GEOMETRICAL CONSTRAINTS ON THE HOT SPOT IN BETA LYRAE

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ABSTRACT

We present results from six years of recalibrated and new spectropolarimetric data taken with the University of Wisconsin’s Half-Wave Spectropolarimeter and six years of new data taken with the photoelastic modulating polarimeter at the Flower and Cook Observatory of beta Lyrae. Combining these data with polarimetric data from the literature allows us to characterize the intrinsic BVRI polarized light curves. A repeatable discrepancy of 0.245 days (approximately 6 hr) between the secondary minima in the total light curve and the polarization curve in the V band, with similar behavior in the other bands, may represent the first direct evidence for an accretion hot spot on the disk edge.

Key words: accretion, accretion disks – binaries: eclipsing – stars: individual (beta Lyrae) – techniques: polarimetric

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

Beta Lyrae A (also known as HD 174638, HR 7106, and ADS 11745A; hereafter “β Lyr”) is a bright, well-studied semi-detached eclipsing binary star system. The primary star is a B6-B8 II, giant star (“loser”) with a mass of 3 $M_\odot$ that is transferring matter to its main-sequence B0.5 V, 12.5 $M_\odot$ companion (“gainer”) at about 10$^{-5}$ $M_\odot$ yr$^{-1}$ via Roche lobe overflow (Hubeny & Plavec 1991; Harmanec & Scholz 1993). This process has created a thick accretion disk that obscures the gainer (Huang 1963; Wilson 1974; Hubeny & Plavec 1991; Skulskii 1992). A bipolar flow or jet has also been detected in the system through interferometric and spectropolarimetric methods (Harmanec et al. 1996; Hoffman et al. 1998, hereafter HNF). The system’s mass ratio, $q$, has been placed between 4.2 and 6 with an inclination angle, $i$, of 85° (Wilson 1974). Other studies have suggested $i = 83°$ with $q = 5.6$ and $i = 80°$ with $q = 4.28$ (Hubeny & Plavec 1991; Skulskii 1992). More recent determinations of the orbital inclination place its value at $i = 86°$ (Linnell et al. 1998; Linnell 2000). These large mass ratios are evidence for mass reversal in the system’s history. The disk’s ability to obscure the gainer is due to the nearly edge-on inclination angle of the system.

The system has a well-established orbital period of 12.9 days that increases at a rate of 19 s yr$^{-1}$ (Harmanec & Scholz 1993). Recent interferometric observations have produced the first images of the system, which show the loser and the disk as separate objects and confirm the orientation of the system axis, near 254°, previously inferred from HNF’s polarimetric analysis (Harmanec et al. 1996; Zhao et al. 2008; Schmitt et al. 2009). Understanding how mass moves between and around the stars and leaves the system is imperative to understanding the evolutionary future of β Lyr. However, interferometric techniques have yet to resolve the mass stream or bipolar outflows. We have used spectropolarimetry to study the system and begin to unlock the evolutionary clues contained within the circumstellar material.

Light scattering from electrons in the highly ionized circumstellar material in β Lyr produces a variable phase-dependent polarization. Since electron scattering preserves information about the orientation of the scattering region, analyzing polarimetric behavior as a function of wavelength allows us to determine from where in the system different spectral features have arisen. In this way, spectropolarimetric observations of β Lyr can be used to infer the geometrical properties of the scattering material in the system.

Optical polarimetry was used to study β Lyr as early as 1934, but it was not known until 1963 that the system exhibited variable polarization (Öhman 1934; Shakhovskoi 1963). Appenzeller & Hiltner (1967, hereafter AH) were the first to publish interstellar polarization (ISP) corrected broadband UBV polarization curves of β Lyr. More recently, HNF published ISP-corrected polarized light curves in the V band and Hα and He i λ5876 emission lines using a subset of the data we present here. HNF used the position angles (P.A.s) of the polarized UV continuum and the hydrogen Balmer emission lines to confirm that a bipolar outflow exists in the β Lyr system after their discovery by Harmanec et al. (1996). HNF also interpreted the average P.A. of the visible polarized light (164°) to be the physical axis of the binary system, an interpretation which was borne out by the interferometric images presented by Zhao et al. (2008) and Schmitt et al. (2009).

In this paper we present new BVRI and He i λ5876 polarization curves and polarized light curves of β Lyr. The details of our spectropolarimetric observations and our ISP corrections are in Section 2. Section 3 presents and displays our observational results. We analyze our findings in Section 4 and summarize conclusions in Section 5.

2. OBSERVATIONS

This study compiles data from three distinct data sets. The first consists of 69 optical spectropolarimetric observations of

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for our ISP estimate are 
P
β
curve to the error-weighted mean of the 11 observations of REDUCE software package (described by Wolff et al. 1996). A study. We reduced all of the HPOL observations using the published in HNF and have undergone recalibration for this midpoints of each observation of \( \beta \) Lyr B is a member of the same association as \( \beta \) Lyr taken over six years with the University of Wisconsin’s Half-Wave Spectropolarimeter (HPOL) at the 0.9 m telescope at Pine Bluff Observatory (PBO); the second data set comprises six years of broadband optical polarimetric data obtained at the Flower and Cook Observatory (FCO); and the third is three years of archived broadband optical polarimetric data from AH taken with the 24 inch rotatable telescope at the Yerkes Observatory. To calculate the phase for each observation, we subtracted this ISP estimate from the HPOL observations, 1995 May 27 and 1995 August 14, used only the red grating (3200–6000 Å). Each individual observation typically lasted between 45 minutes and an hour (approximately 0.03–0.04 days) when both gratings were used.

We used 11 HPOL observations of \( \beta \) Lyr B taken between 1995 May and 1999 November to obtain an ISP estimate. Beta \( \beta \) Lyr B is a member of the same association as \( \beta \) Lyr A and is located 45° away (Abt et al. 1962). All of these observations were made using HPOL’s CCD-based system. Table 1 also lists the civil and heliocentric Julian dates that correspond to the midpoints of each observation of \( \beta \) Lyr B and indicates which \( \beta \) Lyr CCD (after HNF, recalibrated)

