ANTI-CORRELATED OPTICAL FLUX AND POLARIZATION V ARIABILITY IN BL LAC

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ABSTRACT

We present the results of photometric (V band) and polarimetric observations of the blazar BL Lac during 2008–2010 using TRISPEC attached to the KANATA 1.5 m telescope in Japan. The data reveal a great deal of variability ranging from days to months with detection of strong variations in fractional polarization. The V band flux strongly anticorrelates with the degree of polarization during the first of two observing seasons but not during the second. The direction of the electric vector, however, remained roughly constant during all of our observations. These results are consistent with a model with at least two emission regions being present, with the more variable component having a polarization direction nearly perpendicular to that of the relatively quiescent region so that a rising flux can produce a decline in degree of polarization. We also computed models involving helical jet structures and single transverse shocks in jets and show that they might also be able to agree with the anticorrelations between flux and fractional polarization.

Key words: BL Lacertae objects: individual (BL Lac) – galaxies: active – galaxies: photometry

Online-only material: color figures

1. INTRODUCTION

BL Lacertae, also known as 1ES 2200+420 (z = 0.0688 ± 0.0002; Miller & Hawley 1977), is the prototype of the blazar class and is hosted by an elliptical galaxy consisting of a stellar population of about 0.7 Gyr in age (Hyyönen et al. 2007). The spectral energy distribution of BL Lacertae peaks at optical/IR bands and is classified as a low-frequency peaked BL Lac object (Fossati et al. 1998). These objects are characterized by a high degree of optical polarization and rapid flux variability at all wavelengths. Their spectra are dominated by featureless no-thermal continua. The approaching jet of BL Lac is within 6°–10° of our line of sight and has a flow speed of 0.981–0.994c, or a Lorentz factor of 7.0 ± 1.8 (Jorstad et al. 2005). It has been one of the favorite targets of several multiband campaigns organized by the Whole Earth Blazar Telescope (Raiteri et al. 2009; Villata et al. 2009 and references therein).

Polarization observations at different wavelengths, together with flux measurements, offer valuable information in trying to understand the behavior of blazars and to model their jet physics. It is commonly thought that the emission mechanism in blazars in radio-through-optical bands is predominantly synchrotron radiation that originates in the jets. Polarimetric observations are required to investigate the magnetic field structures in the jets that are necessary to produce synchrotron radiation. In the case of the basic shock-in-jet model, because of the strengthened ordering of the magnetic field in the shocked region, one can expect a positive correlation between flux and polarization, i.e., an increase in polarization with an increase in brightness (Marscher & Gear 1985; Hughes et al. 1985; Marscher 1996; Hagen-Thorn et al. 2008). The shock front partially orders the turbulent magnetic field along the shock, which is usually considered to be roughly perpendicular to the jet direction though oblique shocks are often likely (Hughes 2005). However, if any newly emitted blob of plasma produces an increase in the total flux but possesses either a chaotic magnetic field or one misaligned with the large scale field, then the reverse correlation is possible (Hagen-Thorn et al. 2002; Jorstad et al. 2006). Expanding upon the shock-in-jet model, a modest change in jet direction will yield significant changes in both total and polarized fluxes that can be either correlated or anticorrelated, though substantial changes in the position angle of the polarized emission is common in this case (Gopal-Krishna & Wiita 1992). An analysis of earlier polarimetry of BL Lac with sparse photometric measurements indicated that the polarized flux was relatively constant even while the total flux varied considerably (Hagen-Thorn et al. 2002). Previous authors (Moore et al. 1982, Kikuchi et al. 1988; Sillanpää et al. 1993) have found that the polarization vector often rotates in BL Lac and the similar blazar OJ 287. Marscher et al. (2008) observed very smooth rotations of the polarization position angle by over 200° as the flux rose. The observed rotation of the polarization angle (P.A.) is very likely to be a signature of the disturbance causing the flare passing through a section of the jet that contains a helical magnetic field. Recently, Raiteri et al. (2013) observed an increase in optical degree of polarization in BL Lac when the flux was lower during their observations in 2011–2012. In this Letter, we exhibit strong evidence for a clear anticorrelation between the optical flux and fractional polarization for BL Lac over the course of an observing season. Our photopolarimetric observations were done using the 1.5 m “Kanata” telescope at the Higashi-Hiroshima Observatory during the period May 2008–Jan 2010. In Section 2, we present the observations and data reduction procedure. Section 3 provides the results and analysis of the photopolarimetric observations of BL Lac, while Section 4 presents the discussion and conclusions.

