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Oblique Polarization Structures in AGN and QSO Radio Jets

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Abstract. We interpret the linear polarization structures observed in extragalactic radio sources, even those oriented at oblique angles to the jet flows, to be due to oblique, relativistic shock fronts in the emitting regions. Many sources exhibit indications of such oblique structures, and the goal of this investigation is to test this hypothesis quantitatively. A selected group of ten highly variable extragalactic sources were observed with the VLBA at 15 and 43 GHz, on nine epochs spanning a 30-month period; five of these objects were also observed at 8.0 and 22 GHz. The integrated total flux densities and linear polarizations of the selected objects were also observed several times a month at 4.8, 8.0 and 14.5 GHz with the University of Michigan 26-meter telescope. All objects exhibited variability with several exhibiting more than one independent outburst during the period. We show the evolution of the polarized components with time and discuss the relativistic shock parameters required to match the observed polarization structures. Even cases where the magnetic field is apparently oriented along the jet flow can be fit by oblique shock models when relativistic aberration effects are included.

1. Introduction

There has been considerable past success in fitting quantitative transverse shock models to selected radio outbursts in extragalactic sources where the radio polarized flux is parallel to the VLBI jet axis (Hughes, Aller, & Aller 1989). However, many sources have exhibited bursts where the radio polarization is at an arbitrary angle to the jet flow direction, and we suspect that in these cases, the linear polarization is produced by *oblique* shocks. To better understand the evolution of these oblique polarization structures we made multi-epoch observations of ten highly active extragalactic sources selected from the University of Michigan variability program: DA 55, 0607-157, OJ 287, 1055+018, 3C 279, 1510-089, OT 081, 1928+738, BL Lacertae and 3C 446. The goals of this study are to find if, in fact, the observed polarizations can be produced by the alignment of magnetic fields and acceleration of particles associated with oblique shocks in relativistic jet flows, and to investigate what constraints can be placed on the physical conditions and processes in the jets. The interpretation is made somewhat more complex by the effects of relativistic aberration. Here we report on preliminary results for one program source, BL Lacertae, based on 2 cm measurements with the VLBA at five epochs and the monitoring results from the University of Michigan (hereafter UMRAO) 26-meter telescope.

2. Results

The single-antenna 14.5 GHz measurements of BL Lacertae from the UMRAO are shown in Figure 1. Our observations at 4.8 and 8.0 GHz are not shown, to simplify the figure, but they show similar variations. A relatively large outburst occurred in late 1999 through 2000, and there have been several smaller flux events. The epochs of the VLBA polarization observations are indicated by the arrows along the abscissa in Figure 1, and the epochs of the five maps shown in Figure 2. are designated by the letters a to e. The total polarized flux does not mimic the flux density curve in a simple way. The polarization position angle is consistently offset from the average direction of the jet flow, 197° (defined by the direction from the core to the strongest jet component, and shown as the horizontal line). As discussed below, we believe that this offset is associated with the curvature of the jet structure and the resulting orientation of oblique shock structures to generate a deflection of the flow in the observed direction.

The five VLBA polarization maps are shown in Figure 2. The contour levels (chosen to emphasize the diffuse emission) are the same in all images, but the noise levels vary due to weather conditions or temporary equipment problems. Note that the top three images (a, b, and c) were obtained in a five-month period, while the last two images are at a yearly spacing from the first image. The basic morphology of the source remained unchanged over the two year observing period, and is very similar to the structures observed by Denn et al. 2000. The 'hot spot' evident in the jet appears to change position in an erratic manner; it is not possible to define an 'expansion rate' from these images. There is also considerable brightening and fading of the outer tail of the jet. Although not evident without close inspection, most of the flux variations seen in Figure 1 are produced in the core component; the first three epochs are associated with the development of the burst that peaked in 2000, that event has almost completely faded by epoch d.