\begin{table}[h]
\centering
\begin{tabular}{ll}
\hline
Date & HJD $-$ 2,400,000 & Phase$^a$ \\
\hline
1995 Mar 14$^b$ & 49790.89 & 0.848 \\
1995 May 5 & 49842.82 & 0.862 \\
1995 May 26 & 49863.82 & 0.485 \\
1995 May 27$^c$ & 49864.78 & 0.559 \\
1995 May 30 & 49867.84 & 0.796 \\
1995 Jun 4 & 49872.86 & 0.184 \\
1995 Jul 3 & 49901.66 & 0.410 \\
1995 Jul 10 & 49908.72 & 0.955 \\
1995 Jul 12 & 49910.82 & 0.117 \\
1995 Jul 18 & 49916.70 & 0.572 \\
1995 Jul 24 & 49922.79 & 0.043 \\
1995 Aug 6 & 49935.68 & 0.039 \\
1995 Aug 14$^d$ & 49943.63 & 0.653 \\
1995 Aug 18 & 49947.72 & 0.969 \\
1995 Sep 10 & 49970.74 & 0.749 \\
1996 Aug 21 & 50316.65 & 0.483 \\
1997 May 14$^e$ & 50585.78 & 0.283 \\
1997 May 26$^d$ & 50594.80 & 0.980 \\
1997 Jul 5 & 50634.82 & 0.073 \\
1997 Jul 7 & 50636.72 & 0.219 \\
1997 Jul 7 & 50636.80 & 0.226 \\
1997 Jul 10 & 50639.67 & 0.447 \\
1997 Jul 10 & 50639.77 & 0.455 \\
1997 Jul 10 & 50639.87 & 0.463 \\
1997 Jul 11 & 50640.68 & 0.525 \\
1997 Jul 11 & 50640.79 & 0.534 \\
1997 Jul 15 & 50644.66 & 0.833 \\
1997 Jul 15 & 50644.77 & 0.842 \\
1997 Jul 15 & 50644.86 & 0.848 \\
1997 Jul 16 & 50645.68 & 0.912 \\
1997 Jul 16 & 50645.78 & 0.920 \\
1997 Jul 18 & 50647.71 & 0.069 \\
1997 Aug 1 & 50661.64 & 0.145 \\
1997 Aug 25 & 50685.64 & 0.000 \\
1997 Aug 25 & 50685.74 & 0.008 \\
1997 Aug 25 & 50685.83 & 0.015 \\
1997 Aug 26 & 50686.66 & 0.079 \\
1997 Aug 30 & 50690.62 & 0.385 \\
1997 Sep 7 & 50698.63 & 0.004 \\
1997 Sep 7 & 50698.71 & 0.010 \\
1997 Sep 12 & 50703.77 & 0.401 \\
1997 Sep 21 & 50712.64 & 0.087 \\
1997 Sep 25 & 50716.73 & 0.403 \\
1997 Oct 3 & 50724.60 & 0.011 \\
1997 Oct 3 & 50724.70 & 0.019 \\
1997 Oct 4 & 50725.57 & 0.086 \\
1997 Oct 28 & 50749.54 & 0.939 \\
1997 Nov 17 & 50769.56 & 0.486 \\
\hline
\end{tabular}
\caption{Date and Phase Information for Midpoints of the HPOL \( \beta \) Lyrae and \( \beta \) Lyrae B Observations}
\end{table}
weighted mean of the observed polarization of the associated stars $\beta$ Lyr B, E, and F.

2.2. FCO Data Set

Our second data set is made up of 19 $B$-band, 88 $V$-band, and 17 $R$-band observations obtained at FCO between 1987 and 1992 with the photoelastic modulating polarimeter instrument (Holenstein 1991; Elias et al. 1996). The length of each observation was between 20 and 25 minutes (approximately 0.01 days). The phases along with the civil and heliocentric Julian dates for each observation are listed in Table 2. We have no observations of $\beta$ Lyr B taken with the same instrument as this data set. Therefore, we used the Serkowski fit to the HPOL $\beta$ Lyr B observations (see Section 2.1) to calculate the ISP contributions at the central wavelengths of the $BVR$ bands and subtracted these estimated values from the observations in this data set. We list these data and ISP subtracted data in Table 3.

2.3. AH Data Set

We also used archival $BV$ polarization data taken between 1964 and 1966, originally published in AH. This data set consists of 37 $B$-band and 127 $V$-band observations, the details of which can be found in AH (and references therein). The DC two-channel polarimeter was rotated 30$^\circ$ between 12 separate 20 s exposures of $\beta$ Lyr and the sky (Appenzeller 1965). Therefore, the total integration time for both $\beta$ Lyr and the sky was 4 minutes (approximately 0.003 days). We converted these data from polarization magnitudes to percent polarization and converted their Julian dates to heliocentric Julian dates for use in this study. For consistency between the HPOL and AH data sets, we did not use AH’s published ISP-corrected data because it included two stars ($\beta$ Lyr E and F) that are not included in the HPOL ISP estimate. Instead, we subtracted only the AH $BV \beta$ weighted mean of the observed polarization of the associated stars $\beta$ Lyr B, E, and F.

Table 1

| Date          | HJD−2,400,000 | Phase       |
|---------------|---------------|-------------|
| 1997 Dec 15   | 50797.50      | 0.645       |
| 1998 Apr 19   | 50922.86      | 0.333       |
| 1998 Apr 24   | 50927.90      | 0.723       |
| 1998 Jun 23   | 50987.82      | 0.354       |
| 1998 Jul 31   | 51025.78      | 0.287       |
| 1998 Aug 31   | 51056.62      | 0.671       |
| 1998 Sep 8    | 51064.76      | 0.300       |

Table 2

| Date          | HJD−2,400,000 | Phase       |
|---------------|---------------|-------------|
| 1995 May 21   | 49858.85      | ···          |
| 1996 Jul 3    | 50267.75      | ···          |

Notes.

- $^a$ Phases were calculated using the ephemeris in Harmanec & Scholz (1993).
- $^b$ Table 1 of HNF incorrectly lists this date as 1994 March 14.
- $^c$ These observations used only the red grating; see Section 2.1.
- $^d$ These observations used only the blue grating; see Section 2.1.
| Date       | HJD−2,400,000 | Phasea |
|------------|---------------|--------|
| 1988 Oct 30| 47464.50      | 0.037  |
| 1988 Oct 31| 47465.49      | 0.115  |
| 1988 Nov 4 | 47469.50      | 0.424  |
| 1988 Nov 10| 47475.53      | 0.888  |
| 1988 Nov 14| 47479.50      | 0.197  |
| 1988 Nov 15| 47480.47      | 0.274  |
| 1988 Nov 18| 47483.49      | 0.506  |
| 1989 Apr 12| 47628.85      | 0.733  |
| 1989 Apr 20| 47636.83      | 0.352  |
| 1989 Apr 23| 47639.83      | 0.583  |
| 1989 May 29| 47675.78      | 0.366  |
| 1989 Jun 5 | 47682.80      | 0.907  |
| 1989 Jun 12| 47689.82      | 0.448  |
| 1989 Jun 19| 47696.80      | 0.989  |
| 1989 Jun 30| 47707.78      | 0.840  |
| 1989 Jul 2 | 47709.81      | 0.994  |
| 1989 Jul 25| 47732.76      | 0.772  |
| 1989 Jul 29| 47736.82      | 0.081  |
| 1989 Aug 31| 47769.70      | 0.632  |
| 1989 Sep 3 | 47772.60      | 0.844  |
| 1989 Sep 4 | 47773.61      | 0.922  |
| 1989 Sep 5 | 47774.60      | 0.999  |
| 1989 Sep 9 | 47778.60      | 0.308  |
| 1989 Oct 2 | 47801.68      | 0.105  |
| 1989 Oct 23| 47822.59      | 0.709  |
| 1992 Jun 13| 48786.72      | 0.239  |
| 1992 Jun 18| 48791.65      | 0.625  |
| 1992 Jun 21| 48794.62      | 0.838  |
| 1992 Jun 28| 48801.73      | 0.398  |
| 1992 Jun 29| 48802.67      | 0.476  |
| 1992 Jul 6 | 48809.68      | 0.017  |
| 1992 Jul 8 | 48811.59      | 0.152  |
| 1992 Jul 19| 48822.60      | 0.002  |
| 1992 Jul 29| 48832.57      | 0.775  |
| 1992 Jul 30| 48833.58      | 0.852  |
| 1992 Aug 2 | 48836.61      | 0.084  |
| 1992 Aug 3 | 48837.60      | 0.161  |
| 1992 Aug 5 | 48839.60      | 0.316  |
| 1992 Aug 8 | 48842.56      | 0.548  |
| 1992 Aug 11| 48845.56      | 0.780  |
| 1992 Aug 19| 48853.54      | 0.398  |
| 1992 Aug 30| 48864.56      | 0.248  |
| 1992 Sep 1 | 48866.60      | 0.403  |
| 1992 Sep 13| 48878.55      | 0.330  |

