) \) and \( \sigma_{\text{smooth}}^2 \) is the variance of a smoothed image that is propagated from an unsmoothed image. Given that \( \chi_{\text{smooth}} \) should follow a normal distribution \( N(0, 1) \) for random noise, \( \chi_{\text{smooth}} \) is useful for visualizing low-S/N features. Here, we adopt a tophat kernel with a radius of 3 pixels to match the size of the apertures used for the measurements of \( P_{\%} \) and \( \theta \). The \( Q_{\chi_{\text{smooth}}} \) image shows that the region with \( |\chi_{\text{smooth}}| > 3 \) (outlined with solid contours) is roughly aligned with the major axis, demonstrating the significance of our polarization detections.

The errors shown in Figure 3 are calculated purely from photon noise statistics. One additional source of uncertainty is the extent to which errors in image alignment, i.e., from shifts and rotations, affect the polarization map when we combine images. Polarization is calculated by taking the difference in images. When images are not aligned correctly, the polarization may be affected. Between sequences and within sequences, the point source in the southeast shifts by ~1 pixel and rotates relative to the blob center by only ~0″.5. Thus, the uncertainties in misalignment are dominated by translational errors. To estimate how much translational errors could affect our measurements, we introduce errors of this magnitude into our best-aligned images and repeat the entire reduction procedure. Figure 5 shows four random realizations of the total polarization maps after random alignment errors with ±1 pixel shifts are introduced. Our results do not change significantly.
The UV continuum aligned with the radio lobes of radio galaxies is sometimes polarized, with the continuum polarization fraction $P_{\% \text{cont}}$ typically $<10\%$, but sometimes as high as $\sim 20\%$–$30\%$ (Jannuzi & Elston 1991; Vernet et al. 2001; Tadhunter 2005). As a result, the relative contributions of continuum and Lyα to our total polarization map for B3 J2330+3927 are not clear. Future spectro-polarimetry, which could isolate the line-only polarization signal (e.g., Beck et al. 2016), is needed. For now, we make a conservative argument to place lower limits on the Lyα contribution, asking whether at least some Lyα polarization is required to explain the map in Figure 3.

To separate polarization contributed by the continuum and to place a lower limit on the line polarization, we use the following simple formalism, where $I_{Q, \text{cont}}$ and $I_{Q, \text{line}}$ refer to the total flux in the $Q$ images from the continuum and Lyα, respectively. This light is polarized by $q_{\text{cont}}$ and $q_{\text{line}}$ for the continuum and Lyα, respectively. Because the narrowband filter captures both the continuum and Lyα fluxes at the same time, in one $Q$-sequence, we measure the total polarization parameter:

$$\left( \frac{Q}{I} \right)_{\text{total}} = \frac{I_{Q, \text{cont}} \times q_{\text{cont}} + I_{Q, \text{line}} \times q_{\text{line}}}{I_{Q, \text{cont}} + I_{Q, \text{line}}}. \quad (10)$$

Likewise, in a $U$-sequence, we have

$$\left( \frac{U}{I} \right)_{\text{total}} = \frac{I_{U, \text{cont}} \times u_{\text{cont}} + I_{U, \text{line}} \times u_{\text{line}}}{I_{U, \text{cont}} + I_{U, \text{line}}}. \quad (11)$$

If we assume that the polarization angles of the continuum and Lyα are the same, using the relation

$$\frac{q_{\text{cont}}}{u_{\text{cont}}} = \frac{q_{\text{line}}}{u_{\text{line}}}, \quad (12)$$

we can separate the total polarization into contributions from the continuum and Lyα:

$$P_{\% \text{Lyα}} = (1 - f_c)P_{\% \text{line}} + f_c P_{\% \text{cont}}, \quad (13)$$

where $f_c$ is the fraction of the continuum relative to the total light captured by the narrowband filter:

$$f_c = \frac{I_{\text{cont}}}{I_{\text{cont}} + I_{\text{line}}}. \quad (14)$$

To estimate the continuum light fraction $f_c$, we use a UV continuum image of B3 J2330+3927 constructed from broadband $B$ and $V$ images (Matsuda et al. 2009), which covers a rest-frame wavelength range of 980–1450 Å. Figure 6 shows the SPOL (continuum + Lyα) and Subaru (continuum) images at the same stretch. The flux from the Lyα line dominates that from the UV continuum in our narrowband filter. Using both the SPOL and Subaru images, we calculate $f_c$ for the same apertures where we measured the total polarization in Figure 3. The continuum flux, which is somewhat extended along the radio lobe direction, is only $\sim 10\%$ of the total flux at the blob’s center and drops off at larger radii.