2. OBSERVATIONS AND DATA REDUCTION

We performed photopolarimetric observations of BL Lac in the optical V band over two observing seasons between 2008 May–2010 January. We divided the observations into
three segments (shown in Figure 1); the first consists of JD 2454613–4747, the second is JD 2454751–4864, and the third is JD 2454934–5224. We used TRISPEC attached to the 1.5 m “Kanata” telescope at Higashi-Hiroshima Observatory. TRISPEC is capable of simultaneous three-band (one optical and two NIR bands) imaging or spectroscopy, with or without polarimetry (Watanabe et al. 2005).

The photometry of BL Lac was performed using standard CCD image reduction procedures. After making dark-subtracted and flat-fielded images, the magnitudes were measured using the aperture photometry technique. The radius of the aperture, which depended on the seeing each night, was $\sim 3$–5 arcsec. These correspond to 3–4 pixels on the optical CCD. We calculated differential magnitudes of blazars using standard stars located in the same frame. The standard stars are taken from González-Pérez et al. 2001. We checked the constancy of the brightness of the standard stars using the differential photometry between them and neighboring stars in the same field.

A set of polarization parameters was calculated from four consecutive images, which were obtained with half-wave-plate angles of 0°, 22.5°, 45°, and 67.5°. We took 12 sets of images on one night, from which three sets of polarimetric data were obtained. Observations of unpolarized standard stars allowed us to conclude that the instrumental polarization was less than 0.1% in the V-band. Hence, we did not apply a correction for instrumental polarization in obtaining the degree of fractional polarization (PD). The zero point of the P.A. was corrected to the standard system (measured from north to east). Observations were sometimes carried out under bad sky conditions. Some data obtained under such conditions have very large errors and could disrupt any systematic trends that may exist in the blazar’s variability. Therefore, in this Letter, we only use photometric data with an error of less than 0.1 mag and PD with an error less than 5%. More details are given in Ikejiri et al. (2011).

3. ANALYSIS AND RESULTS

In order to perform the cross-correlation between the optical flux and polarization, we have carried out discrete correlation function (DCF) analyses. The DCF was first introduced by Edelson & Krolik (1988). For more details, see Hufnagel & Bregman (1992), Hovatta et al. (2007), and references therein.

The photometric and polarimetric behavior of BL Lac is shown in Figure 1. The photometric behavior is related with the polarization properties as optical fluxes apparently anticorrelate with the polarization levels, strongly during the second half of the first observing season. There is a gradual decline in the PD between the first and second observing seasons that is likely related to long-term variations in the global magnetic field.

However, the P.A. is roughly constant even in the most and least active states of BL Lac we observed, with the P.A. rms error $\sim 7^\circ.144$.

Figure 1 is divided into three segments (shown by the arrows). Segment 1 is the first half of the first observing season (JD 2454613–4747) and the DCF between flux and polarization degree is displayed in Figure 2. We found no significant correlation between flux and polarization in this DCF. Segment 3 consists of the entire second half of our data (JD 2454925–5160). While there are multiple small peaks and dips in the DCF, both in flux and polarization, there is no significant positive or negative correlation present. Segment 2 is the second slice of the first observing season where the anticorrelation between optical flux and polarization degree appears most clearly. The strong dip present in the DCF is very close to a lag of 0, and this depression represents anticorrelation between flux and polarization. Around this negative peak, the DCF curve is well fit by a Gaussian function of the form (shown in Figure 2):