R Band

| Date       | HJD−2,400,000 | Phase |
|------------|---------------|-------|
| 1989 Apr 12| 47628.90      | 0.753  |
| 1989 Apr 20| 47636.81      | 0.352  |
| 1989 Apr 23| 47639.79      | 0.583  |
| 1989 May 29| 47675.76      | 0.366  |
| 1989 Jun 5 | 47682.83      | 0.907  |
| 1989 Jun 12| 47689.84      | 0.448  |
| 1989 Jun 19| 47696.82      | 0.989  |
| 1989 Jun 30| 47707.80      | 0.840  |
| 1989 Jul 2 | 47709.83      | 0.994  |
| 1989 Jul 25| 47732.78      | 0.772  |
| 1989 Jul 29| 47736.84      | 0.081  |
| 1989 Aug 31| 47769.72      | 0.632  |
| 1989 Sep 3 | 47772.62      | 0.844  |
| 1989 Sep 5 | 47774.62      | 0.999  |
| 1989 Sep 9 | 47778.62      | 0.308  |
| 1989 Oct 2 | 47801.65      | 0.105  |
| 1989 Oct 10| 47809.61      | 0.704  |

Note. a Phases were calculated using the ephemeris in Harmanec & Scholz (1993).
he estimated the P.A. of the system orientation given by Zhao et al. (2008) and Schmitt et al. (2009). Zhao et al. (2008) estimated the P.A. of the polarized light is perpendicular to the P.A.s of the sky. As expected for polarization by electron scattering, the P.A. of the polarized light is perpendicular to the P.A.s describing the system’s ascending node as 253°22 ± 1°97 and 251°87 ± 1°83 using two different image reconstruction techniques on their interferometric data and 254:39 ± 0:83 using a model of the system, while Schmitt et al. (2009) estimate 249:0 ± 4:0. We rotated all of the HPOL, AH, and FCO data to the average P.A. of 164°. This orients our data with respect to the intrinsic polarization axis of the system. After this rotation, %U averages to zero in each band and the polarization varies significantly only in the %Q direction. In the rest of this paper, we present the projected Stokes parameter %Q_p, resulting from this rotation. The use of this quantity is beneficial because it can be positive or negative, whereas %P is always positive. Data points that have a P.A. near 164° will have a positive %Q_p value while points with a P.A. perpendicular to this (near 74°) will have a negative %Q_p. Hereafter we display only %Q_p because %U_p values scatter around zero. Because the rotation is a simple trigonometric calculation, we present in Tables 3 and 4 the results of the fits are displayed as solid curves in each figure and their parameters.

### Table 3

| Phase | HJD−2,400,000 | %Q  | %U  | ISP Sub %Q | ISP Sub %U | σ_i,Q | σ_i,U |
|-------|---------------|------|------|------------|------------|-------|-------|
| 0.081 | 47736.79      | 0.395| −0.432| 0.164      | −0.067     | 0.007 | 0.007 |
| 0.308 | 47778.57      | 0.579| −0.493| 0.348      | −0.128     | 0.016 | 0.014 |
| 0.318 | 47804.45      | 0.617| −0.527| 0.386      | −0.162     | 0.010 | 0.008 |
| 0.352 | 47636.85      | 0.405| −0.438| 0.174      | −0.073     | 0.008 | 0.008 |
| 0.366 | 47675.80      | 0.549| −0.520| 0.318      | −0.155     | 0.009 | 0.008 |
| 0.448 | 47689.80      | 0.257| −0.261| 0.026      | 0.104      | 0.007 | 0.007 |
| 0.543 | 48777.76      | 0.148| −0.350| −0.083     | 0.015      | 0.009 | 0.009 |
| 0.550 | 47807.60      | 0.460| −0.698| 0.229      | −0.333     | 0.016 | 0.023 |
| 0.583 | 47639.85      | 0.421| −0.527| 0.190      | −0.162     | 0.008 | 0.010 |
| 0.632 | 47769.68      | 0.497| −0.517| 0.266      | −0.152     | 0.010 | 0.010 |

**Notes.** The σ_i,Q and σ_i,U columns represent internal errors.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 4

| Phase | HJD−2,400,000 | %Q  | %U  | ISP Sub %Q | ISP Sub %U | σ_i,Q | σ_i,U |
|-------|---------------|------|------|------------|------------|-------|-------|
| B Band Reticon | | | | | | |
| 0.000 | 49663.46      | 0.423| −0.659| 0.2020     | −0.2953    | 0.0019 | 0.0200 |
| 0.121 | 48901.67      | 0.3905| −0.4928| 0.1603     | −0.1289    | 0.0030 | 0.0200 |
| 0.206 | 49562.62      | 0.4691| −0.4456| 0.2388     | −0.0816    | 0.0062 | 0.0200 |
| 0.292 | 49615.49      | 0.4248| −0.5536| 0.1945     | −0.1897    | 0.0015 | 0.0200 |
| 0.358 | 49564.59      | 0.4874| −0.4409| 0.2572     | −0.0770    | 0.0023 | 0.0200 |
| 0.368 | 49603.53      | 0.4823| −0.4503| 0.2521     | −0.0864    | 0.0016 | 0.0200 |
| 0.525 | 48984.52      | 0.2897| −0.4828| 0.0594     | −0.1188    | 0.0034 | 0.0200 |
| 0.657 | 48908.60      | 0.5574| −0.5334| 0.3272     | −0.1695    | 0.0030 | 0.0200 |
| 0.661 | 48895.71      | 0.5392| −0.5076| 0.3090     | −0.1436    | 0.0023 | 0.0200 |

**Notes.** The σ_i and σ_u columns represent internal and systematic errors, respectively.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 5

| Band | HPOL Reticon (deg) | HPOL CCD (deg) | AH (deg) | FCO (deg) |
|------|--------------------|----------------|----------|-----------|
| B    | 139.8 ± 3.5        | 165.0 ± 0.7    | 169.8 ± 1.7 | 165.1 ± 0.9 |
| V    | 147.3 ± 3.0        | 164.0 ± 0.5    | 171.8 ± 1.0 | 163.1 ± 0.4 |
| R    | 158.4 ± 0.4        | 158.3 ± 0.4    | ...     | 162.2 ± 0.7 |
| I    | 57.3 ± 3.0         | 162.7 ± 0.6    | ...     | ...       |
| Index| 158.8 ± 0.6        | 142.1 ± 1.7    | ...     | ...       |
| Hα  | ...                | 47.9 ± 9.7     | ...     | ...       |
| Hβ  | ...                | 71.1 ± 2.5     | ...     | ...       |
| Hελ 5876 | ...                | 63.8 ± 6.4    | ...     | ...       |
| Hελ 7065 | ...                | 51.0 ± 3.2    | ...     | ...       |
| Hελ 6678 | ...                | 138.2 ± 6.6   | ...     | ...       |

**Notes.** These values were calculated by fitting a line in Q–U space to the data, excluding points between phases 0.475 and 0.525. For the HPOL data, we used systematic errors in both Q and U in the least-squares fit calculation for all bands except the Balmer jump index (the vector difference between the polarization above and below the Balmer jump) and the lines, for which we used the intrinsic errors. See Sections 3.1 and 3.2.
Figure 1. Data points represent the B-band polarimetric observations from HPOL Reticon (diamonds), HPOL CCD (squares), AH (circles), and FCO (triangles). From top: normalized V-band Fourier fit light curve (Harmanec et al. 1996), projected polarization (see Section 3.1), and position angle (degrees) vs. phase. Error bars are shown for uncertainties larger than 0.025 in %Qp and 5° in position angle. The HPOL error bars shown represent the larger of the intrinsic and systematic uncertainties. All data have been wrapped so that more than one complete period is shown. The solid line in the middle panel represents our Fourier fit to the %Qp data (see Section 3.1). The dotted horizontal line represents zero projected polarization. Phases 0.0, 0.5, and 1.0 are marked by the dotted vertical lines. The solid line in the bottom panel represents the average position angle of 164°.

