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A MODEL OF THE POLARIZATION POSITION-ANGLE SWINGS IN BL LACERTAE OBJECTS

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ABSTRACT

The polarization position-angle swings that have been measured in a number of BL Lacertae objects and highly variable quasars are interpreted in terms of shock waves which illuminate (by enhanced synchrotron radiation) successive transverse cross sections of a magnetized, relativistic jet. The jet is assumed to have a nonaxisymmetric magnetic field configuration of the type discussed in the companion paper on the equilibria of force-free jets. For a jet that is viewed at a small angle to the axis, the passage of a shock will give rise to an apparent rotation of the polarization position angle whose amplitude can be substantially larger than 180°. The effects of freely propagating shocks are compared with those of bow shocks which form in front of dense obstacles in the jet, and specific applications to 0727−115 and BL Lacertae are considered. In the case of 0727−115, it is pointed out that the nonuniformity of the swing rate and the apparent oscillations of the degree of polarization could be a consequence of relativistic aberration.
Subject headings: BL Lacertae objects — polarization — radiation mechanisms — radio sources: variable

I. INTRODUCTION

A number of BL Lacertae objects and highly variable quasars have now been found to display rapid swings in the radio polarization position angle (e.g., Ledden and Aller 1979; Altschuler 1980; Aller, Aller, and Hodge 1981; Aller, Hodge, and Aller 1981). The swings often accompany outbursts in the total flux density and are approximately linear in time—this has been the case, for example, in AO 0235+164 (Ledden and Aller 1979) and BL Lacertae (Aller, Hodge, and Aller 1981). This behavior, however, is not common to all sources. For instance, in the case of 0727−115 (Aller, Hodge, and Aller 1981), the swing occurred during a period of steady decline in the flux density, and the changes in polarization position angle (P.A.) appeared as a series of jumps.

The inferred association of BL Lac objects with relativistic jets whose emission is beamed toward the observer (which has recently gained support from VLBI observations of apparent superluminal motions [e.g., Phillips and Mutel 1982] as well as from spectral measurements [e.g., Worral 1984]) led Blandford and Königl (1979) to interpret the polarization P.A. swings as a manifestation of the relativistic aberration effect in dense clumps that are accelerated by a beamed, supersonic jet. However, the maximum swing angle that is consistent with this model is 180°, whereas a number of sources are now known to exhibit apparently continuous swings in excess of this value. For example, Aller, Hodge, and Aller (1981) reported total polarization P.A. rotation of 440° during a 38-day period in BL Lacertae, and possibly as much as 340° over a period of more than 3 years in 0727−115. Thus relativistic abberation evidently does not provide a complete explanation of this phenomenon.

In this paper we propose a new model of polarization P.A. swings which accounts naturally for arbitrarily large apparent rotations, as well as for the observed variations in the characteristics of the swing. This interpretation is based on the force-free equilibrium model of magnetized jets that was presented in the preceding paper (Königl and Choudhuri 1985, hereafter Paper I). In that paper we showed that a magnetically dominated, super-Alfvénic jet which moves supersonically relative to a confining ambient medium while conserving magnetic helicity will have a minimum-energy state that is generally a superposition of an axisymmetric ($m = 0$) mode and a helical ($m = 1$) mode (eqs. [6] and [11], respectively, in Paper I). We further demonstrated that the helical mode, whose wavelength along the jet is fixed at ~ 5 times the jet radius, is energetically favorable and may dominate the field configuration when either the confining pressure or the magnetic flux is sufficiently low (see § II*c* in Paper I). In Paper I we found that this model could account for many observed features of the total and the polarized synchrotron emission in resolved jets that are observed at a large angle to the axis. In the present paper we assume that the same model also describes the magnetic field structure in jets which display rapid polarization P.A. swings—namely, unresolved, relativistic jets that are observed at a small angle to the axis.

