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Relativistic Alfvén Waves on the jet of BL Lacertae

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Abstract. The jet of BL Lac displays transverse patterns that propagate downstream superluminally. We suggest that they are transverse Alfvén waves propagating on the longitudinal component of a helical magnetic field. The speed of the wave adds relativistically to the speed of the beam, and the apparent speed of the pattern is greater than the beam speed. Models for the jet and the MHD waves give values for the Lorentz factor of the beam of $3 - 4.4$ and pitch angle of the helical magnetic field of $43° - 65°$. These are consistent with other estimates, if the beam and pattern speeds are allowed to differ.

Keywords. BL Lacertae objects: individual (BL Lacertae), galaxies: active, galaxies: jets, magnetohydrodynamics (MHD), polarization, waves

1. Introduction

The bright AGN BL Lacertae ($2200 + 420, z = 0.0686$) has a variable radio structure and is one of the most commonly-observed objects at the VLBA. We have assembled a large set of the resulting images, 75 made with the MOJAVE program† and 39 taken from the VLBA archive, for a total of 114 high-resolution images of BL Lac at 15 GHz obtained between 1995.26 and 2012.94.

The study of these images has resulted in two papers; the first (Cohen *et al.* 2014a) describes the moving superluminal components and suggests that they are compressions set up by slow and/or fast MHD waves. The second (Cohen *et al.* 2014b) defines the ridge line of an image and shows that the ridge lines are not straight but display transverse patterns that move downstream. It suggests that these motions are transverse Alfvén waves moving on the longitudinal component of a helical magnetic field. In this paper we summarize the evidence for the transverse waves and the helical field, and show a simple model for the jet and the Alfvén wave.

2. Ridge lines and transverse waves

Figure 1 shows three images of BL Lac with their ridge lines, and the crosses show the centroids of the Gaussian components that add up to the image. Note that in all cases there is a narrow wiggling jet that becomes wider around 3 mas from the core, and bends to the east at around 5 mas. When the bends are shallow (Figure 1a) the component centroids accurately lie on the ridge, but when the bend is sharp or the jet bifurcates as in Figure 1c, then the components can be off the ridge by up to 1 mas. This is due to the ridge-finding algorithm, which cannot follow a sharp bend, and cannot deal with a bifurcation.

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† `http://www.physics.purdue.edu/astro/MOJAVE/`

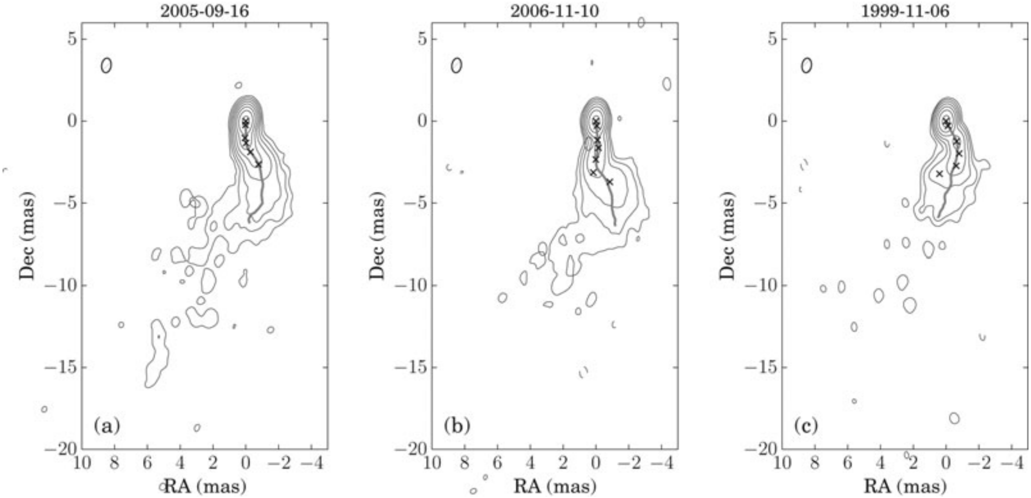

Figure 1. Images of BL Lac showing the ridge lines and the components, whose centroids are indicated by crosses. In (a) the bends are shallow and the components are close to the ridge lines. In (b) the true ridge has a sharp bend and the algorithm has difficulty following it. In (c) the ridge appears to bifurcate, and has a sharp bend or step near the core. The algorithm is unable to deal with these features.

