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Magnetic Field Structure in the Radio Core of BL Lac: Variable Core Rotation Measure and Detection of a Jet Boundary Layer

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Abstract. We have monitored the morphology and magnetic field structure of BL Lac's parsec-scale radio jet at nine epochs from 1998.7 - 2002.5 using the VLBA. The jet components all have low rotation measure (RM) and nearly perpendicular magnetic field structure at all epochs, consistent with transverse shocks and little foreground thermal gas. In contrast, the core has high variable RM, up to 8,200 rad-m^{-2} at some epochs, but the true RM may be underestimated by blending from emerging jet components. We also detected weak peripheral emission surrounding the main jet at some epochs with nearly parallel magnetic field and high fractional polarization. We suggest this may be a boundary layer caused by interaction with the ambient medium. Finally we searched for a 2.3 yr periodic variation in the structural position angle (SPA) of the innermost core component of BL Lac, as reported by Stirling et al. (2003). Although we found several possible periodicities, including one near the period reported by Stirling et al., our data are also consistent with no position angle variations.

1. Introduction

The relatively nearby blazar BL Lac ($300h^{-1}$ Mpc, $H_0 = 70h^{-1}$ km-s^{-1}-Mpc^{-1}) remains a touchstone for AGN studies, primarily because of its relative proximity, high flux density, and rapid time variability at all wavelengths. Recent VLBI polarization studies of BL Lac have established that superluminal jet components have nearly transverse magnetic fields (Denn, Mutel, & Marscher 2000; Gabuzda & Cawthorne 2003), very low rotation measure (Reynolds, Cawthorne, & Gabuzda 2001) and move in non-rectilinear, possibly helical trajectories (Denn et al. 2000; Stirling et al. 2003). The core component has a much higher, probably variable rotation measure (Reynolds et al. 2001) and has much lower fractional fractional polarization than the jet components (Denn et al. 2000).

In this paper we summarize measurements of core and jet rotation measures obtained over nine epochs. We also report the the discovery of jet boundary layer and investigate whether these observations confirm the recent claim of Stirling et al. (2003) of a periodic variation in the orientation of the inner core. A more complete analysis of these data will be published shortly.

2. Observations

We used the VLBA in full-polarization mode to monitor the radio core of BL Lac at 15, 22, and 43 GHz during nine epochs between 1998.74 to 2002.05. Calibration and hybrid mapping were done using standard NRAO AIPS and Caltech DIFMAP software. The electric vector position angle (EVPA) calibration was done in two ways. We compared the NRAO VLBA polarization monitoring database[1], interpolated to our observing epochs) to the observed EVPA computed using the summed Q and U fluxes. In addition, we used the University of Michigan database [2], epochs 1998.74 to 1999.41) as a secondary EVPA calibration at 15 GHz. The resulting maps had typical RMS noise levels ranging from 0.4 to 0.8 mJy per beam at 15 to 43 GHz.

3. Rotation Measure of the Core, Jet Components

Reynolds et al. (2001) measured the rotation measure (RM) of BL Lac using full polarization VLBA observations at four frequencies between 5 and 22 GHz. They found that the jet components have RM's close to zero, while the core RM was variable, with a value of $-427 \pm \pm 19$ rad-m^{-2} at epoch 1997.26. Our observations at 15,22, and 43 GHz are not directly comparable, since the effective angular resolution of RM measurements is determined by the restoring beam at the lowest observing frequency (0.6 mas vs. 1.8 mas for Reynolds et al.). Nevertheless, we also find that the jet component RM's were close to zero at all nine epochs within our measurement uncertainty (typically ± 300 rad-m^{-2}). However, our measurements of core RM were much higher, up to 8,200 rad-m^{-2}. However, even given the higher angular resolution of these observations, we believe that core RM measurements may not represent the RM of the true core, but are often a blend of closely spaced components of differing RM.