We suggest that the observed polarization P.A. swings result from the propagation of strong shock waves along a force-free jet in which the relative magnitude of the $m = 1$ field component is sufficiently large ($\epsilon \gtrsim 1$ in the notation of Paper I). Such shocks will "illuminate" (by enhanced synchrotron radiation due to particle acceleration and field amplification behind the shock) successive transverse cross sections of the jet (see Fig. 1). The integrated polarized emission from each cross section has a well-defined position angle which is determined essentially by the $m = 1$ field orientation. Because of the "twisted, oppositely directed flux tubes" geometry of the $m = 1$ mode (see Fig. 1 in Paper I), this position angle varies systematically along the jet. When viewed at a small angle to the jet axis, the propagation of a shock will thus lead to an apparent rotation of the polarization P.A. (Some preliminary ideas along these lines were discussed by O'Dea *et al.* [1983] in connection with the polarization P.A. swings in 0727−115.)

The swing characteristics predicted by this model are discussed in § II where, in addition to freely propagating shocks,

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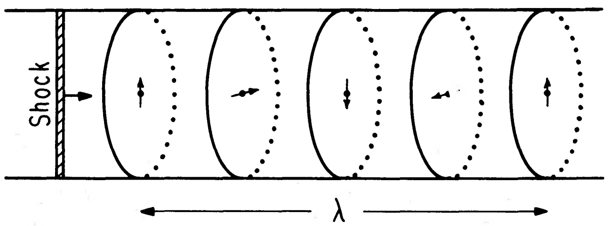

FIG. 1.—Schematic representation of the model. A shock wave propagating along a magnetized jet with a nonaxisymmetric equilibrium field configuration will "illuminate" different magnetic field orientations in successive cross sections. This is illustrated by the rotation of the arrows, which represent the transverse components of the magnetic field vectors at the center of the jet. When viewed at a small angle to the jet axis, the propagation of the shock will lead to an apparent rotation of the synchrotron polarization P.A., with each 180° increment corresponding to motion across half a wavelength λ of the $m = 1$ mode.

we also consider bow shocks attached to dense obstacles in the jet. The model is then applied to the interpretation of observed swings in § III. Our results are summarized in § IV.

II. POLARIZATION POSITION-ANGLE SWINGS IN RELATIVISTIC FORCE-FREE JETS

We first consider the polarization P.A. swings that are induced by relativistic shocks which propagate freely along the jet. In this case, it is necessary to distinguish between the Lorentz factors γ_j of the jet and γ_s of the shock, where we assume that $\gamma_s \gtrsim \gamma_j \gg 1$. The compression of the jet magnetic field in the shock depends on the Lorentz factor, $\gamma_{sj} = \gamma_s \gamma_j (1 - \beta_s \beta_j)$, that corresponds to the relative motion of the shock and the jet (speeds $\beta_s c$ and $\beta_j c$, respectively, where c is the speed of light). When γ_s is much greater than γ_j, the shock is ultrarelativistic ($\gamma_{sj} \approx [\gamma_s / 2\gamma_j] \gg 1$), in which case the compression factor of the transverse field component between the preshock and the postshock frames approaches $\surd(2)\gamma_s/\gamma_j$ (e.g., Blandford and McKee 1976); the component parallel to the direction of propagation is, of course, unaffected by the shock. In the ultrarelavistic limit, the Lorentz factor of the postshock gas (as measured by a stationary observer) is $\gamma_{ps} \approx \gamma_s/\surd(2)$. The synchrotron radiation emitted in the postshock frame satisfies $\delta \boldsymbol{E}_{ps} \cdot (\delta \boldsymbol{B}_{ps} + \boldsymbol{B}_{ps}) = 0$, where $\delta \boldsymbol{E}$ and $\delta \boldsymbol{B}$ are, respectively, the electric and magnetic fields of the radiation. But the dot product of electric and magnetic fields is a Lorentz invariant, so it vanishes also in the observer's frame. Hence,

$$(\delta \boldsymbol{E}_{obs} - \boldsymbol{\beta}_{ps} \times \boldsymbol{B}_{obs}) \cdot (\boldsymbol{B}_{obs} + \boldsymbol{n} \times \delta \boldsymbol{E}_{obs}) = 0 , \qquad (1)$$