Figure 2 shows five ridge lines from 2005.71 to 2006.86. Along the vector D the progression in space is also a progression in time, and the velocity of this disturbance is $\mu = 1.25 \pm 0.11$ mas y^{-1} at PA $= 179^\circ.8$. This is equivalent to an apparent speed of $\beta_{\rm app} = 5.6 \pm 0.5$ in units of c, the speed of light. The calculation of the speed and PA are discussed in Cohen *et al.* (2014b), along with further examples of similar moving transverse patterns.

3. The magnetic field

Figure 3 shows the polarization image for 2005.713, the first epoch in Figure 2. The image on the right contains tick marks showing the electric vector position angle (EVPA), corrected for Galactic Faraday Rotation. The EVPA stays longitudinal around the bend; see also O'Sullivan & Gabuzda (2009) who have shown the same result for the epoch 2006.50. At left the polarization fraction p rises smoothly along the jet up to 30% except for a slice at 2 mas, where the jet bends; the field direction changes there and, within the beam, the superposition of orthogonal components results in a reduced polarization. The high polarization shows that the magnetic field is well-ordered, and the longitudinal EVPA shows that it has a strong transverse component. Here "strong" means that the transverse component dominates the longitudinal component. We assume that the field has a helical configuration with a dominant toroidal component; i.e., the pitch angle α is not small.

4. Excitation of the transverse waves and the relativistic whip

BL Lacertae has a recollimation shock (RCS) in the jet at ≈ 0.25 mas from the core; and the position angle of the RCS from the core, $\mathrm{PA_{RCS}}$, is variable (Stirling *et al.* 2003; Mutel & Denn 2005; Caproni *et al.* 2013; Cohen *et al.* 2014a). Figure 4 shows $\mathrm{PA_{RCS}}$ as a function of time at two frequencies, 15 and 43 GHz. Note that the independently-measured 15 and 43 GHz points track very well, showing that the $\mathrm{PA_{RCS}}$ measurements

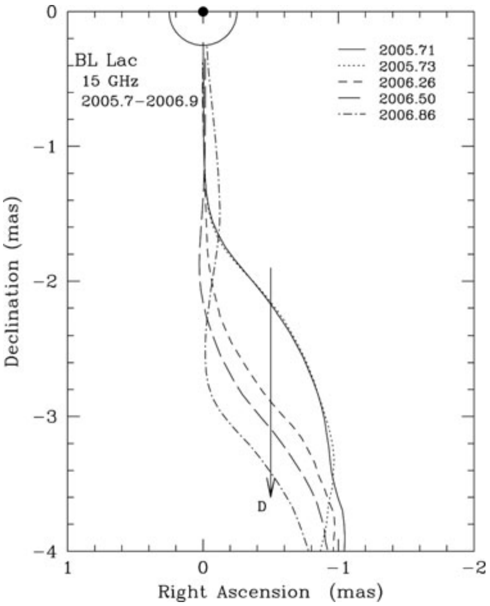

Figure 2. Ridge lines for Wave D, showing 5 epochs between 2005.71 and 2006.86. The velocity is $\beta_{\mathrm{app}} = 5.6 \pm 0.5$ at PA $= 179^\circ.8 \pm 1^\circ.1$. See text.

are accurate to about 3°, and that the 43 GHz points can be used to fill in some of the gaps in the 15 GHz data. In Figure 4, $\mathrm{PA_{RCS}}$ goes through an irregular series of east and west swings with amplitude up to 25°, until 2010; after 2010 the swinging essentially stops and the PA is constant to within about 5°.

The position angle of the ridge line near 1 mas, PA_1, is also shown in Figure 4. In 1997, PA_1 was roughly the same as $\mathrm{PA_{RCS}}$, but it fell progressively behind $\mathrm{PA_{RCS}}$ in an irregular manner and during 2006 - 2010 it lagged $\mathrm{PA_{RCS}}$ by perhaps a year. A lag can be explained heuristically in terms of the RCS being a nozzle that fixes the direction of the emergent jet. Position angle changes will travel downstream as a wave. The change in lag through the observing period is not understood, and may be due to a combination of a changing velocity and geometric effects, including motions in the third dimension and their accompanying relativistic effects.