Figure 1, which shows EVPA vectors overlaid on 22 and 43 GHz Stokes I maps at epoch 1999.41, provides a good illustration of core blending. The core component at both frequencies appears to be a blend of a northern, subcomponent with very high RM and a southern subcomponent with little or no RM (perhaps an emerging jet component). The inset RM plot shown in Fig. 1(b) is derived from a fit to EVPA vectors at all three frequencies convolved with the 15 GHz beam, which blends these subcomponents. Note that if the southern component has little or no RM, the measured RM of the blended core component is a lower limit to the true core RM. For five of the nine observed epochs, we

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[1]http://www.vla.nrao.edu/astro/calib/polar

[2]http://www.astro.lsa.umich.edu/obs/radiotel/umrao.html

found good fits to the expected EVPA vs. wavelength squared relation with RM between 7200 and 8200 rad-m^{-2}. For the other four epochs, the RM vs. wavelength squared relation could not be fit with a simple linear fit so that the RM could not be reliably determined.

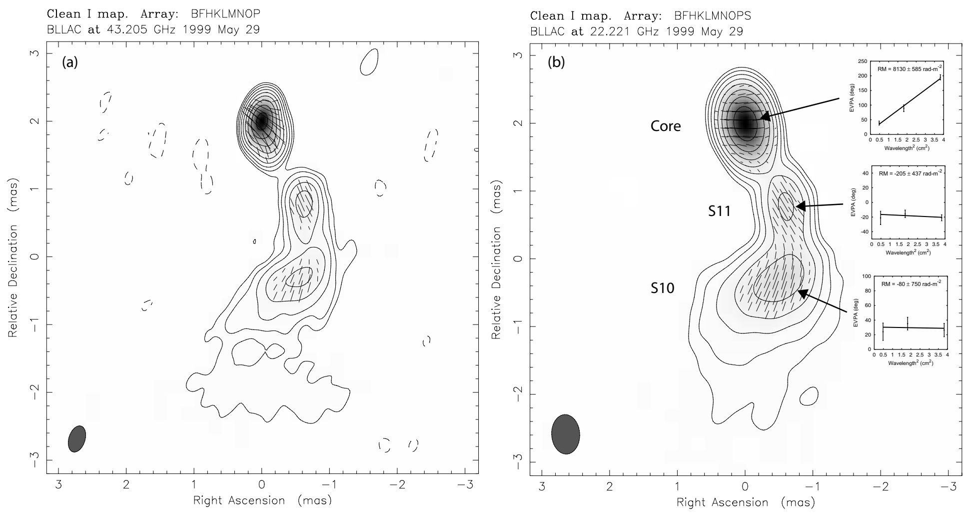

Figure 1. (*a*) 43 GHz Stokes-I map of BL Lac at epoch 1999.41 with superposed EVPA vectors (1 mas = 25 mJy beam^{-1}. Contours are -0.5, 0.5, 1.0,..,64 percent of 1080 mJy per beam. (*b*) Same as (*a*), but at 22 GHz with peak 850 mJy per beam and with inset rotation measure plots of the core, and jet components S10 and S11. Note the large rotation of EVPA vectors in the northern part of the core.

4. Discovery of a Jet Boundary Layer

Several of the 15 GHz maps show weak polarized emission on the periphery of the main jet with a magnetic field component nearly parallel to the jet axis (figure 2). This appears to be a boundary layer formed by the jet's interaction with the surrounding medium, causing a shear parallel magnetic field. This is similar to the boundary layer found in the parsec-scale jet of the quasar 1055+018 (Attridge et al. 1999) and in several kiloparsec-scale jets (e.g., 3C31, Laing 1996). The fractional polarization of the boundary layer emission is quite high (40% at the lowest reliable contour), consistent with the results of Attridge et al. and indicating a very well ordered magnetic field. We reliably detected the boundary layer in several 15 GHz maps and marginally at 22 GHz in two maps.

The boundary layer was most evident when the jet contained a bright knot. In figure 3 we plot the total flux of the eastern boundary layer (most easily detected) versus the flux of the jet component, showing that they appear to be well correlated. This suggests that the boundary layer emission is enhanced by the passage of a shock traversing the main channel of the jet.