where $\boldsymbol{\beta}_{ps}$ is the (normalized) velocity of the postshock gas, and where we substituted $\delta \boldsymbol{B}_{obs} = \boldsymbol{n} \times \delta \boldsymbol{E}_{obs}$ ($\boldsymbol{n}$ being the direction from the emission point to the observer). From this equation one directly obtains the P.A. of the observed electric vector (Blandford and Königl 1979). If we identify the z-axis with the axis of the jet, then the observed magnetic field components are given by $B_{obs,z} = B_{ps,z}$ and $(B_{obs,x}/B_{ps,x}) = (B_{obs,y}/B_{ps,y}) = \gamma_{ps}$. Thus, if the vector $\boldsymbol{n}$ lies in the y-z plane and makes an angle δ to the jet axis, then the observed P.A. χ with respect to the y-z plane is given by

$$\tan \chi = \frac{B_{ps,y}}{B_{ps,x}} \frac{\left[\beta_{ps} - \cos \delta \left(1 - \dfrac{B_{ps,z} \tan \delta}{\gamma_{ps} B_{ps,y}}\right)\right]}{(1 - \beta_{ps} \cos \delta)} . \qquad (2)$$

In the ultrarelativistic limit, the ratio $B_{ps,z}/\gamma_{ps} B_{ps,y}$ is given in terms of the field components in the jet's frame by $(\gamma_j/\gamma_s{}^2)$ $(B_{j,z}/B_{j,y}) \ll (B_{j,z}/B_{j,y})$. Hence, the last term in the numerator of equation (2) can be neglected except when $B_{j,y}$ is very close to zero (and $B_{j,z} \neq 0$). If, in addition, the angle of observation is sufficiently small ($\delta^2 \ll \gamma_{ps}{}^{-2}$), then it is seen that equation (2) reduces almost everywhere to $\tan \chi = -(B_{j,y}/B_{j,x})$, which is just the nonrelativistic result in the limit $\delta \approx 0$.

The polarized emission from an unresolved shock is obtained by summing up the Stokes parameters over the cross section of the jet in the manner discussed in § III*a* (eqs. [18]–[20]) of Paper I. The P.A. swing is then found by considering the emission from successive cross sections traversed by the shock. Two representative examples, calculated for a pure $m = 1$ force-free field configuration and for $\gamma_{ps} = 5$, are shown in Figure 2 by the dashed and solid curves, which correspond to $\delta = 3°$ and $\delta = 10°$, respectively. These plots illustrate the fact that the apparent rate of change of the polarization P.A. is highly nonuniform when δ is close to $\cos^{-1}(\beta_{ps})$ (see eq. [2]), even though the velocity of the shock is constant. This is because, for $\cos \delta \approx \beta_{ps}$, the radiation which reaches the observer is emitted in the postshock frame in a direction which is approximately perpendicular to the line of sight (a manifestation of the relativistic aberration effect), so the electric vector rotates in a plane which is roughly parallel to the line of sight. Under these conditions, the apparent swing is generally small except when the electric vector is nearly perpendicular to the y-z plane (i.e., except when $[B_{ps,y}/B_{ps,x}] = [B_{j,y}/B_{j,x}] \gg 1$), which leads to the steplike variation shown by the solid curve in Figure 2. On the other hand, when the angle of observation is smaller, the apparent swing is more nearly uniform (dashed curve). We note in this connection that $\cos \delta = \beta_{ps}$ is observationally a "favored" combination, in that it maximizes the Doppler factor and hence the apparent brightness of the shock (see Blandford and Königl 1979). An additional feature which is predicted by this model for sources that are viewed at an angle $\delta \approx \cos^{-1}(\beta_{ps})$ is an apparent oscillation of the degree of polarization P (see Fig. 3). In particular, it is predicted that the