$$DCF(\tau) = A \times \exp \left[\frac{-(\tau - m)^2}{2\sigma^2}\right]$$  \hspace{1cm} (1)
showed a different mean preferred polarization direction of 24° being present in the emission region. Previous measurements as high observed polarizations. Because there is an ambiguity of the flux is low, so when BL Lac is dimmer, there are low as well from Figure 3 that there is a significant scatter in the PD when BL Lac tended to be low when the PD was highest. It is also clear extremely strong trend, there is an indication that the flux of BL Lac is a higher degree of polarization. From Figure 4, it is seen where A denotes the peak value of the DCF, m represents the time lag in days at which the DCF peaks, and σ represents the width of the Gaussian function. The values of these parameters are: A = −0.664; m = 7.53 ± 3.65; and σ = 11.63 ± 3.65. The peaks found near +60 days and −55 days are too close to the ends of the temporal period to ascribe physical meaning to them. The variations in the DCF of the unpolarized star, also plotted in Figure 2, show no significant peaks or dips. This illustrates that the wiggles seen in the BL Lac DCFs in Segments 1 and 3 are not significant and that no instrumental problem was present during Segment 2.

Figure 3 illustrates the relation between the degree of polarization and V band flux for all of the data. Although there is no extremely strong trend, there is an indication that the flux of BL Lac tended to be low when the PD was highest. It is also clear from Figure 3 that there is a significant scatter in the PD when the flux is low, so when BL Lac is dimmer, there are low as well as high observed polarizations. Because there is an ambiguity of ±180° in the value of the P.A., we subtracted 180° from the P.A.s to plot the dependence between PD and P.A. shown in the right panel of Figure 3. The dependence between PD and P.A. possibly indicates that the polarization vectors are scattered around the dominant direction in the jet, which is shown by a straight line at 15°. This could be ascribed to a chaotic magnetic field being present in the emission region. Previous measurements showed a different mean preferred polarization direction of 24° (Hagen-Thorn et al. 2002), and we have observed an average P.A. of 15°.7.

4. DISCUSSION AND CONCLUSIONS

In most of the previous observations of blazars including polarimetry (e.g., Marscher et al. 2008, 2010; Sasada et al. 2010; Jorstad et al. 2010), a smooth rotation of the P.A. with the rise in optical flux has been noticed on long-term polarimetric observations. This can be explained by a nonaxisymmetric magnetic field distribution, a swing of the jet across our line of sight, or a curved trajectory of the dissipation/emission pattern (Konigl & Choudhuri 1985; Gopal-Krishna & Wiita 1992; Marscher et al. 2008; Larionov et al. 2010). It also may be due to the propagation of a knot of emission that follows a helical path in a magnetically dominated jet, as considered in the context of the event seen in BL Lac in long-term observations in 2005–2006 (Marscher et al. 2008). The large swings of polarization can be explained by “bending jet” models where the angle the jet makes with our line of sight varies (e.g., Gopal-Krishna & Wiita 1992). If variability arises from helical structures, the observed polarization can be calculated following Lyutikov et al. (2005) and Raiteri et al. (2013). The behavior of the observed polarization for optically thin synchrotron emission with helical magnetic fields can be calculated using $P = P_{\text{max}} \sin^2 \chi'$, where $\chi'$ is the viewing angle in the jet rest frame and is related to the observed viewing angle $\chi$ through the Lorentz transformation

$$\sin \chi' = \frac{\sin \chi}{\Gamma_b (1 - \beta \cos \chi)},$$

where $\Gamma_b$ is the bulk Lorentz factor of the plasma.

We compared the observed polarization with the polarization behavior predicted by this model. Following Raiteri et al. (2013), we varied $\Gamma_b$ (7 ± 1.8, Jorstad et al. 2005) or $\chi_{\text{min}}$ and found that when we lower $\Gamma_b$ and $\chi_{\text{min}}$ (from Larionov et al. 2013) to 5.2 and 2°, respectively, in this case, the variations are more toward low polarization values (Figure 4), but when we increase the values of $\Gamma_b$ and $\chi_{\text{max}}$ (e.g., 8.8 and 6°, respectively, in this case), the variations are smaller and the flux is lower but there is a higher degree of polarization. From Figure 4, it is seen...
that the observed polarization of Segment 2 can be very roughly reproduced by the first parameter set; however, the model always shows a flat trend in Segment 3.