(A color version of this figure is available in the online journal.)

Figure 2. Same as Figure 1, but for V-band polarimetry. The dashed blue curve (in the online version, otherwise dashed light gray) represents the three-term Fourier fit and the red curve (in the online version, otherwise solid) represents the two-term Fourier fit. Note the two fits differ at primary and secondary eclipse, the quadrature phases, and near phases 0.15 and 0.9.

(A color version of this figure is available in the online journal.)

Figure 3. Same as Figure 1, but for R-band polarimetry.

(A color version of this figure is available in the online journal.)

Figure 4. Same as Figure 1, but for I-band polarimetry.

(A color version of this figure is available in the online journal.)

we are not as confident in the third frequency as we are in the first two because the PERIOD04 fitting program produces a reasonable third term for the V band only. Therefore, in Table 6 we report parameters for only the first two terms, but we display both the two-term and three-term fits in Figure 2. These fits provide the first quantitative representations of the polarization variations in the β Lyr system.

The data in the BVRI bands are almost always positive, indicating that their P.A.s stay near 164° throughout the orbital period. Each of the bands displays an increase in %Qp at primary eclipse and two other increases near the quadrature phases (0.25 and 0.75). The height difference between the polarization bumps at the quadrature phases noted by HNF disappears now that more data are added, but we note that the B and V phase 0.25 bumps have a higher dispersion around the average %Qp value than does the 0.75 phase bumps. The R and I bands show the opposite behavior; future observations will be able to tell us whether this
is due to their poor phase coverage or whether it indicates that the R and I bands are probing a different region of the disk than the B and V bands. We calculated the variance of the two quadrature bumps between phases 0.25 and 0.35, and 0.65 and 0.75 to formally show this. The first quadrature bump has BVRI variances of 0.081 ± 0.006, 0.110 ± 0.005, 0.040 ± 0.002, and 0.016 ± 0.002, respectively, while the second quadrant bump has variances of 0.048 ± 0.005, 0.027 ± 0.002, 0.281 ± 0.005, and 0.069 ± 0.004.

The R and I bands also produce a lower polarization signal than the B and V bands. This change in polarization behavior with wavelength could indicate that scattering mechanisms other than electron scattering are present in the system. However, more observations in the R and I bands are needed to rule out the possibility that the low signal is due to a lack of phase coverage in these bands.

Figures 1 through 4 also show that in each band, the polarization curve has a fitted minimum in polarization that occurs just prior to the secondary eclipse in total light. This minimum is accompanied by a rotation in the P.A. of the polarized light away from its average value. Table 7 gives the Fourier fit minimum is accompanied by a rotation in the P.A. of the polarized light away from its average value. Table 7 gives the minimum is accompanied by a rotation in the P.A. of the polarized light away from its average value. Table 7 gives the minimum is accompanied by a rotation in the P.A. of the polarized light away from its average value. Table 7 gives the percentage of the $Q_p$ Fourier fit minimum in all bands. The offset between secondary eclipse in polarized light and total light is a new result, seen here for the first time due to the improved phase coverage in these data. We discuss the implications of this phenomenon in Section 4.

At primary eclipse, there are hints of similar behavior: the polarization maxima in the $B$ and $V$ bands occur slightly before phase 0.0, and all bands show a deviation from the mean P.A. at and just after phase 0.0. However, we consider the primary eclipse features to be less significant than the ones at secondary eclipse for the following reasons. The three data points showing noticeable deviations from the mean P.A. all occurred on the same night, 1997 August 25, which suggests that this effect may be due to a non-periodic process intrinsic to the β Lyrae system or to a change in observing conditions that affected that night’s data. If the same structure is responsible for the phenomena at both eclipses, we expect that a similar P.A. scatter should exist in observations from the same orbit of the system whose phases are between primary and secondary eclipse, when such a structure should be most visible to the observer. However, neither the data from 1997 August 26 nor 1997 August 30 show such behavior. Additionally, the polarization maximum in the $B$ band occurs at phase 0.0 within the uncertainties, and in the I band the maximum occurs just after phase 0.0. If we include the third term in the $V$-band Fourier fit, the primary polarization maximum occurs at phase 0.0 within uncertainties. Because the eclipse behavior is not consistent between bands and the associated P.A. scatter appears to have occurred during only one orbit of the system, we consider it unlikely that these are due to a stable physical structure within the system (see Section 4 for further discussion of the effects seen at primary eclipse).

Figure 5 displays the projected polarized BVRI flux light curves for the β Lyrae system. To create these polarized light curves, we multiplied the fitted polarization curves shown in Figures 1 through 4 by their respective Fourier fit light curves. The secondary eclipse offset seen in Figures 1 through 4 persists in Figure 5, while quadrature phases display local maxima. The $B$ and $V$ bands appear to be the most similar; they overlap for most phases, while outside of secondary eclipse and the first quadrature phase the $R$ and $I$ bands produce the lowest net projected polarized flux. We do not consider the apparent

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### Table 6

| Band | Zero Point | Term | Ω   | A       | φ   |
|------|-----------|------|-----|---------|-----|
| B    | 0.239470  | 1    | 2.98 ± 0.01 | 0.127 ± 0.009 | 0.30 ± 0.01 |
|      |           | 2    | 1.00 ± 0.02 | 0.078 ± 0.008 | 0.37 ± 0.02 |
| V    | 0.243419  | 1    | 2.98 ± 0.01 | 0.096 ± 0.007 | 0.30 ± 0.01 |
|      |           | 2    | 1.01 ± 0.03 | 0.050 ± 0.006 | 0.36 ± 0.02 |
| R    | 0.241148  | 1    | 3.00 ± 0.01 | 0.107 ± 0.008 | 0.32 ± 0.01 |
|      |           | 2    | 4.02 ± 0.03 | 0.052 ± 0.009 | 0.08 ± 0.03 |
| I    | 0.195021  | 1    | 3.00 ± 0.01 | 0.093 ± 0.006 | 0.30 ± 0.01 |
|      |           | 2    | 4.01 ± 0.02 | 0.050 ± 0.006 | 0.10 ± 0.02 |

Notes. These parameters describe our Fourier fits to the broadband polarimetric data in the combined HPOL, FCO, and AH data sets. See Section 3.1.

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### Table 7

| Band | Phase | Min P.A. Phase Rot | Max P.A. Phase Rot | Hot Spot Size in Phase | $q_{16C}$ | $q_{1mu}$ | HS$P_A$ | HS$SM (i = 90°)$ | HS$SM (i = 86°)$ |
|------|-------|-------------------|--------------------|------------------------|----------|----------|---------|----------------|----------------|
| B    | 0.481 ± 0.004 | 0.448 | 0.543 | 0.095 | 0.186 | 0.045 | 22 R⊙ | 33 R⊙ | 31 R⊙ | 26 R⊙ |
| V    | 0.481 ± 0.004 | 0.385 | 0.554 | 0.169 | 0.184 | 0.080 | 22 R⊙ | 58 R⊙ | 18 R⊙ | 9 R⊙ |
| R    | 0.449 ± 0.005 | 0.448 | 0.524 | 0.076 | 0.171 | 0.080 | 33 R⊙ | 26 R⊙ | 19 R⊙ | 10 R⊙ |
| I    | 0.449 ± 0.004 | 0.448 | 0.524 | 0.076 | 0.140 | 0.077 | 33 R⊙ | 26 R⊙ | 12 R⊙ | 2 R⊙ |

Notes. Columns 2–6 are parameters used in the three hot spot size estimates (see Sections 4.1–4.3). Flux normalized to maximum light was used for $q_{16C}$ and $q_{1mu}$. The last four columns represent the width of the hot spot calculated using our different estimates (see Section 4). All three polarimetric data sets were used in this analysis and the resulting estimates.
height differences between bands at the quadrature phases to be significant due to the scatter in the observational points and the lack of coverage in the $R$ and $I$ bands.