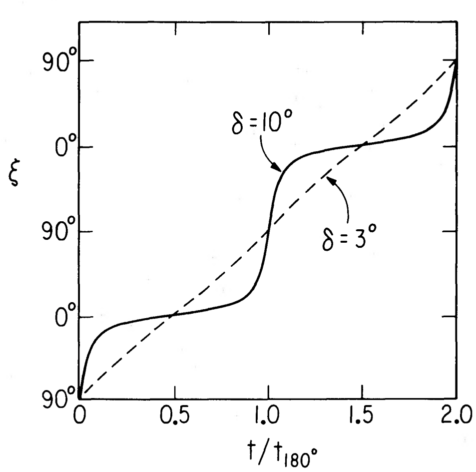

FIG. 2.—The apparent swing of the polarization P.A. ξ induced by the propagation of an unresolved, ultrarelativistic shock (postshock Lorentz factor $\gamma_{ps} = 5$) along a force-free jet with a pure $m = 1$ field configuration. The solid and dashed curves correspond to observation angles $\delta = 10°$ and $\delta = 3°$, respectively. For each curve, the observer's time is normalized by $t_{180°}$, the duration of an apparent 180° swing. The synchrotron emissivity was calculated by assuming a spectral index of $\alpha = 1$ and a density distribution of radiating particles that scales with cylindrical radius r as e^{-r^2/R^2} (where R is the jet's radius).

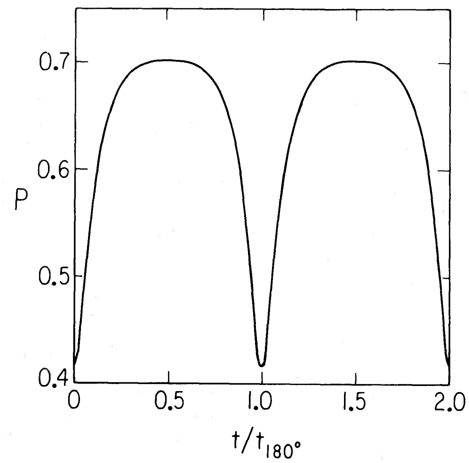

FIG. 3.—The apparent variation of the degree of polarization P corresponding to the P.A. swing described by the solid curve in Fig. 2.

minima of P should coincide with the polarization P.A. jumps exhibited by these sources (cf. Figs. 2 and 3).

Freely propagating shocks of the type that we have considered could develop from velocity fluctuations near the origin of the jet (Rees 1978), and their expected morphology is, in fact, consistent with the observed structure of certain bright emission knots in resolved jets (e.g., Biretta, Owen, and Hardee 1983). However, the shocks that give rise to polarization P.A. swings could also be associated with dense clumps which enter the jet and which are subsequently accelerated by the flow (see Blandford and Königl 1979). In this case, the postshock gas may be assumed to move with the speed $\beta_c c$ of the clump. As can be seen from equation (2), the gradual increase of β_c will lead to an apparent rotation of the polarization P.A. which will be most rapid when β_{ps} reaches $\cos\delta$ (for $[B_{ps,y}/B_{ps,z}] \neq 0$). This relativistic aberration effect was originally proposed as the source of the polarization P.A. swings in BL Lac objects (Blandford and Königl 1979). The amplitude of the swing depends essentially on the ratio $B_{ps,y}/B_{ps,x}$ at the time of the most rapid rotation, but it cannot exceed 180°. Hence, as noted in § I, this mechanism cannot explain the much larger swings that have subsequently been measured in some of these sources. However, if the acceleration of the clump is sufficiently slow, then it may be possible for jet material encompassing more than half a wavelength of the $m = 1$ mode to pass through the clump shock before the clump attains the jet velocity, which would lead to an apparent swing in excess of 180°. A conservative estimate of the condition for the appearance of such a swing may be obtained by considering the initial stage of the acceleration, when the velocity of the clump is not yet highly relativistic. We imagine that a clump of (transverse) radius R_c and (upstream) rest-mass density ρ_c is immersed in a cylindrical jet of radius $R_j(\gg R_c)$ and proper density $\rho_j(\ll \rho_c)$. By integrating the equation of motion in the limit $\beta_c \ll 1$, we can estimate the acceleration time of the clump to $\gamma_c \beta_c \approx 1$ to be