The majority of the variability (and the polarized flux) originates in the unresolved (and part of the time partially opaque) 'core'. The most highly polarized component, however, is often the 'hot spot' located two or more

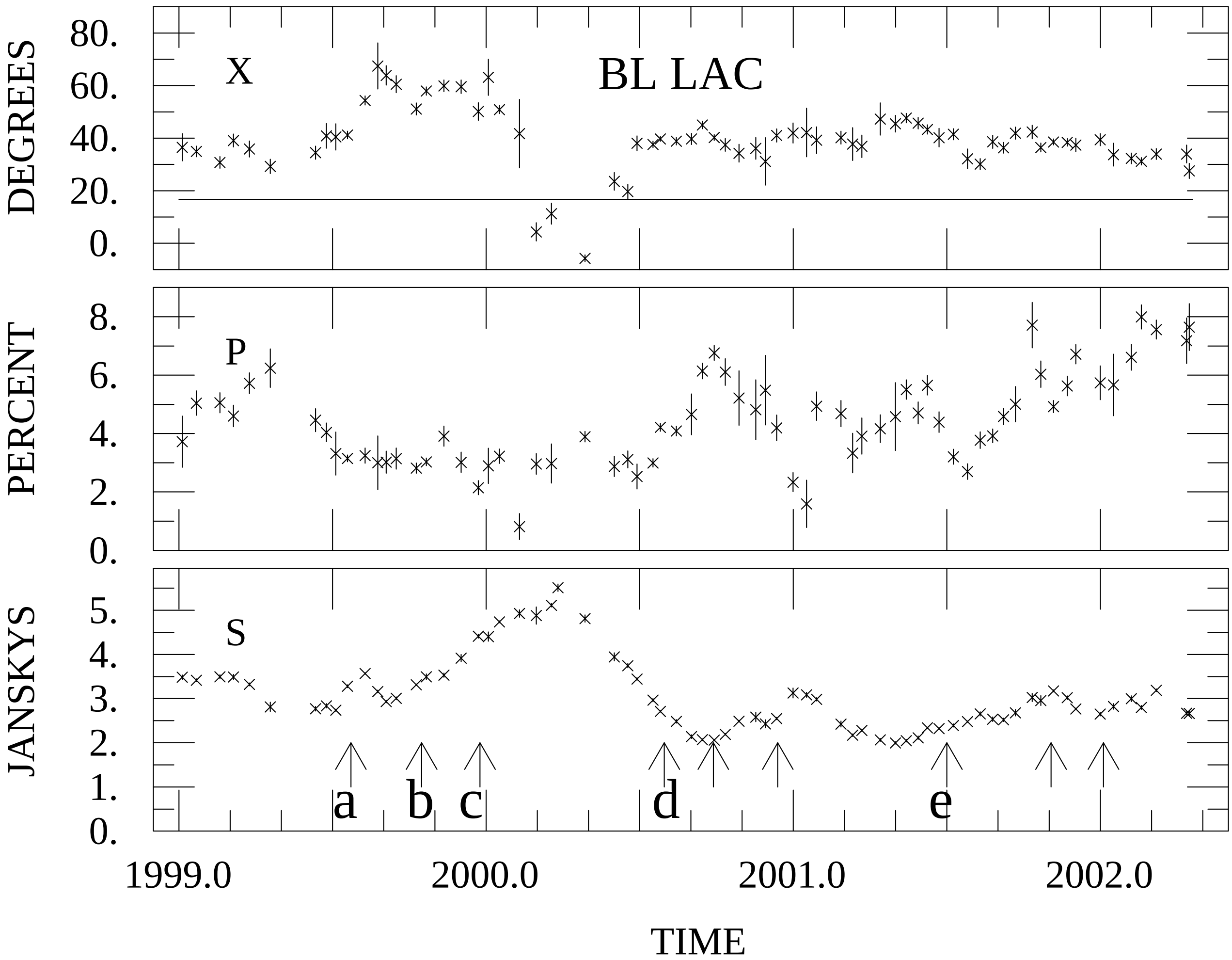

Fig. 1. UMRAO light curves for BL Lacertae at 14.5 GHz based on two-week averages of the data. From bottom to top: total flux density, fractional linear polarization, and position angle of the electric vector of the polarized emission. The polarization has been corrected for Faraday rotation assuming a rotation measure of -205 rad/m^2. The labeled arrows refer to the epochs of the images shown in Figure 2.

mas from the core, where the degree of polarization is as high as 25%. We believe that this is the site of a relatively strong shock in the jet flow. The striking feature is that this region maintains a relatively fixed polarization position angle (in the vicinity of 45°) from epoch to epoch. This is certainly not associated with a transverse shock (such as fit the BL Lacertae data in the early 1980s). The observed orientation is consistent with an oblique shock which could be associated with the deflection or bending of the jet flow towards the south east.