We then consider two cases to estimate the lower limit on $P_{\% \text{Lyα}}$ within each aperture. First, we use Equation (13) to determine $P_{\% \text{Lyα}}$ under the highly conservative assumption that the UV continuum is $20\%$ polarized and has a polarization direction aligned with the total polarization. A $P_{\% \text{cont}}$ of $20\%$ is typical of the highest values measured in radio galaxy lobes (Jannuzi & Elston 1991; Vernet et al. 2001; Tadhunter 2005). Even in this case (Figure 7(a)), $P_{\% \text{Lyα}}$ contributes significantly to $P_{\% \text{cont}}$ in all nine apertures where significant $P_{\% \text{cont}}$ is detected. The $P_{\% \text{Lyα}}$ values here range from $3\%$ to $17\%$ at $\sim 10$–25 kpc, with no significant Lyα polarization detected near the blob center. Like the total polarization, the Lyα polarization detections occur more often along the blob’s major axis. If we assume instead that $P_{\% \text{cont}}$ is $100\%$ (panel (b)), an assumption so extreme that it requires negative (unphysical) $P_{\% \text{Lyα}}$ values for many apertures given $P_{\% \text{cont}}$, there remain five apertures in the southeast where $P_{\% \text{Lyα}}$ is detected at $\geq 2\sigma$.

4.3. Physical Interpretation

From the first Lyα imaging polarimetry of a radio-loud Lyα nebula, B3 J2330+3927, we find that the total polarization...
fraction $P_{\alpha}$ increases from $<2\%$ at the blob center to $17\%$ at $\sim 15$–$25$ kpc. Significant polarization is detected preferentially along the blob’s major axis at angles perpendicular to that axis. In this section, we briefly discuss the implication of our measurements. Future papers will focus on detailed comparisons with numerical models.

Imaging polarimetry is a useful tool to differentiate between a central powering geometry and an extended power source. In the former case, Ly$\alpha$ photons are produced by a central point source or sources (i.e., embedded star-forming galaxies or AGNs) and transported to large radii. When the central source illuminates the surrounding neutral gas, the Ly$\alpha$ photons do not experience much resonant or core scattering, and escape the system via Rayleigh or wing scattering. The resultant Ly$\alpha$ radiation is highly polarized at large radii, and the polarization angle is aligned tangentially to the overall geometry of the system (Rybicki & Loeb 1999; Dijkstra & Loeb 2008). In contrast, in the latter case of extended emissivity, Ly$\alpha$ photons are produced in situ in the extended gas through hydrogen recombination following ionization by photo-ionizing sources (e.g., AGNs) or superwind-driven shock heating. Because the Ly$\alpha$ photons have no preferential orientation with respect to the neutral medium and the observers, little or no polarization is expected.

In B3 J2330+3927, the observed high Ly$\alpha$ polarization fraction ($\sim 20\%$ at the largest radii) and extended continuum emission suggest that Ly$\alpha$ photons are produced in the center, instead of arising throughout the nebula itself.

Likewise, the observed increase of polarization with the radius is consistent with theoretical predictions from Dijkstra & Loeb (2008), assuming a simple geometry and central source. In their expanding-shell model, a Ly$\alpha$ polarization gradient arises when photons at larger radii scatter by larger angles (closer to $90^\circ$) toward the observer. In an alternative model of an optically thick, spherically symmetric, collapsing gas cloud, the Ly$\alpha$ radiation field becomes more anisotropic at larger radii. 

Figure 5. Four random realizations of the total polarization map after random alignment errors ($\pm 1$ pixel shifts) are introduced into the process of reducing the science images. Their similarity to one another and to the observed map (Figure 3) suggests that our results are robust to the positional shifts from one image to another and from one sequence to another.
radii. In other words, photons tend to propagate more radially outward than in their prior scattering events, requiring a larger scattering angle to reach the observer, and are thus more polarized.