$$t_{acc} \approx 0.9 \frac{\rho_c}{\rho_j} \frac{R_c}{\gamma_j^2 c}, \tag{3}$$

where the numerical coefficient corresponds to an isothermal clump model and to adiabatic indices of 5/3 and 4/3 for the clump and the postshock gas, respectively (cf. Blandford and Königl 1979). A rough criterion for the occurrence of a $\gtrsim 180°$ swing is that the distance ($\sim 0.5ct_{acc}$) traversed by the clump during the time t_{acc} should be larger than half a wavelength λ of the $m = 1$ mode as measured in the observer's frame. Substituting for λ from equation (15b) in Paper I and taking into account the Lorentz contraction of the wavelength in the stationary frame, the condition becomes $t_{acc} \gtrsim \pi R_j/1.25c\gamma_j$. Hence,

$$\left(\frac{\rho_c}{\rho_j}\right)\left(\frac{R_c}{R_j}\right) \gtrsim 5.5\gamma_j, \tag{4}$$

which implies that the initial column density of the clump must be substantially larger than the transverse column density of the jet. (According to our numerical calculations, however, the coefficient on the right-hand side of equation [4] decreases to a value $\lesssim 1$ if t_{acc} is taken to be the total acceleration time to the velocity of the jet.)

III. APPLICATIONS

The model proposed in this paper can, in principle, account for arbitrarily large apparent polarization P.A. swings. In practice, the angular extent of the observed rotation is limited by the distance along the jet over which the shock remains strong enough to provide the necessary "illumination" of the nonaxisymmetric field configuration. The idea that the temporal swings correspond to a spatial variation of the mean polarization P.A. along the jet receives indirect support from optical and infrared polarization measurements of several BL Lac objects (e.g., Sitko, Stein, and Schmidt 1984), which indicate a systematic change in the polarization P.A. with wavelength. Since the jets associated with these sources are probably inhomogeneous (e.g., Blandford and Königl 1979), it is likely that the peak emission at different wavelengths is dominated by different regions in the jet, so that the observed dependence on wavelength reflects a variation with distance along the jet. Although we have focused on a specific field geometry, it is conceivable that other nonaxisymmetric field configurations could also account for the observed swing events. However, the quasi-periodic behavior of a source like 0727−115 as well as the general physical arguments given in Paper I strongly suggest that it is the $m = 1$ force-free mode which is, in fact, involved. It is worth pointing out, though, that other variants of this model could mimic the effect of the $m = 1$ field component. For example, one might imagine a jet with a directed longitudinal field (but random transverse field) which is being perturbed from its straight trajectory towards the observer by a helical Kelvin-Helmholtz instability, thereby giving rise to a projected normal field component which rotates with distance from the origin. In view of the constraints imposed by relativistic beaming, we regard this scenario as being less probable than the one we have adopted. Nevertheless, this example illustrates the possibility of producing shock-induced periodic swings even in jets which are not magnetic-pressure dominated.

The model outlined in this paper also provides a natural explanation of the apparent difference in the time evolution of the swing in sources like BL Lacertae and 0727−115 (see § I). As we demonstrated in Figure 2, the measured swing rate depends sensitively on the observation angle δ; in particular, for δ near $\cos^{-1}(\beta_{ps})$, the polarization P.A. exhibits a series of jumps even in the case of constant shock velocity. This behavior is illustrated again in Figure 4, where we have used our model to fit the data in 0727−115. (In this figure, we have arbitrarily chosen the value of γ_{ps}, and then adjusted the value of δ for best results. However, other combinations of these