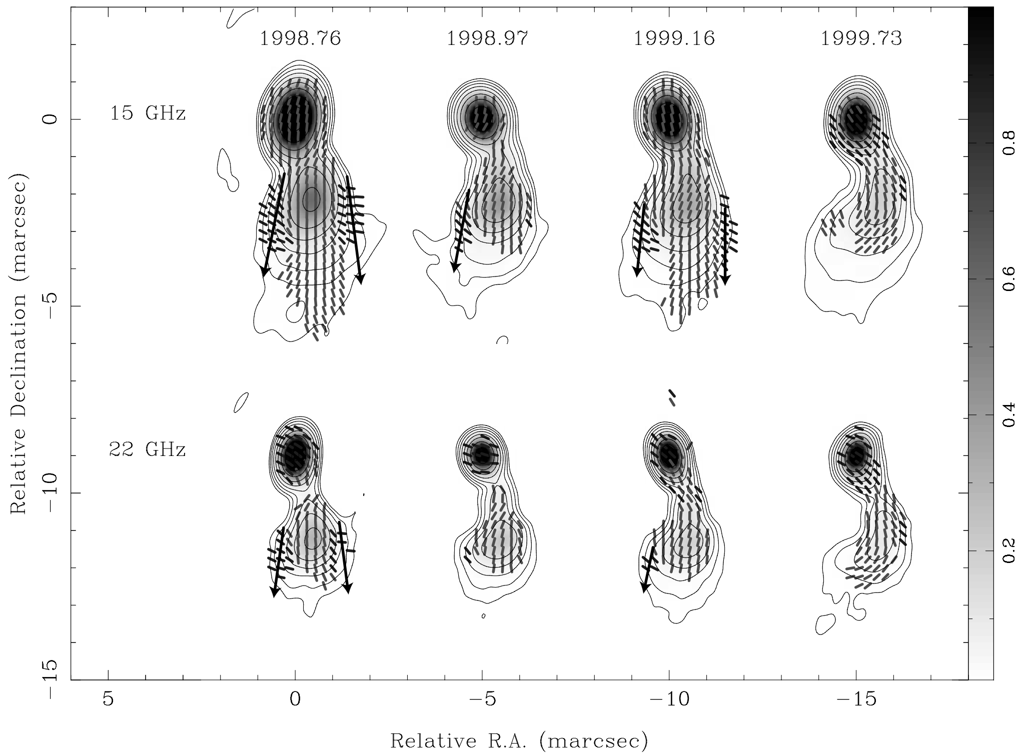

Figure 2. Total intensity (Stokes I) maps of BL La at 15 and 22 GHz at four epochs with EVPA vectors overlaid (1 mas = 25 mJy beam^{-1}). . Contour levels are 5, 10, 20, ... (powers of 2) mJy. Note that while the inner jet emission has EVPA nearly parallel to the jet axis (perpendicular magnetic field), the weak boundary layer (overlaid arrowed vectors) has nearly parallel magnetic field.

5. Is BL Lac precessing?

Stirling et al. (2003) argue that the jet 'nozzle' of BL Lac is precessing with a period of $\sim$ 2 years. They base this remarkable claim on analysis of two independent datasets: periodic variations in JCMT observations of the polarization position angle at 1 mm wavelength, and in the structural position angle of the innermost radio core component in 7 mm (43 GHz) VLBI maps. In both cases, they find strong evidence of periodicity with a timescale of 2.29 ± 0.35 yrs and an angular amplitude of $24.4° \pm 16°$. The VLBI maps spanned 23 epochs over the time range 1997.58 - 2001.28. They modeled the source brightness at each epoch using a variable number of elliptical Gaussian components, including a two closely-spaced ($\sim$ 0.1 mas) circular Gaussian subcomponents in the core. The model component parameters were adjusted for best-fit to the observed brightness distribution. They found a periodic variation in the core 'structural position angle' (SPA), defined as the relative position angle between the two closely spaced core subcomponents.