3.2. Line Polarimetry

We also took advantage of the spectropolarimetric nature of the HPOL data by studying the polarization behavior of the strongest optical emission lines in $\beta$ Lyr’s spectrum: H$\alpha$, H$\beta$, He $\lambda$ 5876, H$\epsilon$ $\lambda$ 6678, and He $\epsilon$ $\lambda$ 7065. HNF hypothesized that the H$\alpha$, H$\beta$, He $\lambda$ 5876, and He $\epsilon$ $\lambda$ 7065 lines, which show a negative projected polarization, scatter in the bipolar outflow, while the He $\epsilon$ $\lambda$ 6678 scatters on the edge of the disk. However, HNF did not have enough data to construct a full polarization phase curve for the lines. Our expanded data set allows us to do this. However, we present only our He $\epsilon$ $\lambda$ 5876 results in graphical form because our uncertainties are relatively large due to signal-to-noise limitations. Rather than present the H$\alpha$, H$\beta$, He $\epsilon$ $\lambda$ 6678, and He $\epsilon$ $\lambda$ 7065 data, we describe their general behavior below. Future observations will allow us to use these data to draw quantitative conclusions about the scattering regions that give rise to the polarization in these lines.

In order to calculate the polarization for each emission line, we used the flux equivalent width method described by HNF, using the same line and continuum regions as far as possible. We corrected the H$\alpha$ and H$\beta$ lines for underlying unpolarized absorption components (arising from the loser) in the same manner as HNF, using their preferred absorption equivalent widths of $8 \pm 2$ Å for H$\alpha$ and $6 \pm 1$ Å for H$\beta$. This has the following effect on the data. The continuum is positively polarized while the lines are negatively polarized. If we do not correct for unpolarized absorption, we remove too much continuum, and thus our resulting line polarization is too negative. With the absorption correction, the continuum contribution is smaller and the magnitude of the polarization is also smaller, resulting in a less negative $%Q_p$.

We do not present the HPOL Reticon line polarization values due to their large uncertainties. Figure 6 shows $%Q_p$ and P.A. curves for the He $\epsilon$ $\lambda$ 5876 line. It has a negative $%Q_p$, thus its P.A. is perpendicular to the intrinsic axis of the system. In addition, the polarization for the line approaches zero at both primary and secondary eclipses. For this to happen, the scattering region for this line must lie near enough to the orbital plane of the system to be occulted both by the loser and by the disk. HNF previously suggested that this line scatters in the bipolar outflows because its average P.A.s lie near 74°, corresponding to negative values of $%Q_p$. The results from our extended data set support this interpretation and further suggest that the He $\epsilon$ $\lambda$ 5876 scattering region within the outflows must lie between the loser and the disk and have a vertical extent comparable to the height of the disk.

The H$\alpha$, H$\beta$, and He $\epsilon$ $\lambda$ 7065 lines also all display a negative $%Q_p$ and are likely scattered in the same region as the He $\epsilon$ $\lambda$ 5876 line. Their average P.A.s are listed in Table 5.

The He $\epsilon$ $\lambda$ 6678 data show a polarization behavior different from that of the other lines. The data are generally positively polarized and their average P.A., 138°±2, agrees more closely with the intrinsic axis of the system than do those of the other emission lines (see Table 5).

3.3. Period Analysis

Besides the primary orbital period of $\beta$ Lyr (12.9 days), analysis of light curves has revealed several longer periodicities.

A 340 day period was detected by Peel (1997), while both van Hamme et al. (1995) and Harmanec et al. (1996) detected a 282 day period. Wilson & van Hamme (1999) searched polarimetry from AH, HNF, Serkowski (1965), and Shulov (1967) for periodicities but did not detect anything significant.

We performed a Lomb–Scargle power spectrum analysis to search for any periodic behavior in our polarimetric broadband (HPOL, AH, and FCO) and line data (H$\alpha$ and He $\epsilon$ $\lambda$ 5876) not associated with the 12.9 day orbital period of the system. While none of the previously detected longer periods were found, our analysis indicates the presence of periods of approximately 4.3 days in both the $V$ and $B$ bands with a False Alarm Probability (FAP; Horne & Baliunas 1986) of 10−6 when using all three data sets. None of the other bands or the line polarization data appear to contain periods other than the orbital period. We also searched for periods within the HPOL, AH, and FCO data sets individually to look for any transient periodic variations. We find that the 4.3 day period also appears in the $V$ and $B$ AH data set with a FAP of 10−6, but it does not appear in the other two data sets. This period is exactly one-third of the 12.9 day orbital period of the $\beta$ Lyr system and results from the combination of two separate effects: the increase in polarization at the quadrature phases due to light scattering off the disk edge and the increase in polarization at primary eclipse due to the occultation of unpolarized light by the loser (Hoffman et al. 2003, hereafter HWN). These two effects cause the $%Q_p$ curves to form a complete cosine curve between phases 0.0 and 0.3, a second cosine curve between phases 0.3 and 0.6, and a third cosine between 0.6 and 1.0 (see Figures 1 through 4). Therefore, this period does not provide new information about the $\beta$ Lyr system.

We also performed a much simpler analysis to search for signatures of the 282 day period, which has been ascribed to variability of the conditions of the circumstellar and circumbinary gas (Wilson 1974; Ak et al. 2007). Time plots of $%Q_p$, $%U_p$, P.A., and percent polarization for each of the $BVRI$ bands.
and the He $\lambda$ 5876 line did not reveal the 282 day period and are therefore not shown. However, the time coverage of our observations is very uneven and could have prevented us from detecting variations on this timescale. The observations in our data set were taken between 1964 and 1998, but we have no polarimetric observations taken during 1990, 1991, or between 1966 and 1987. The number of observations performed per year only adds further complications; several years have very few observations. We also note that the only the HPOL data set has observations of every band and the He $\lambda$ 5876 line. For these reasons, we also performed an analysis similar to Harmanec et al. (1996) on the $Q_p$ data for each band and the He $\lambda$ 5876 line. Plotting the data on the 282.37 day period mitigates the lack of time coverage by “folding” observations onto one cycle.

We plotted the data from selected orbital period phase bins versus their phase on the 282.37 day period (see Harmanec et al. 1996 for a similar analysis of a large amount of $V$ band total-light photometry). We chose the following five orbital phase bins for several reasons: the 0.0–1.0 bin allows us to use all of the data, the 0.6–0.15 bin is where Harmanec et al. (1996) detected the 282.37 day period the most strongly, the 0.25–0.35 and 0.65–0.75 bins allow us to determine whether the polarization of the quadrature phases changes on a 282.37 day timescale, and the 0.425–0.575 bin allows us to determine whether the secondary eclipse has a 282.37 day periodic behavior. The 0.25–0.35, 0.425–0.575, and 0.65–0.75 orbital period bins are too tight to leave a useful number of observations in the $R$ and $I$ bands and the He $\lambda$ 5876 line. While the $B$ and $V$ bands are slightly less affected by the size of the 0.25–0.35, 0.425–0.575, and 0.65–0.75 orbital phase bins, their behavior does not indicate, by eye or by using PERIOD04, the presence of a variation on a 282.37 day period. The size of the 0.6–0.15 and 0.0–1.0 bins presents the best chance of detecting this period because the amount of data is not severely reduced. However, neither bin reveals the presence of the 282.37 day period. We also subtracted the Fourier fits from the data in the $BVRI$ bands (see Section 3.1) and searched the residuals for the 282.37 day period with the same bins used for the original $Q_p$ data. The analysis on the residuals produced similar results; we do not find evidence of a 282.37 day period in either the $Q_p$ data or the Fourier fit subtracted residuals. However, we note that the Fourier fits deviate from the data at some phases (see Section 3.1). Plots from this analysis resemble scatter plots and are therefore not shown.