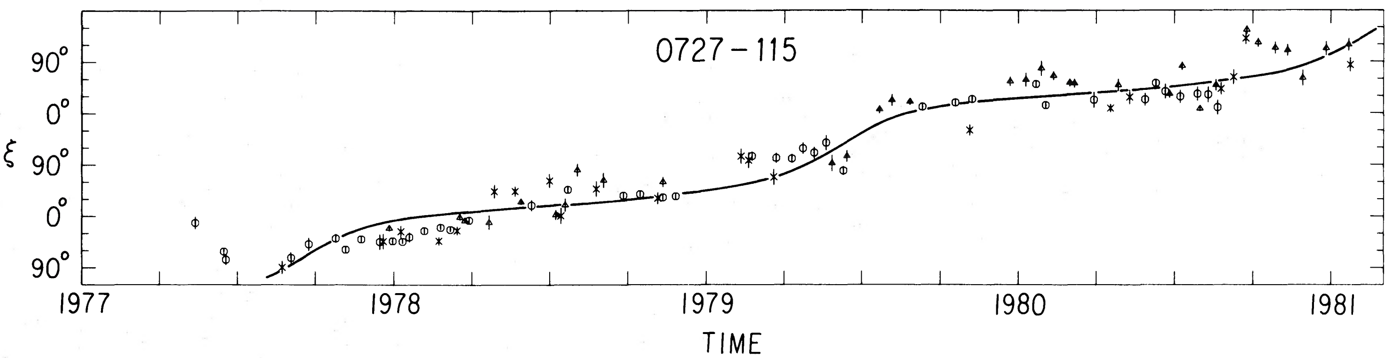

FIG. 4.—A model fit to the polarization P.A. swing in 0727−115. The data points (reproduced from Aller, Hodge, and Aller 1981) represent measurements at 4.8 GHz (*triangles*), 8.0 GHz (*circles*), and 14.5 GHz (*crosses*). The solid curve was calculated under the same assumptions as the curves in Fig. 2, but with $\delta = 8°$.

parameters also give rise to acceptable fits.) In the case of BL Lacertae, where the apparent swing was approximately linear in time, this interpretation implies that β_{ps} could not be too close to cos δ. Additional support for this picture is provided by the observed oscillations of the degree of polarization in 0727−115 and, in particular, by the coincidence of polarization minima and P.A. jumps in this source (Aller, Hodge, and Aller 1981). This is just the behavior predicted by our model for jets with $\beta_{ps} \approx \cos \delta$ (see Fig. 3). The predicted values of P, however, are much larger than what is typically measured ($\lesssim 5\%$), but this could be due to the presence of random magnetic field fluctuations in the jet (see § III*b* in Paper I). The relativistic-aberration interpretation for 0727−115 also leads to the prediction that the P.A. of the putative jet in this source is *orthogonal* to the polarization P.A. in midswing (i.e., the jet P.A. is $\sim 30°$; see Fig. 4). This result could serve to differentiate between the nonaxisymmetric-field picture and the accelerated-clump scenario since, in the latter case, the jet P.A. is predicted to *coincide* with the midswing polarization P.A. (see Blandford and Königl 1979).

In § II we noted that the observed polarization P.A. swings could in principle be induced either by freely propagating shocks or by shocks attached to dense clumps in the jet. In the latter case, the shock (and hence the synchrotron emission) will be strongest at the time when the relative velocity between the jet and the clump is large, which will also be the time when the apparent polarization P.A. swing is most rapid. The accelerated-clump interpretation thus accounts readily for the frequent association of polarization P.A. swings with radio flux outbursts as well as for the fact that not all outbursts are accompanied by large-amplitude swings (which could be a consequence of the fact that condition [4] is not always fulfilled). On the other hand, freely propagating shocks account more naturally for swings that are not associated with major changes in the flux density, as in 0727−115. These differences, however, are not absolute, and most of the observed characteristics of swings could in principle be explained in either one of these scenarios.