The description of an oblique shock in a relativistic flow is more complex than for the case of a transverse shock. We use the same notation as Cawthorne & Cobb 1990 who considered the case of conical shocks in relativistic flows. Their parameters, β_u (the upstream flow velocity), and the angles η, θ, θ' and ϕ are illustrated in Figure 3. We have added an additional parameter (derivable from the others) χ, the flow deflection angle. This angle can be quite extensive as is illustrated in Figure 4. Note that the deflection of the flow is in the opposite sense from the rotation of the EVPA from the initial flow direction.

We can define limits for the parameters of the shocks required to reproduce individual maps, but there are many possible combinations of shock obliquity and observer viewing angle that can produce the same apparent polarization structure. Figure 5 illustrates the range of η, θ, and ϕ which will produce a 25% polarized component at an EVPA of 30° to the initial flow direction. The deflection angles shown in Figure 4 are certainly large enough to generate the jet structures trailing off to the Southeast in Figure 2. However, the erratic motion of the polarized peak, together with the unknown flow rate down the tail, makes it difficult to measure the apparent deflection angle of the flow. The erratic motion of the 'hot spot' where the deflection in flow direction takes place may contribute to the widening of the tail region, even if the deflection angle remains fixed.

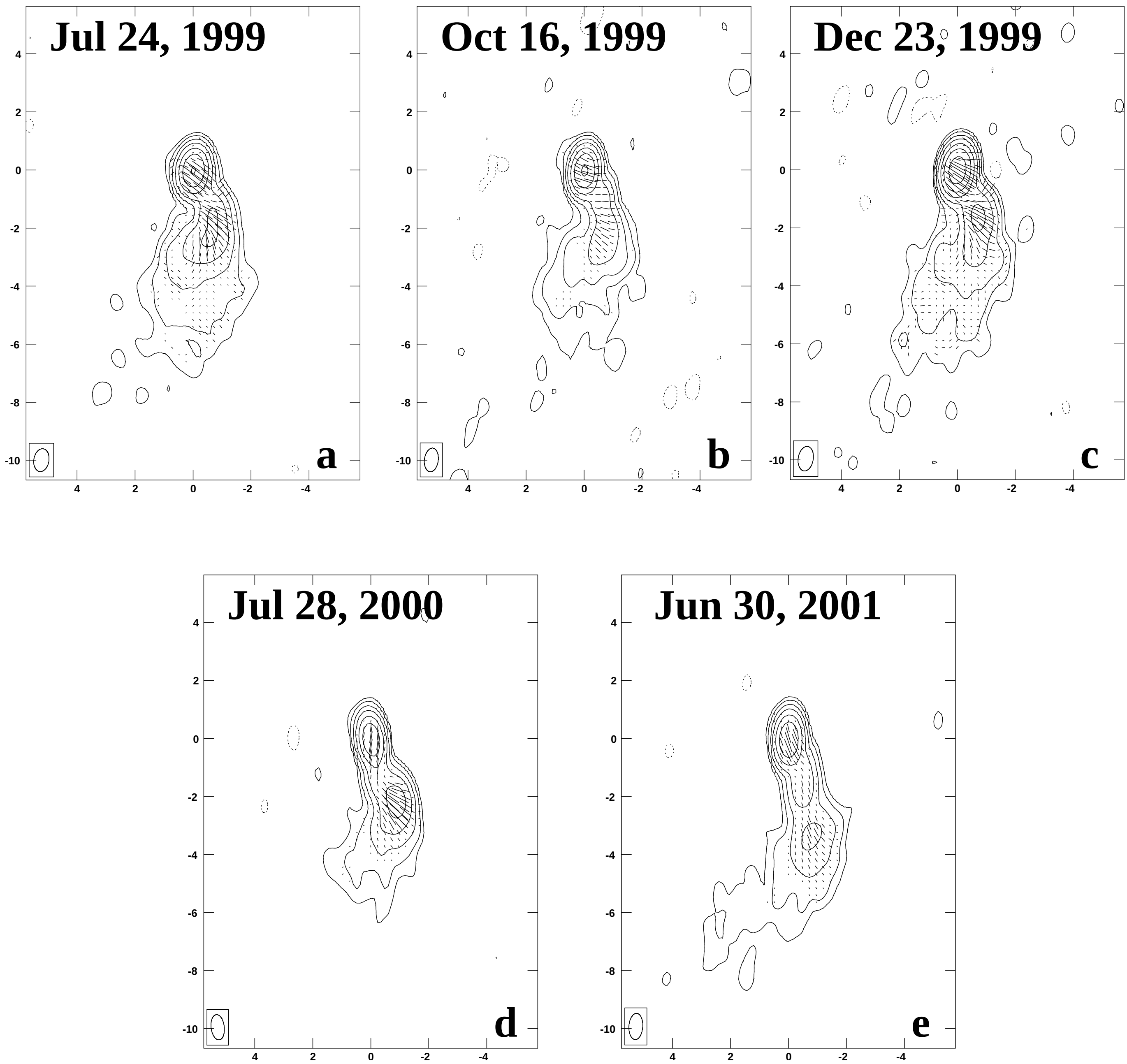