The ridge line stays within a cylinder beyond $r = 1$ mas, and does not expand into a cone in the manner of water from a swinging hose (Caproni *et al.* 2013; Cohen *et al.* 2014b). The waves are analogous to waves on a taut string shaken at one end, with the tension in the jet provided by the magnetic field. But the jet is not fastened at the far end, and a better analogy might be to waves on a relativistic whip. Note that the jet of BL Lac is at a small angle ($\theta \approx 6^\circ$) to the line-of-sight (LOS) and the deprojection is about a factor of 10, so that the wave in Figure 2 does not have a large amplitude, as might be surmised from the figure. The maximum projected slope of the wave pattern, with respect to the propagation direction, is about 5° and not 40° as it seems to be in Figure 2.

5. Alfvén waves

We suggest that the transverse waves on the jet of BL Lac, including the one shown in Figure 2, are Alfvén waves, traveling on the longitudinal component of the helical magnetic field. In this case the velocity of the waves is given by $\mathrm{V} = \mathrm{V_A} \cos\alpha$ where α

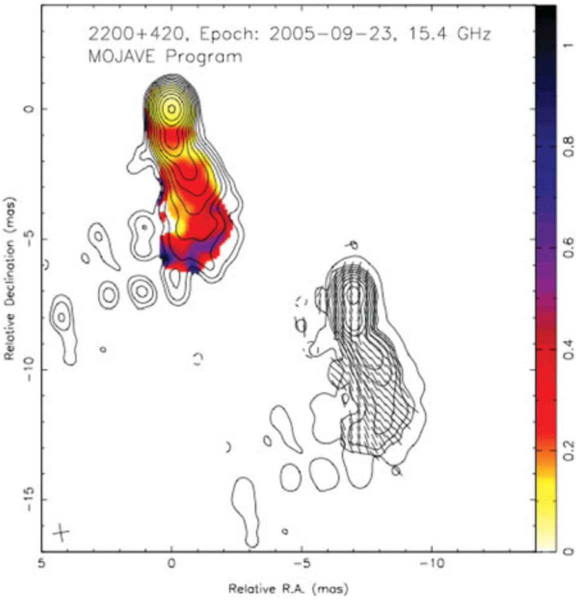

Figure 3. Polarization image for BL Lac on 2005.71, the first epoch in Figure 2. Linear polarization fraction p is indicated by the color bar; at the core $p \approx 6\%$ and increases to the south, in the slice at ~ -2 mas p drops to 15%, and on the ridge p remains near 30% from 2 to 4 mas. In the right-hand image tick marks show the EVPA corrected for Galactic Faraday Rotation. The EVPA stays nearly parallel to the jet out to about 5 mas.

is the pitch angle of the magnetic helix and V_A is the Alfvén speed, $V_A = B/\sqrt{(4\pi\rho)}$ where B is the strength of the magnetic field and ρ is the density of the plasma. This is the non-relativistic formula for V_A; the relativistic formula is given in the Appendix of Cohen *et al.* (2014a). Note that estimating the field strength from a measurement of V_A requires knowing the particle density and the baryonic fraction.

In the model we advocate, the Alfvén wave propagates on the jet, and the wave speed in the frame of the host galaxy, $\beta^{\rm gal}_{\rm wave}$ will be the relativistic sum of the beam speed $\beta_{\rm beam}$ and the wave speed in the frame of the beam

$$\beta^{\rm gal}_{\rm wave} = \frac{\beta^{\rm gal}_{\rm beam} + \beta^{\rm beam}_{\rm wave}}{1 + \beta^{\rm gal}_{\rm beam}\beta^{\rm beam}_{\rm wave}}. \tag{5.1}$$

Hence the pattern speed is greater than the beam speed. The observed pattern speed is increased by the reduction in apparent time due to relativistic motion and the small angle to the LOS, θ and the apparent velocity is

$$\beta_{\rm app,wave} = \frac{\beta^{\rm gal}_{\rm wave}\sin\theta}{(1 - \beta^{\rm gal}_{\rm wave}\cos\theta)}. \tag{5.2}$$