4. DISCUSSION

In interpreting their polarized flux curves, HNF proposed two different possibilities for the origin and scattering location of the visible light. In their “disk–disk” case, this light arises from within the disk and scatters from the disk edge; in the “loser-lobe” case, the $V$-band continuum light arises from the loser and scatters from material between the loser and the disk. In this analysis, HNF implicitly assumed that all features of the visible polarized flux curve are due to the same origin and scatterer. However, modeling work by J. L. Hoffman has shown that the scattered light can originate both from the loser and from the disk in differing proportions over the binary cycle. These newer results suggest the following interpretations of our $BVRI$ polarization curves. The net increase in $Q_p$ at primary eclipse (Figures 1–4) is the result of the unpolarized light from the primary star being blocked by the disk material at phase 0.0. HNF interpreted the increase in $Q_p$ at the quadrature phases as arising in one of the two ways: light originating from within the disk and scattering from the disk edge, or light originating from the loser and scattering from material between the stars. We propose, based on the HWN results and the recent modeling work by J. L. Hoffman, that these “quadrature bumps” form simply by loser light scattering from the disk edge. The minimum at secondary eclipse occurs because the unpolarized primary star blocks light scattered in the secondary component.

Near secondary eclipse in all four broadband $Q_p$ curves, the minimum in polarization precedes the minimum in total light; the phases for the polarization minimum in the $BVRI$ bands are listed in Table 7. In each band, this minimum corresponds to a rotation in P.A. away from the average value; the phase ranges for this rotation are also listed in Table 7. In the basic star–star–disk model for the system, there is no mechanism to produce this disparity. If the loser is an unpolarized source, as indicated by the absence of a primary eclipse in the polarized flux curves (Figure 5; HNF), then the polarization minimum produced by its transit across the disk should be centered at flux minimum (phase 0.5; HWN). Thus, to explain this offset, we need to invoke another system component. Since $\beta$ Lyr is a mass transfer system, it most likely contains a mass stream connecting the loser and the disk as well as a “hot spot” where the mass stream from the loser interacts with the disk edge (Lubow & Shu 1975, see also the geometries proposed by HNF). Some studies (for example, Bisikalo et al. 2000 and references therein) suggest that the manner in which the mass stream approaches the disk prevents a hot spot from forming. Instead, a portion of the stream makes a full revolution around the disk and then interacts with the original stream. The process of this interaction allows the material that has made a full revolution around the secondary star to become part of the mass stream again; Bisikalo et al. (2000) do not consider it to be part of the disk. Since this material’s P.A. is the same as the disk in the system, polarimetry cannot distinguish between the two possibilities. Therefore, we use the term “hot spot” to refer to the region where the mass stream interacts with material already encircling the secondary star and assume that any material which has completed a revolution around the secondary star is part of the disk.

Even if a true “hot spot” is not created by the mass stream–disk interaction, the region where the stream and disk meet could potentially decrease observed polarization from the disk edge by disrupting the otherwise smooth structure of the disk edge and adding unpolarized light at phases when it is visible. On the other hand, the mass stream, which is elongated in the same direction as the disk, should produce a polarization P.A. very similar to that of the disk. Therefore, the presence of the mass stream should not lead to a decrease in the observed polarization. The effects of a hot spot would be detectable in the polarization light curves in the $BVRI$ bands because the disk is the primary scattering region for visible light in the $\beta$ Lyr system. But, if it is not significantly brighter than the surrounding disk, the hot spot would not be visible in the total light curves. Therefore, we interpret the $Q_p$ minimum associated with the randomization of the polarized P.A. prior to secondary eclipse as the first direct evidence for the proposed hot spot on the $\beta$ Lyr disk edge (Lubow & Shu 1975; Harmanec 2002).

We expect the hot spot to create an unstructured region on the disk edge where the polarization vectors of the scattered light are randomized in P.A. When this part of the disk is visible, the hot spot should cause a decreased polarization signal and a rotation in P.A., both of which occur in our polarization
curves (Figures 1–4). As long as the hot spot does not lie on the line connecting the centers of mass of the two stars, and its brightness in the visible continuum is similar to that of the undisturbed disk, its effect should result in a minimum in polarization that does not correspond to a minimum in flux. Hydrodynamical modeling of the β Lyr system indicates that the mass stream, and therefore its associated hot spot, should lead the loser in the sense of rotation of the system (Lubow & Shu 1975; Nazarenko & Glazunova 2006). In the β Lyr polarization curves, the polarization minimum and concurrent P.A. variation occur just before secondary eclipse, suggesting that the hot spot begins its transit of the disk before the loser does. In fact, the larger dispersion of points in the $B$ and $V$ bands at the first quadrature phase when compared to the second quadrature phase suggests that the hot spot is already in view by phase 0.25. In this picture, the minimum polarization occurs at the phases where the disk area disrupted by the hot spot and eclipsed by the loser is maximized. The minimum in flux occurs as the hot spot is rotating off the edge of the visible disk. The second maximum in polarization occurs when the area eclipsed by the loser in the sense of rotation of the system (Lubow & Shu 1975; Nazarenko & Glazunova 2006). In the $B$ and $V$ bands at the first quadrature phase and phase 0.5.) The P.A. rotation does not heavily depend on the number of points, is apparent in all bands, and has a larger effect at pre-secondary eclipse phases than post-secondary eclipse phases. Finally, the uncertainties on the phases at which the minima occur are small (see Table 7) compared to the difference between phase 0.5 and the polarization secondary minimum. Future work will include filling in the post-secondary data gap with new HPOL observations to improve the Fourier fits and quantify the %Q$_P$ near secondary minimum offsets more reliably.

In the subsections below, we outline three different estimates of the size of the hot spot, assuming it has the same height as the edge of the disk. We use the following values for system parameters: a loser radius of $R_L = 15\, R_\odot$, a disk diameter of $D_D = 60\, R_\odot$, a binary separation of $R_S = 58\, R_\odot$, and a disk height of $H_D = 16\, R_\odot$ (Linnell 2000; Harmanec et al. 1996).

