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Swinging jets and the variability of active galactic nuclei

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Abstract. We consider a kinematic model for the rapid variability of AGN in both total and polarized flux density. This picture emphasizes the changes in relativistic aberration produced when the trajectories of the shocks propagating down relativistic jets deviate slightly from linearity. This simple model can quantitatively explain the reported correlation (and anti-correlation) between the varying total (S) and polarized (P) flux densities as well as the offsets in time recorded between the extrema of these quantities. A key prediction is that changes in the apparent transverse velocity will almost always be positively correlated with changes in the fractional polarization (Π), although the sense of their correlation with the variation in total flux will depend on the viewing angle. It is further predicted that anti-correlated variations in S and Π should be more common among the most core-dominated radio sources. We compare several features of the model with the widely discussed two-component model for AGN variability and indicate how future very long baseline array (VLBA) observations could distinguish between them.

Key words: BL Lacertae objects – galaxies: active – galaxies: radio – polarization – quasars: jets of

1. Introduction

Compact radio sources dominated by partially opaque cores of synchrotron emission are known to vary in continuum and polarized emission on timescales as short as ~ 1 h in the optical/UV/IR regions and ~ 1 d at centimetre wavelengths (e.g. Miller et al. 1989; Edelson et al. 1991; Wagner et al. 1990; Quirrenbach et al. 1989a). Both positive and negative correlations between the total flux (S) and the polarized flux (P) have been reported in optical as well as radio bands. A particularly striking example of the anti-correlation is seen in the recent radio observations at $\lambda = 6$ cm of the quasar 0917+62, which shows large intensity variations on daylike timescales (Quirrenbach et al. 1989a). The variation of S is well correlated over a wide range of radio frequencies (Witzel & Quirrenbach 1990; Qian et al. 1991). Over longer periods the variations in the polarized flux are often more pronounced (e.g. Aller et al. 1985). Although a similarly good correlation does not seem to extend to optical frequencies, there is still a fairly good general relation between the events of rapid flux variability at radio and optical wavelengths for several blazars (Wagner et al. 1990). In particular, a continuous monitoring of the BL Lac object 0716+714 displayed a simultaneous transition from a typical variability time scale of ~ 1 d to ~ 7 d at both optical and radio wavelengths (Quirrenbach et al. 1991). Such multiband correlations clearly distinguish these variations from the flicker (Heeschen 1984) which is believed to arise from refractive interstellar scintillations (RISS) (Heeschen & Rickett 1987).

A frequently discussed model tries to explain the radio-flux–linear-polarization anti-correlation by invoking two synchrotron components with essentially orthogonal polarizations of similar magnitude, one component being relatively steady (Quirrenbach et al. 1991 and references therein; Qian et al. 1991). While the more variable and highly polarized component is usually identified with a shock or VLBI-scale knot, where the magnetic field, B, is expected to be compressed perpendicular to the flow direction of the relativistic fluid, the quasi-steady component is usually considered to be primarily jet emission with B parallel to the flow. As the shock strengthens, the total flux rises, but when the polarized flux from the shock becomes comparable to that from the jet, the net polarization shows a dip, thereby explaining the S–P anti-correlation. A further strengthening of the shock could, on the other hand, lead to a positive S–P correlation, which has also been observed in some blazars at both radio and optical wavelengths (Aller et al. 1985; Mead et al. 1990; Valtaoja et al. 1991a, b).