The roughly constant P.A. seen in our observations is likely to arise in a fairly uniform, straight, and axially symmetric jet. A perpendicular shock moving along the jet, which is viewed at a small but nearly constant angle to the jet axis, would not result in a gradual change of the P.A. but it could lead to the change in degree of polarization (Jorstad et al. 2006). If variability arises by the transverse shock wave model, the observed fractional polarization of the shocked plasma radiation was calculated by Hughes et al. (1985) as

\[ P \approx \frac{\alpha + 1}{\alpha + 5/3} \frac{1}{2} (1 - k^{-2}) \sin^2 \chi, \]  

(3)

where \((\alpha + 1)/(\alpha + 5/3)\) is the synchrotron polarization factor due to a relativistic electron population with particle distribution \(dN/dE \propto E^{-p}\), with \(p = 2\alpha + 1\), \(k\) is the degree of compression of the shock wave, and a value \(\sim 1.4\) is chosen for the best agreement between observed and predicted polarization. Again, we varied the values of \(\Gamma_0\) or \(\chi_{\text{min}}\) (similarly to the helical jet model) and found that lowering the values of \(\Gamma_0\) or \(\chi_{\text{min}}\) (and hence flux) would increase the variations at lower PD values, with the opposite being the case for the higher values of \(\Gamma_0\) or \(\chi_{\text{min}}\) (these are shown in green and cyan color in Figure 4). The shock model also seems to favor the set of parameters with a smaller Lorentz factor and viewing angle, as the higher values overpredict the PD. This model can also possibly explain the anticorrelation between flux and polarization.

The third possibility to explain the observations of strong anticorrelation between the flux and percentage polarization of BL Lac in Segment 2 involves the existence of both an underlying, slowly varying component and short-lived variable components with different polarization directions (e.g., Hagen-Thorn et al. 2002; Uemura et al. 2010). A specific scenario, proposed by Marscher et al. (2008), has the radiation source consisting of two or more emission regions: one is a global jet region and the others are local emission regions. Here, the local emission arises from the highly polarized shocked “clumps” moving inside the jet and is characterized by short-term variability because of the small emission regions. The dependencies between flux level, PD, and P.A. seem to be consistent with this multicomponent model. P.A.s are clustered around the preferred direction (shown in Figure 3) at the majority of flux levels; this reveals the presence of a constant underlying source always contributing to the total flux. Figure 3 shows the inverse dependence of degree of polarization with respect to flux. Newly formed polarized components lead to a rise in total flux but many randomly oriented polarized components having comparable strengths and different position angles produce partial cancellations (e.g., Hagen-Thorn et al. 2002). This could lead to the observed decrease in total polarization at high brightness levels. At low brightness levels (when only a few variable components contribute), there is significant scatter in the degree of polarization. Then, the appearance of an additional highly polarized component with position angle along the preferred direction will increase the relative strength of the underlying source, thus resulting in higher observed polarizations at low flux levels. However, if this new polarized component has a position angle perpendicular to the preferred direction, it can significantly cancel the polarization of the underlying source, causing low polarization to be observed. This can explain the significant scatter in the degree of polarization when the flux is low.

We have used Monte Carlo simulations with two components to estimate the probability of observing an anticorrelation between flux and polarization, and if it is present, the probability of seeing P.A.s as constant as those actually observed. To do so, we obtained the underlying probability distributions of the fluctuations of Stoque’s parameters \(Q, U,\) and \(I\) in the actual data. Using these probability distributions, we generated 15,000 random realizations of season-long light curves (LCs) for flux and polarization degree as well as P.A.s with the underlying statistical properties of the original LCs for flux, PD, and P.A. Next, taking these randomly generated LCs, we determined the DCFs between flux and polarization and found the probability of finding a strong anticorrelation to be 0.005 if we put 0.50 as the conservative minimum required DCF value (our actual DCF had a maximum absolute value of 0.66). Finally, we calculated the probability of getting nearly constant P.A.s (±20° of the mean P.A.) out of the LCs showing anticorrelation between flux and polarization and found it to be \(p = 0.08\). Hence, the chance of randomly producing a situation similar to that we observed using this model is quite low, and most of the time, one would expect to see either no correlation between flux and PD or a positive one, as is indeed usually seen. The strong anticorrelation between flux and PD seen during a portion of the first year of our observations supports the hypothesis that the local emission is very important in Segment 2, while the global emission is dominant in Segments 1 and 3, indicating that the second component became stronger rather quickly, and by the following observing season this second component had faded. This interpretation is strengthened as the anticorrelation appears after a flare with a very rapid rise-time.