4.1. Hot Spot Size Estimate: %Q$_P$ Method

We can use the offset in secondary eclipse to estimate a maximum size for the hot spot. Assuming circular orbits, we have the scenario depicted in Figure 8. Knowing that phase 0.5 occurs at an angle of 180° on the circle depicting the loser’s orbit, we can use a simple ratio to find the angle $\theta$,

$$\frac{0.5}{180^\circ} = \frac{P}{180^\circ - \theta},$$

Figure 8. Sketch of the geometry we used for our hot spot size estimates (not to scale; see Section 4). We used parameters obtained by Linnell (2000) for the disk height, disk diameter, loser radius, and separation between the two components. The hatched region in the Observer’s View represents the hot spot size based on the %Q$_P$ method (see Section 4.1). The blackened area of the circle in the Observer's View is the un eclipsed area of the loser at primary eclipse. The filled square inside the accretion disk in the Polar View indicates the location of the roots of the bipolar outflows as given by the $H\alpha$ absorption core while the filled star represents the same thing for the $H\alpha$ emission wings (Harmanec et al. 1996).
where \( P \) is the phase for which secondary eclipse occurs in polarized light (Table 7) and 180° - \( \theta \) is the angle from zero at which phase \( P \) occurs. If we know \( \theta \), we can also find the length of line \( x \),

\[
x = R_S \sin(\theta),
\]

where \( R_S \) is the radius between the center of the disk and the center of the loser. With the length of line \( x \) we can estimate the projected size of the hot spot, \( H_{SQ} \) (hatched region in the Observer’s View in Figure 8), with the following equation:

\[
H_{SQ} = \begin{cases} 
60 R_\odot & \text{for } x \geq \frac{1}{2} D_D, \\
(x - R_L) + \frac{1}{2} D_D & \text{for } \frac{1}{2} D_D > x > R_L, \\
\frac{1}{2} D_D - (R_L - x) & \text{for } R_L > x > 0
\end{cases}
\]

where \( D_D \) is the diameter of the accretion disk and \( R_L \) is the radius of the loser.

Using the above formulae we can calculate the maximum projected hot spot size for the \( BVRI \) bands. Table 7 lists the results. The maximum hot spot size ranges from 22 \( R_\odot \) to 33 \( R_\odot \). Since we assume that the hot spot has the same height as the disk, these values represent “widths” along the projected face of the disk. We do not calculate formal error bars on these estimates because the estimates vary so widely.

4.2. Hot Spot Size Estimate: Position Angle Method

We also used the variations in P.A. to estimate a maximum size for the hot spot. First, we calculated the size of the disk in phase. To do this we solved Equation (2) for \( \theta \) when \( x = (1/2)D_D \). The phase for the left side of the disk as depicted in Figure 8 is then given by Equation (1). We calculate this phase to be 0.413, Similarily for the right side of the disk we calculate a phase of 0.587. The resulting size of the disk in phase is the difference of these phases, or 0.174.

We then estimated the size of the hot spot in phase by finding how long the randomization of P.A. lasts. We assumed any points near secondary eclipse that deviated significantly from the average P.A. were due to the hot spot. We did not use a formal calculation to find these points; we chose the smallest and largest phases for the randomized P.A.’s by eye. We then took the difference in phase between the deviant observations with the smallest and largest phases to calculate the size of the hot spot in phase, \( \theta_{HS} \) (Table 7). In this case the maximum hot spot size, \( H_{SP,A} \), is given by the ratio

\[
\frac{60 R_\odot}{0.174} = \frac{H_{SP,A}}{\theta_{HS}}.
\]

Table 7 lists the maximum projected size of the hot spot across the edge of the disk for each band. Our hot spot size estimates found with this method range from 26 \( R_\odot \) to 58 \( R_\odot \).

4.3. Hot Spot Size Estimate: Simple Model

We used a simple model for a third estimate of the size of the hot spot. For this model we assume that the polarization of the disk is uniform across the disk edge. We first calculated a baseline \( q_{fDC} \), the polarized flux due to the disk’s self-illumination, by taking the error-weighted mean \( %Q_F \) multiplied by the normalized Fourier fit flux of the observations between phases 0.7 and 1.2 for each band (HWN). This assumes that all the polarized flux at these phases is due to light originating within the disk rather than from the loser, a reasonable assumption given the results of HWN. We also define \( q_f_{min} \), the minimum polarized flux near secondary eclipse due to the primary star’s eclipse and hot spot’s transit of the disk, to be the error-weighted mean \( %Q_F \) multiplied by the normalized Fourier fit flux for observations between phases 0.4 and 0.55. If we subtract from \( q_{fDC} \) the amount of polarized flux blocked by the primary star and displaced by the transit of the hot spot, the result should be \( q_f_{min} \), the polarized flux observed at secondary eclipse.

The amount of polarized flux lost due to the primary eclipsing the disk and the hot spot transiting the disk is given by

\[
q_{fDC} - q_{fDC} A_{ecl} - q_{fDC} A_{HS} = q_f_{min},
\]

where \( A_{ecl} \) is the area of the disk eclipsed by the primary star (see Figure 8), \( A_D \) is the observed area of the edge of the disk, and \( A_{HS} = H_D H_{SM} \) is the area of the disk edge disrupted by the hot spot. The fraction \( q_{fDC}/A_D = q_{fDC}/D_D H_D \) gives the polarized flux per unit area from the disk. The second term is the polarized flux observed by the primary star and the third term is the polarized flux subtracted by the hot spot. We note that Equation (5) assumes an inclination angle of \( i = 90^\circ \) and that each unit area of the disk contributes to the polarized flux equally. In reality, the relative contributions of each portion of a disk with an inclination angle of \( i = 90^\circ \) are not equal due to limb darkening. Taking limb darkening into account would complicate our estimates; a hot spot near a limb darkened edge of the disk would need to be larger to account for the same amount polarized flux that would be lost by a hot spot closer to the center of the disk. Table 7 gives \( q_{fDC}, q_f_{min} \), and the resulting hot spot size estimate for the \( BVRI \) bands using Equation (5).

Assuming an inclination angle of \( i = 86^\circ \) (Linnell et al. 1998; Linnell 2000) instead of 90° changes the equation we use to calculate \( H_{SM} \). In this case, the area of the disk that we see is larger than in the edge-on case; projection effects allow us to see a small portion of the back side of the disk. The visible portion of the interior of the disk is polarized differently than the disk edge; the polarized flux from the interior should cancel with some of the polarized flux from the disk edge. Also, the area eclipsed by the primary star is larger and the center of the star is no longer aligned with the plane that cuts the disk into equal bottom and top halves.

In order to calculate an estimate for \( i = 86^\circ \), we make the assumption that the area of the disk we see is rectangular. This makes our calculations easier since the projected height of the disk does not change across the disk edge, but has the effect of making our estimate smaller; if the edges of the projected disk have a height of \( H_D \) and the center of the projected disk has a larger height due to the projection, the total area of the disk is smaller than the rectangle whose height is the projected height (see Figure 9). This assumption allows us to use Equation (5) with a slight adjustment:

\[
q_{fDC} - \frac{q_{fDC}}{D_D H_{PD}} A_{ecl} - \frac{q_{fDC}}{D_D H_{PD}} A_{HS} = q_f_{min}.
\]
where $H_{\text{PD}}$ is the projected disk height. A simple calculation reveals that $H_{\text{PD}} = 20 R_{\odot}$. The area of the hot spot, $A_{\text{HS}} = H_{\text{PD}}H_{\text{SMS}}$, remains unchanged because the hot spot is only on the front portion of the disk. Therefore, it does not take up the full projected disk height. We note that we do not have to account for the cancellation of polarized light due to the contribution from the interior of the disk. We are using our observations to estimate $q_{f\text{DC}}$ and $q_{f\text{min}}$, and these numbers should therefore already incorporate this effect, if it is present. However, we still make the assumption that each portion of the disk contributes to the polarized flux equally. Besides the complication due to limb darkening mentioned previously, this enlarges our size estimate because more area is needed to cancel out the same amount of polarized flux. Table 7 gives the resulting hot spot size estimate for the $BVRI$ bands when $i = 86^\circ$ using Equation (6).