Cohen *et al.* (2014b) develop a simple model for the jet by using $\beta_{\rm app,Tr} = 5$ as the apparent speed of the transverse Alfvén wave, $\beta_{\rm app,F} = 10$ as the apparent speed of the MHD fast wave corresponding to the fastest superluminal component in BL Lac (Lister *et al.* 2013; Cohen *et al.* 2014a), and $\theta = 6°$ as the angle to the LOS. These give the wave speeds in the coordinate frame of the host galaxy: $\beta^{\rm gal}_{\rm Tr} = 0.985$ and $\beta^{\rm gal}_{\rm F} = 0.995$. The corresponding Lorentz factors are $\Gamma^{\rm gal}_{\rm Tr} = 5.8$ and $\Gamma^{\rm gal}_{\rm F} = 10.0$. This problem still contains a number of interconnected variables: the speed of the MHD slow wave β_S, the Lorentz factor of the jet $\Gamma_{\rm jet}$, the Alfvén speed V_A, the sound speed β_s, and the pitch

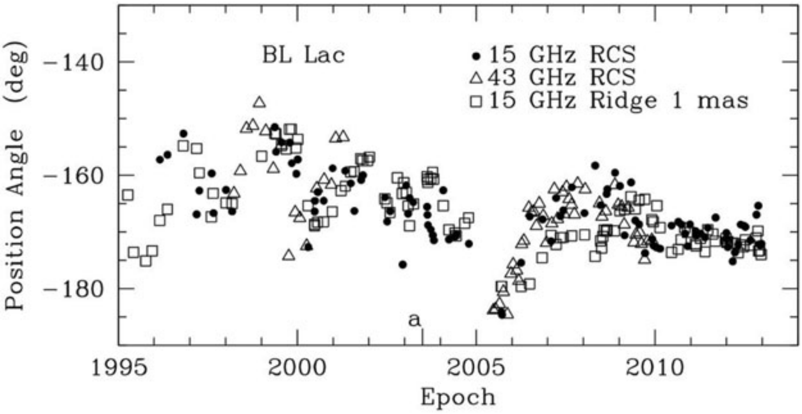

Figure 4. Position Angle *vs* Epoch for the RCS at 15 and 43 GHz, and for the Ridge Line at $r \approx 1$ mas. Epoch a represents the advected start of Wave D; see text.

angle of the helical magnetic field, α. In Cohen *et al.* (2014b) we chose $\beta_{\rm app,S} = 2.1$ as the apparent speed of slow waves, to match the slowest superluminal component in BL Lac, and $\beta_{\rm s} = 0.3$. This closes the set of equations and the solution is $\Gamma_{\rm jet} = 2.8$, $\alpha = 43°$, $\beta_{\rm A} = 0.857$, and the magnetosonic Mach number is $M_{\rm ms} = 1.49$. See Cohen *et al.*(2014b, Figure 17) for details and for a graphical interpretation of the procedure.

The derived Lorentz factor, $\Gamma_{\rm jet} = 2.8$, is sufficient to suppress the radiation from the counterjet and make BL Lac appear one-sided. However, it is less than the values usually quoted for BL Lac, $\Gamma_{\rm jet} \sim 7$ (Jorstad *et al.* 2005; Hovatta *et al.* 2009). These values are based on beaming studies. If the pattern speed and the beam speed are allowed to differ (as we do in this paper), then the beaming studies give $\Gamma_{\rm jet} > \delta/2 \approx 3.6$, where δ is the Doppler factor. A value near this lower limit in fact is statistically unlikely because it requires θ to be near 0°, and so we are left with a discrepancy: beaming studies suggest that the Lorentz factor of the beam is substantially larger than our estimate.

Another problem with our solution is that the derived pitch angle, $\alpha = 43°$, is less than the pitch angle estimated from polarization analyses (D. Homan, private communication); and indeed it is not large enough to say that the toroidal field dominates the poloidal field. Both this α problem and the $\Gamma_{\rm jet}$ problem in the preceding paragraph are eased if a higher value is assumed for the apparent speed of the slow MHD wave. We chose $\beta_{\rm app,S} = 2.1$ to match the speed of an observed slow component, but it is possible, for example, that that particular component was actually a reverse slow or fast MHD shock, traveling upstream in the beam frame. If we take $\beta_{\rm app,S} = 4$ with $\beta_{\rm s} = 0.3$, then $\alpha = 65°$, and $\Gamma_{\rm jet} = 4.4$ (Cohen *et al.*2014b). This value of α matches values found in the polarization analyses. If we now combine $\Gamma_{jet} = 4.4$ with $\theta = 6°$ then we have $\delta = 7.2$, which is in close agreement with the values found in variability and beaming studies. This shows that interpreting the transverse structures on the jet of BL Lac in terms of MHD waves on a relativistic beam can produce results in agreement with other investigations.

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