Although the polarization P.A. data are generally obtained by measurements in which the source is unresolved, it may nevertheless be possible, in the context of the present model, to combine them with other observations in order to deduce the location of the emission region in the jet. We illustrate this possibility in the case of BL Lacertae. This source exhibited a number of radio outbursts in recent years which have been interpreted in terms of shocks moving along the VLBI jet associated with this object (see Aller, Hodge, and Aller 1983). In particular, the 440° polarization P.A. swing that was measured in BL Lacertae in 1980 occurred during a major radio outburst (Aller, Hodge, and Aller, 1981). Although the angular rotation rate during this swing was not strictly constant, the average value implies a time interval $t_{180°} \approx 15.5$ days for a 180° rotation. According to our model, this time interval corresponds to the shock having traversed a distance $(\pi/1.25)R_j$ in the frame of the jet. In view of the remarks made in the preceding paragraph, it is plausible to associate the shock in this outburst with an accelerating clump; in this case, the most rapid polarization P.A. swing would have occurred when the clump was still nonrelativistic, so

$$R_j \lesssim 0.4\gamma_j c t_{180°} \tag{5}$$

(cf. eq. [4]). The jet Lorentz factor γ_j can be estimated from the apparent superluminal expansion with $\beta_{obs} \approx 5$ (for a cosmological redshift of 0.0695 and $H_0 = 55$ km s^{-1} Mpc^{-1}) that was measured in this source in 1981 (Phillips and Mutel 1982). In fact, if the expansion occurred at the jet velocity and the source was observed at the Doppler-favored angle $\delta \approx \cos^{-1}(\beta_j)$, then $\gamma_j \approx \beta_{obs}$ (see Blandford and Königl 1979). (Note that for $\beta_c \ll 1$ the Doppler-favored angle would be much smaller than $\cos^{-1}(\beta_{ps})$, which is consistent with the nearly uniform apparent rate of the 1980 swing.) With this value of γ_j, we get from equation (5) $R_j \lesssim 8 \times 10^{16}$ cm. We may then estimate the distance z_{em} of the emission region from the origin by assuming that the jet has a conical geometry of half-angle $\sim 2.°4$ (which is the apparent angle in the VLBI map of Phillips and Mutel [1982], multiplied by the estimated projection factor $\sin \delta \approx 0.2$). This gives $z_{em} \lesssim 2 \times 10^{18}$ cm. This result does not necessarily imply that the putative large-scale jet associated with this object is nonaxisymmetric (or even magnetically dominated) near the origin, since that jet need not be a direct extension of the VLBI jet considered here (see Henriksen, Bridle, and Chan [1982] and § III*b* of Paper I). The inferred limit on R_j is consistent with the upper limit of $\sim 8 \times 10^{17}$ cm (for the adopted cosmological parameters) on the radius of the unresolved core in the 5 GHz VLBI map of Bååth *et al.* (1981). This core probably represents the region which is optically thick at that frequency, and is presumably where the source of the observed polarization P.A. swing is located. In fact, since the swing was detected at frequencies of 8.0 and 14.5 GHz, but not at 4.8 GHz (see Aller, Hodge, and Aller 1981), it is likely that it originated fairly close to the boundary of the 5 GHz optically thick core. If future observations succeed in resolving the region where the polarization P.A. swings occur, then one could obtain from equation (5) a direct estimate of γ_j. (This equation does not apply, however, to swings induced by freely propagating shocks; in that case, $t_{180°}$ depends on γ_j, γ_s, and δ, so at least one other parameter [e.g., β_{obs}] would be required in order to estimate γ_j.)

IV. SUMMARY

In this paper the force-free model of magnetized jets (Paper I) was applied to the interpretation of the large polarization P.A. swings that have been measured in certain BL Lac objects and highly variable quasars. Such swings could result from shock "illumination" of successive cross sections in a relativistic jet which has a nonaxisymmetric magnetic field configuration and which is observed at a small angle to the axis. This model accounts in a simple way for the occurrence of swings in excess of 180° and for the variations in the swing characteristics from source to source. In the case of 0727 − 115, the apparent jumps in the polarization P.A. and the accompanying oscillations of the degree of polarization could be attributed to relativistic aberration; this interpretation also implies that the P.A. of the putative jet in this source is orthogonal to the polarization P.A. in midswing. Although similar polarization effects could, in principle, arise also in other nonaxisymmetric field geometries or in jets undergoing a helical Kelvin-Helmholtz instability, the force-free equilibrium model offers what seems to be the most natural interpretation, one which leads to a unified picture of nonaxisymmetric phenomena in compact and extended jets.

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