In our estimates, the size of the hot spot is smaller when the inclination angle is $86^\circ$ compared to $90^\circ$ for the following reason. The area of the disk is larger in the $i = 86^\circ$ method compared to the $i = 90^\circ$ method by a factor of approximately 1.3. This causes the amount of polarized flux per unit area to decrease by a factor of 0.8. However, the area eclipsed by the primary star increases by more than a factor of two. Therefore, the amount of polarized light lost due to the hot spot is smaller when $i = 86^\circ$ than when $i = 90^\circ$.

4.4. Comparison and Review of Hot Spot Size Estimates

Comparing all three methods, we find a wide range of sizes for the hot spot. The smallest size estimate is $2 R_{\odot}$ ($I$ band) while the largest is $58 R_{\odot}$ ($V$ band). The $R$- and $I$-band estimates are the most likely to change with additional data because their current phase coverage is not as good as the $B$ and $V$ bands. The $B$-band estimates have the closest agreement between the three methods; they range from $22 R_{\odot}$ to $33 R_{\odot}$, while the $V$-band estimates have the largest range, $9 R_{\odot}$ to $58 R_{\odot}$. The overlap region for size ranges in all the bands is $22 R_{\odot}$ to $33 R_{\odot}$.

The large size of our estimates lends support to the possibility that we are actually detecting the portion of the mass stream which has not interacted with the disk and not a hot spot, similar to the findings of Bisikalo et al. (2000). The largest hot spot size estimate, $58 R_{\odot}$, is similar in size to the diameter of the disk, $60 R_{\odot}$, and the same as the binary separation, $58 R_{\odot}$. However, this scenario would not likely produce the phenomena seen in Figures 1 through 4 because light scattering from the mass stream would tend to have a P.A. similar to that of the disk; therefore, we prefer a large hot spot interpretation.

The $22 R_{\odot}$ to $33 R_{\odot}$ range is likely an upper limit for the size of the hot spot for several reasons. The P.A. method (see Section 4.2) relies on using the randomization of P.A.s around secondary eclipse. We determined the length of time that the randomization in P.A.s lasts by using data from multiple orbits of the system. If the spot varies, either in size or location, on a timescale similar to the orbital period, this variation would cause our estimate to be larger than the actual size of the hot spot. Also, we made the assumption that the hot spot contributes only unpolarized light to the observations. It is possible that the hot spot contributes light polarized at a different P.A. than light polarized in the disk. This would cause a cancellation effect to occur; light polarized in the hot spot would cancel some of the light polarized in the disk. In this case, our estimate would again be larger than the area of the hot spot.

If the hot spot is indeed larger than $30 R_{\odot}$, a portion of it may already be visible to the observer during primary eclipse. If this were the case, we would expect the polarization maxima in the affected bands to shift from phase 0.0 to an earlier phase. This line of reasoning suggests that the primary eclipse effects seen in Figures 1 through 4, if real, may also be due to the hot spot (see Section 3.1). However, such a scenario does not explain why the $I$-band polarization maximum occurs just after primary eclipse. The $R$-band and three-term $V$-band Fourier fits do not show an offset at primary eclipse, suggesting that the hot spot is not visible at this phase (see Section 3.1). We propose that the primary eclipse offsets are likely a result of the Fourier fits in some bands being less well determined around primary eclipse due to an incomplete phase coverage.

The P.A. scatter around primary eclipse in Figures 1 through 4 could also be interpreted as evidence that the hot spot is visible at this phase. As the system moves from primary eclipse to secondary eclipse, the amount of the hot spot visible to the observer should only increase if the timescale for changes in the hot spot is large compared to the orbital period. This suggests that if the scatter in the P.A. of the 1997 August 25 observations (squares between phases 0.000 and 0.015 in Figures 1 through 4) is due to the hot spot, then a similar scatter should also exist in observations where the hot spot was fully visible during the same orbit. In particular, the 1997 August 26 (phase 0.079) and 1997 August 30 (phase 0.385) observations should show this effect. However, these two observations appear to have a P.A. more similar to the system average than the 1997 August 25 observations. If that the mass transfer rate varies on timescales shorter than an orbital period, then the hot spot size may have changed over this five-day period to change the amount of P.A. scatter. This scenario would explain the P.A. scatter at primary eclipse for a single cycle, but it would not address the fact that no other orbits of the system were observed to have a P.A. scatter near primary eclipse. The combination of the arguments for and against the visibility of the hot spot at primary eclipse does not clearly determine whether its effects are discernible near phase 0.0. Multiple spectropolarimetric observations from the same orbit near primary eclipse will provide more insight into the cause of this phenomenon and assess its repeatability. In particular, the evolution of the color index of the polarized flux through primary eclipse compared to the evolution of the color index of the total light flux may shed new light on this situation.

Harmanec et al. (1996) derived the location of the “roots” of the bipolar outflows, where the bipolar outflows originate within the disk, using the $H\alpha$ absorption core and the $H\alpha$ emission wings seen in many epochs of spectra (see Figure 1 in Harmanec 2002 for an artist’s view of the location of the outflows). The location of the roots (marked by a filled square in Figure 8 for the $H\alpha$ absorption and by a filled star for $H\alpha$ emission) is in the same quadrants of the disk in which we interpret the hot spot being located. However, the location of the roots is in the interior of the disk while we suggest that the hot spot is a disruption in the structure of the disk edge. Certainly, the bipolar outflows and the hot spot are related; both components are the result of the system’s high mass transfer rate. How far into the interior of the disk the hot spot reaches is unknown. Additionally, the disk is made up of two components: a dense inner disk and an outer less dense disk (Skulskii 1992). What constitutes the “disk edge” where the hot spot disruption occurs is unclear, although we have assumed it is the outermost edge of the disk (whose diameter is $60 R_{\odot}$) in our size estimates. Because the scattering region for the $H\alpha$ line is thought to be the bipolar outflows (HNF), future high-precision $H\alpha$ line polarization measurements may
be able to link the two structures. If the hot spot location is consistent with the roots of the outflows, we expect the Hα line polarization to show a secondary minimum offset, similar to those characterizing the broadband curves (Figures 1 through 4), while maintaining a P.A. consistent with the outflows. Radial velocity curves of the Hα line’s polarized flux may also provide valuable insight into the relationship between the hot spot and bipolar outflows.

5. SUMMARY

We have presented a large new data set of polarimetric observations of β Lyr in the BVRI bands and the first Fourier fits to the polarimetric variations in these bands and the He i λ5876 emission line. We have interpreted the minimum in the BVRI projected polarization prior to secondary eclipse and the associated P.A. rotations as the first direct evidence for a hot spot on the edge of the accretion disk in the β Lyr system. Using the phases of polarization minimum, the scatter of the P.A., and a simple model, we have estimated the maximum size of the hot spot to be between 22 and 33 R⊙ across the face of the disk. More extensive polarimetric modeling of β Lyr is needed in order to fully understand these results. Insights into the importance of the effects at primary eclipse and more accurate estimates of the hot spot size could be derived from such models.

We expect the hot spot may also be detectable in X-rays. Both ROSAT HRI (Berg hofer & Schmitt 1994) and Suzaku (Ignace et al. 2008) have detected strong and variable hard X-ray emission from β Lyr. However, neither set of observations has provided information on the origin of the X-ray emission or observed the system at phases at which we see the hot spot effects. An X-ray light curve with more complete phase coverage will help locate the source of the X-ray emission.

The large uncertainties and scatter in Figure 6 make it difficult to pinpoint a location for the origin of the jets with confidence. Future, higher-precision line polarization measurements will provide much needed insights and determine their source.

Advancements in technology will soon allow for the combination of long-baseline optical interferometry with polarimetry (Elias et al. 2008). We expect such a technological development will provide new and exciting geometrical insights into the β Lyr system and others like it.

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