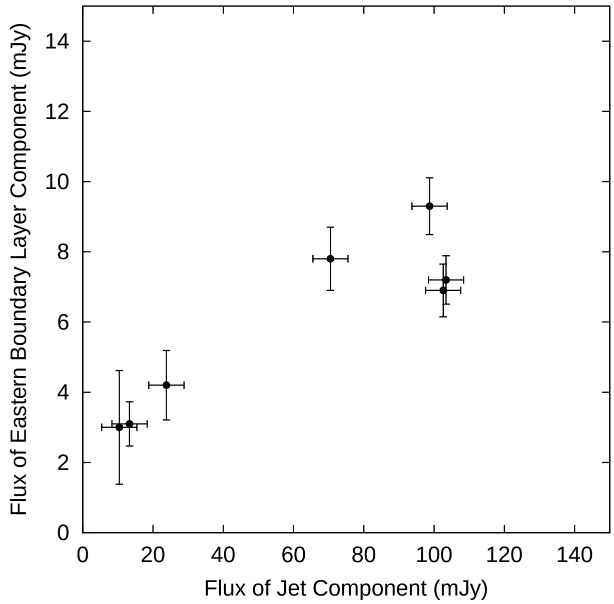

Figure 3. Total flux density of the eastern boundary layer at 15 GHz versus flux density of the associated jet component.

We observed BL Lac using the VLBA at 43 GHz in an overlapping time range (1998.73 - 2002.02), allowing a possible independent test of this hypothesis. We followed a similar analysis procedure as Stirling et al., using the program DIFMAP (Shepard 1997) to fit Gaussian components to each map. We determined uncertainties in each SPA measurement in the following manner using the program DIFWRAP (Lovell 2000). The relative positions of the core subcomponents were varied systematically, followed by self-calibration and model fitting for each position offset. We examined the resulting maps and reduced chi-square for each set of relative offsets to find the SPA range for which the resulting maps were not significantly different from the best-fit map. As a check, we also fitted a one-dimensional elliptical Gaussian model to the core and compared the orientation of the ellipse to the SPA value at each epoch. The ellipse orientation agreed with the SPA value within the SPA uncertainty at all epochs.

The resulting core SPA's and associated uncertainties as a function of epoch are shown in figure 4(a) along with those of Stirling et al. The dashed line shows the periodic model of Stirling et al., defined as

$$\phi_{spa}(t) = A_0 \sin\left(2\pi \cdot \frac{(t - t_0)}{P}\right) + \phi_0 \qquad (1)$$

where the model parameters are taken from Stirling's paper. Figure 4(b) shows SPA vs. epoch for the nine epochs in the present study. The dashed line shows equation (1) using Stirling et al.'s original model parameters, while the solid line is a best-fit model derived using only our SPA data. Figure 4(c) is the same as (b) but with a 'straw-man' constant model. Table 1 lists the model