While some of the polarization properties of B3 J2330+3927 (fractions, angles, and radial gradient) are qualitatively similar to those of SSA22-LAB1 (Hayes et al. 2011), one difference is that the significant polarization in B3 J2330+3927 favors the major axis (and radio-jet direction). We speculate that the lack of polarization detected along the minor axis could be due to strong obscuration from an AGN torus perpendicular to the radio jet. Another possibility is that ionization states and optical depths vary from one axis to the other due to photo-ionization along the jet or its interaction with the IGM. In this case, Lyα photons can escape the system with fewer scatterings in the major axis direction. It is not known whether this polarization pattern is common to other giant Lyα nebulae around high-z radio galaxies. To investigate these issues further, we need deeper and higher spatial resolution observations of this system and a systematic survey of polarization for a larger sample.

5. CONCLUSIONS

We present the first narrowband imaging polarimetry of a Lyα nebula, or “blob,” with an embedded, radio-loud AGN. The blob, B3 J2330+3927, lies at $z = 3.09$, extends over $\sim 150$ kpc, and has a Lyα luminosity of $2.5 \times 10^{44}$ erg s$^{-1}$ (De Breuck et al. 2003; Matsuda et al. 2009). The AGN lies near the Lyα emission peak, and its radio lobes align roughly with the major axis of the blob’s extended Lyα emission. Our findings are as follows:

1. We map the total (Lyα plus continuum) polarization in a grid of circular apertures of a radius of 0"6 (4.4 kpc), detecting significant ($\geq 2\sigma$) polarization in nine apertures and achieving strong upper limits (as low as 2% in the total polarization fraction $P_{\%}$) elsewhere.
2. The gradient in the total polarization map increases from $P_{\%} < 2%$ at $\sim 5$ kpc from the blob center to 17% at $\sim 15$–25 kpc. The detections lie mostly along the blob’s major axis, and the polarization angles are generally perpendicular to it.
3. Comparing the total flux to that of the continuum and assuming conservatively that the continuum is 20%–100% polarized and aligned with the total polarization, we place lower limits on the Lyα polarization fraction $P_{\%,Lyα}$. Under these assumptions, $P_{\%,Lyα}$ is 3%–17% at $\sim 10$–25 kpc. No significant Lyα polarization is detected at $\sim 5$ kpc of the blob center. Like the total polarization, the Lyα polarization detections tend to lie along the blob’s major axis.

Our polarization measurements for B3 J2330+3927 complement past polarization work, which focused on radio-quiet blobs and on radio galaxies within Lyα clouds. For example, the polarization of SSA22–LAB1 is not measurable at its center, but rises to $\sim 10%$ at $\sim 30$ kpc and to $\sim 20%$ at $\sim 45$ kpc, forming an almost complete polarized ring (Hayes et al. 2011). While the polarization that we detect in B3 J2330+3927 is also tangentially oriented and outside the blob center (and AGN), it is generally significant only along the blob’s major axis (and radio lobe direction).

Unlike previous studies, we have constrained and mapped the Lyα contribution to the total polarization. The one spectro-polarization measurement isolating the Lyα line in a radio-loud Lyα blob also reveals its polarization fraction to be high (16%) and perpendicular to the radio lobe axis in a region 10–40 kpc from the nucleus, at least on one side of the nebula (Humphrey et al. 2013). Such a high $P_{\%,Lyα}$ has not been observed in radio
Figure 7. Lower-limit Lyα polarization maps overlaid on the total flux image. To determine the P_{Lyα,cont} values shown, we assume conservatively that the continuum flux is either 20% (panel (a)) or 100% (panel (b)) polarized and that its polarization angle is the same as the angle of the total polarization. We draw circular apertures at the same positions as in Figure 3. For a P_{Lyα,cont} of 20%, consistent with some of the highest continuum polarization fractions measured in the lobes of radio galaxies (Jannuzi & Elston 1991; Vernet et al. 2001; Tadhunter 2005), P_{Lyα,cont} contributes significantly to P_α in all nine apertures where significant P_α is detected. Even under the extreme and unlikely case that P_{Lyα,cont} is 100%, there remain five apertures where P_{Lyα,cont} is detected at >2σ.

 galaxies (e.g., Dey et al. 1997; Cimatti et al. 1998), which might imply a physical difference or arise from P_{Lyα,cont} being measured on smaller physical scales. Spatially resolved measurements of P_{Lyα,cont} for a larger sample of radio galaxies are required to discriminate between these scenarios.

A direct comparison of our narrowband imaging polarimetry of B3 J2330+3927 with our on-going survey of Lyα blobs without known AGNs and with radio-quiet AGNs will greatly improve our understanding of the mysterious source of their extended Lyα emission.

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