Fig. 2. VLBA images of BL Lacertae at 15.4 GHz at five epochs, (shown in Figure 1). The contours show the intensity distributions on a logarithmic scale; each level differs by a factor of square root of ten. In each panel the bottom contour represents 1.5 mJy/beam. Dashed contours indicate regions of negative flux in the maps. The effective beam is shown in the lower left of each image. The lines superimposed on the contours show the polarized flux and orientation of the electric vector: a line length of 1–mas equals 40 mJy/beam of polarized flux.

Some regions of the BL Lacertae images presented here, and a dominant characteristic of many QSO jets are polarization structures which are perpendicular to the flow direction. Although this might be due to a shear layer, such structures can also be generated by oblique shocks when the effects of relativistic aberration are taken into account. Figure 6 shows the region of parameter space where an apparently perpendicular EVPA could be generated.

3. Conclusions

The polarized structures observed in the images that we have analyzed to date are all consistent with oblique shock structures which have similar shock strengths to those found in previous studies of transverse shocks. While the spacing of outbursts and the time–scales of gross changes in the parsec scale jet structure of BL Lacertae are measured in years, images obtained months apart reveal that there are significant changes in polarization structures and

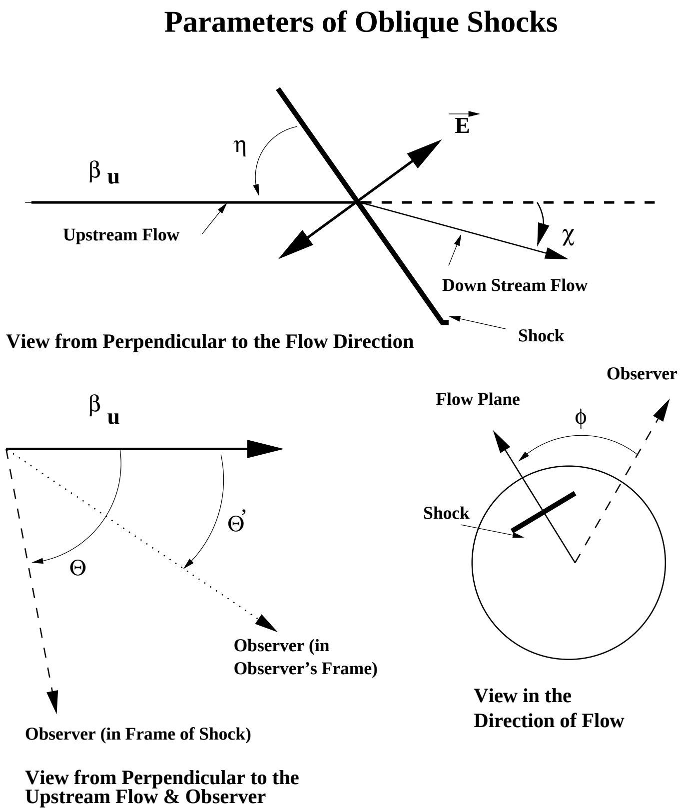

Fig. 3. Parameters needed to describe an oblique shock in a relativistic flow (following Cawthorne & Cobb 1990). The strength of the shock (which sets the degree of compression and hence the degree of polarization) is set by β_u and η. The observed polarization (orientation and degree of polarization) also depend on the velocity of the shock, the angle to the observer, θ', and the angle of the flow plane to the observer, ϕ.