Marscher et al. (2008) showed that the optical flux and polarization variability in BL Lac seen in 2005, which included a large swing in the P.A. coincident with rapid changes in the PD, is very nicely explained in terms of a shock wave leaving the vicinity of the central black hole and propagating down only a portion of the jet’s cross section. In this case, the disturbance follows a spiral path in a jet that is both accelerating and becoming more collimated. This interpretation is supported for that flare by the presence of a bright superluminal knot in their Very Long Baseline Array radio maps and the agreement between the optical and 7 mm radio polarization directions. The relative constancy of the P.A. during our observations seems to indicate that this particular phenomenon was not being observed. However, recently Lariolov et al. (2013) have extended the Marscher et al. (2008) model to model multiwavelength variations of an outburst in the blazar 0716+714. They allowed for variations in the bulk Lorentz factor, \(\Gamma\), jet viewing angle, temporal evolution of the outburst, shocked plasma compression ratio, \(k\), spectral index \(\alpha\), and pitch angle of the spiral motion. They found that even if all of these parameters, other than \(\Gamma\), were fixed, a wide variety of flux and polarization behaviors still could be reproduced (Lariolov et al. 2013). We conclude that a temporary anticorrelation between total flux and PD, even while the P.A. remains nearly constant, such as we found in BL Lac in late 2008, actually can be incorporated into the shock-in-spiral-jet picture as long as the shock Lorentz factor is relatively low.

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REFERENCES

Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
González-Pérez, J. N., Kidger, M. R., & Martín-Luis, F. 2001, AJ, 122, 2055
Gopal-Krishna, & Wiita, P. J. 1992, A&A, 259, 109
Hagen-Thorn, V. A., Larionov, V. M., Jorstad, S. G., et al. 2008, ApJ, 672, 40
Hagen-Thorn, V. A., Larionova, E. G., Jorstad, S. G., Björnsson, C. I., & Larionov, V. M. 2002, A&A, 385, 55
Hovatta, T., Tornikoski, M., Lainela, M., et al. 2007, A&A, 469, 899
Hufnagel, B. R., & Bregman, J. N. 1992, ApJ, 386, 473
Hughes, P. A. 2005, ApJ, 621, 635
Hughes, P. A., Aller, H. D., & Aller, M. F. 1985, ApJ, 298, 301
Hyvönen, T., Kotilainen, J. K., Falomo, R., Örndahl, E., & Pursimo, T. 2007, A&A, 476, 723
Ikejiri, Y., Uemura, M., Sasada, M., et al. 2011, PASJ, 63, 639
Jorstad, S., Marscher, A., Stevens, J., et al. 2006, ChJAS, 6, 247
Jorstad, S. G., Marscher, A. P., Larionov, V. M., et al. 2010, ApJ, 715, 362
Kikuchi, S., Mikami, Y., Inoue, M., Tabara, H., & Kato, T. 1988, A&A, 190, L8
Konigl, A., & Choudhuri, A. R. 1985, ApJ, 289, 188
Larionov, V. M., Jorstad, S. G., Marscher, A. P., et al. 2013, ApJ, 768, 40
Lyutikov, M., Pariev, V. I., & Gabuzda, D. C. 2005, MNRAS, 360, 869
Marscher, A. P. 1996, in ASP Conf. Ser. 110, Blazar Continuum Variability, ed. H. R. Miller, J. R. Webb, & J. C. Noble (San Francisco, CA: ASP), 248
Marscher, A. P., & Gear, W. K. 1985, ApJ, 298, 114
Moore, R. L., Angel, J. R. P., Duerr, R., et al. 1982, ApJ, 260, 415
Raiteri, C. M., Villata, M., Capetti, A., et al. 2009, A&A, 507, 769
Sasada, M., Uemura, M., Arai, A., et al. 2010, PASJ, 62, 645
Sillanpää, A., Takalo, L. O., Nilsson, K., & Kikuchi, S. 1993, Ap&SS, 206, 55
Uemura, M., Kawabata, K. S., Sasada, M., et al. 2010, PASJ, 62, 69
Villata, M., Raiteri, C. M., Larionov, V. M., et al. 2009, A&A, 501, 455
Watanabe, M., Nakaya, H., Yamamuro, T., et al. 2005, PASP, 117, 870

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