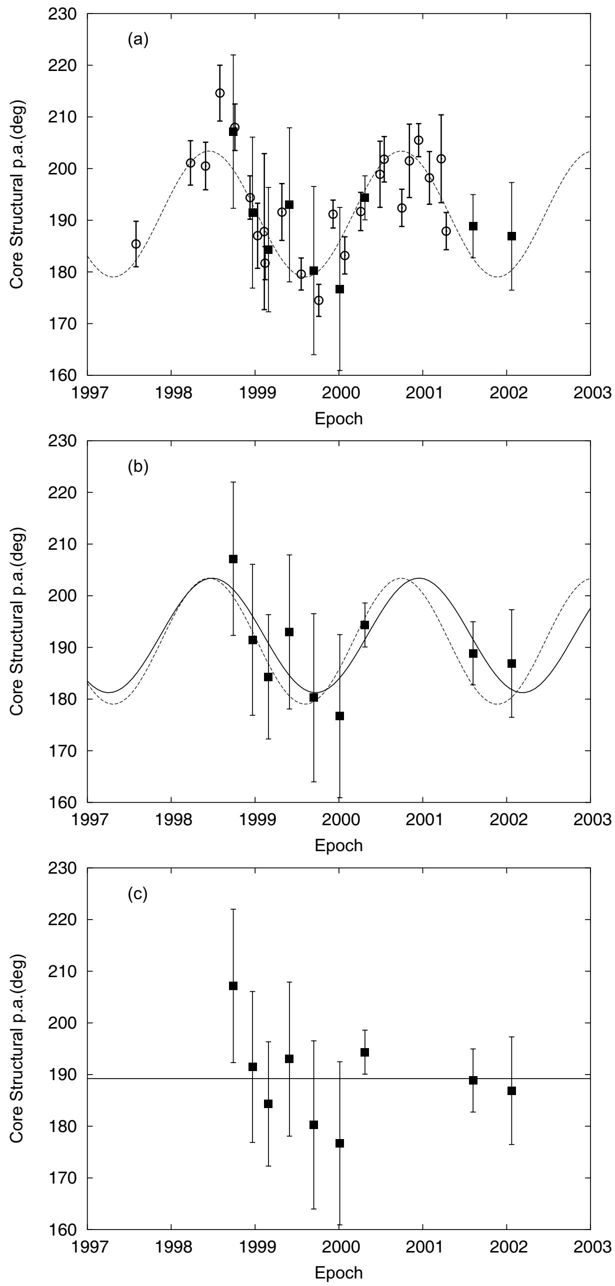

Figure 4. (a) BL Lac core structural position angle (SPA) vs. epoch for data of Stirling et al. (2003) (open circles) and present data (filled squares). The periodic model of Stirling et al. is also shown (dashed line). (b) Same as (a) but only present data, with periodic model fit to present data (see Table 1 for model parameters). (c) Same as (b) but showing non-variable straight-line model. This model is an equally good fit to the present data.

parameters, reduced chi-square, and goodness of fit for Stirling's and our SPA data separately and for the combined dataset.

Table 1. Periodic model fits to core structural position angles.

Data	Model	Epochs	Model Parameters				$\chi_r{}^2$	p
			A_0	$P(yr)$	t_0	ϕ_0		
Stirling et al.	eqn (1)	23	12.2	2.29	1997.9	191°	2.28	0
This paper	eqn (1)	9	11.1	2.65	1997.7	191°	0.58	0.72
This paper	constant	9	0.0	-	-	190°	0.83	0.53
Combined	eqn (1)	32	11.2	2.36	1997.9	192°	1.74	0.01

Do the present support the Stirling et al. claim for periodicity? The results are ambiguous: While the SPA's derived from the present data are consistent with the Stirling et al. model, they are also consistent with several other periodic models, as well as with a constant model, i.e., one in which there is no core precession! Using only our SPA data, we performed a generalized least-squares search using equation (1). We found acceptable best-fit solutions with periods of 0.78 and 3,827 years, as well as 2.65 yr, very close to the Stirling et al. value. A similar parameter search using only the Stirling et al. data or the combined dataset found only the 2.29 yr period reported by Stirling. In fact, the combined dataset has a lower reduced chi-square (1.74) to a periodic function than the original Stirling data (2.28). We note, however, that a model with a reduced chi-square value of 2.28 can be formally rejected at 99.9% confidence.

This ambiguity results partly from the larger uncertainties for our SPA values compared with those of Stirling et al. who observed BL Lac using an identical instrument (VLBA), but with a larger (u,v) dataset. (We observed BL Lac using 5-7 5 minute scans, vs. 12 six minute scan for Stirling et al.). We are confident that our uncertainties have been derived in a consistent, well established manner. Furthermore, our SPA uncertainties are sufficiently small to test for consistency: A random reshuffling of our SPA with epoch produces a combined dataset that is a significantly poorer fit to the Stirling model. We conclude that although the present data are consistent with Stirling et al.'s precessing jet model, they equally consistent with several other periodicities and even with no periodic variation, and hence neither confirm nor disprove their model.

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