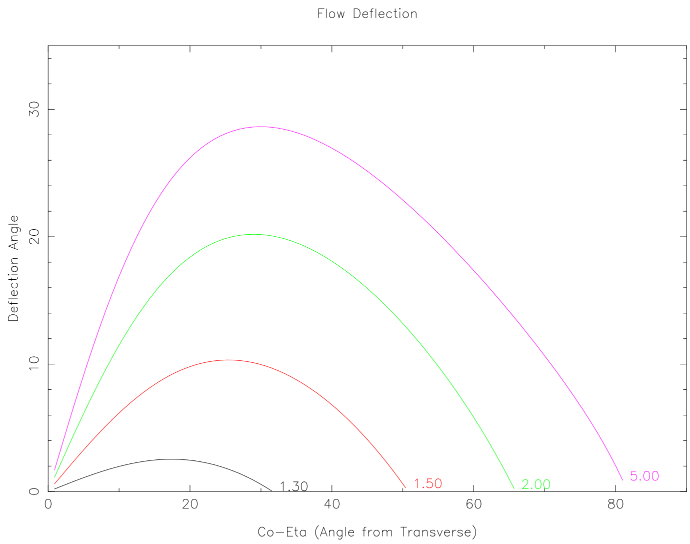

Fig. 4. The angle through which the flow is deflected at the shock front, χ, versus the strength of the shock (parameterized by the Lorentz factor of the upstream flow) and the orientation of the shock plane relative to the transverse direction.

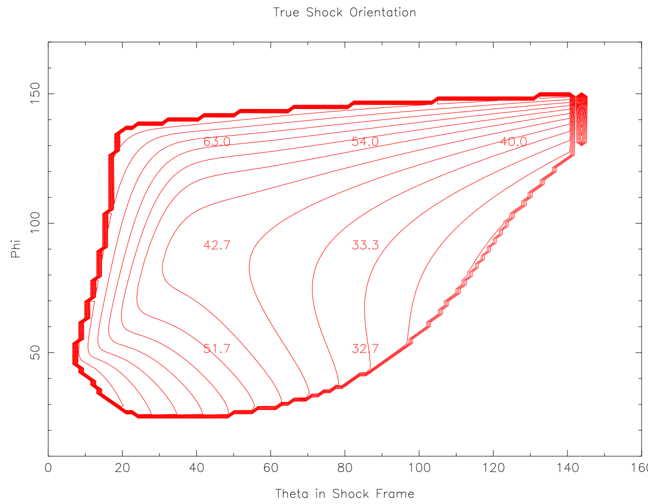

Fig. 5. Possible solution angles for the true angle of the shock front relative to the initial flow direction for an apparent polarization of 25% at an EVPA (relative to the initial flow) of 30°. The contours are at 5° intervals.

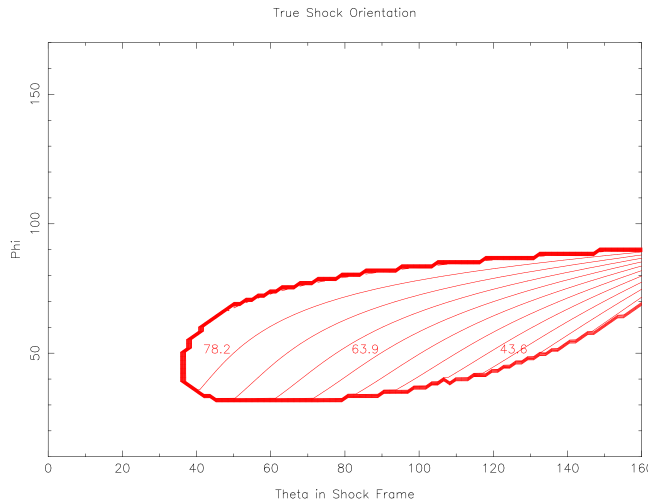

Fig. 6. Possible solution angles for the true angle of the shock front relative to the initial flow direction for an apparent polarization of 10% at an EVPA (relative to the initial flow) of 90°. The contours are at 5° intervals.

erratic motions of intensity peaks on much shorter time scales.

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References

Hughes, P. A., Aller, H. D., & Aller, M. F. 1989, ApJ, 341, 68
Denn, G. R., Mutel, R. L., & Marscher, A. P. 2000, ApJS, 129, 61
Cawthorne, T. V. & Cobb, W. K. 1990, ApJ, 350, 536