We wish to point out that in order to understand the correlations of flux with polarization, the requirement of a "steady" component with orthogonal polarization of comparable magnitude to that of the "variable" shock emission need not necessarily be satisfied. If, as supported by VLBI observations, (e.g. Bååth et al. 1991; Hough & Readhead 1989) one takes into account the likely directional swings of small amplitude exhibited by jets, the variation in relativistic aberration can be sufficient to cause appreciable changes in polarized as well as total flux. (Possible variations in the fluid speed could also produce some of those effects (e.g. Zaninetti & van Horn 1988), but in order to keep the treatment simple, we shall ignore that effect in this paper). Such marginal swings in jet direction on the VLBI scale are physically quite plausible, and besides causing the observed wiggles in the VLBI fine-structure, they can substantially change the total and polarized flux, depending upon the jet's kinematics and the viewing angle. The sense of Π–S correlation predicted in this model would, in fact, have a corresponding prediction for the

Send offprint request to: P. J. Wiita (Georgia State University) variation of the apparent proper motion of the shocks, which could be verified by VLBA observations in the near future. In view of this possibility, our discussion focuses on the radio domain where the proposed observational links between the varying flux, polarization, and nuclear fine-structure can be directly studied.

In Sect. 2 we describe an admittedly simple, essentially one-component, model where the effects of changes in the viewing angle are evaluated. Similarly simple schemes have yielded potentially valuable insight when confronted with the data sets (e.g. Orr & Browne 1982; Cohen 1989). In Sect. 3 we examine a possible link between these results and the observed radio and optical variability of blazars, and briefly contrast the relative merits of our model with the two-component model. In Sect. 4 we give our conclusions and outline some possible observational tests.

2. The model

The standard model for BL Lac objects comprises a relativistic jet of synchrotron emission pointing close to the direction of the observer (Blandford & Rees 1978; Blandford & Königl 1979; Rees 1984). VLBI observations have shown that the compact radio emission can usually be resolved into a series of discrete knots on one side of an apparently "stationary core" component which is usually synchrotron self-absorbed (Pearson 1990; Porcas 1987; Kellermann & Pauliny-Toth 1981). These knots are usually interpreted as shocks propagating down the jet and detailed models of flux and polarization variations over the course of years have been successfully developed (Marscher & Gear 1985; Hughes et al. 1985, 1989a, b, 1991).

Recent millimetre VLBI of 3C 273 with much improved angular resolution has shown that the "core" visible at centimetre wavelengths gets further resolved into a string of knots which could be partially opaque at longer wavelengths (Bååth et al. 1991). Further, this micro-arcsecond structure is strikingly non-linear, indicating that the wiggles seen at centimetre wavelengths corresponding to larger distances (Unwin et al. 1985; Cohen et al. 1988) continue right into the core region. Such departures from rectilinearity are also seen in the kpc-scale jets, e.g. in M 87 and NGC 6251 (Laing 1980a; Perley et al. 1984; Saunders et al. 1981). Either the jet flow itself propagates along a helical path (Hardee 1987), or the bulk of the emission arises from a helical filament wrapped around a straight jet (Owen et al. 1989; Rosen 1990).

Observations of kpc-scale jets in powerful radio sources show a weak polarization perpendicular to the jet direction, suggesting that the magnetic field is slightly ordered along the jet flow (Bridle & Perley 1984). Although the magnetic field is mostly randomly oriented inside the jets, it has been pointed out that a compression produced by the shock can induce a substantial ordering of such a magnetic field in the plane of the shock, i.e. perpendicular to the flow direction (Laing 1980b; Hughes et al. 1985; Marscher & Gear 1985). Besides enhancing the synchrotron emissivity, such a compression will produce a substantial polarization, the degree of which will be greatest when the shock is viewed as edge-on by an observer (Laing 1980b). For a bulk Lorentz factor, Γ, of the emitting material, such an alignment occurs when $\sin\theta=\Gamma^{-1}$, where θ is the angle at which the emitter is moving from the line-of-sight (Eichler & Smith 1983); as is well known this condition also maximizes the apparent proper motion:

$$\beta_{app}=\frac{\beta\sin\theta}{1-\beta\cos\theta}. \qquad (1)$$

The apparent flux of the knot, on the other hand, increases monotonically with decreasing θ (Scheuer & Readhead 1979):

$$S_{obs}(\nu')=S_{em}(\nu)\left[\Gamma(1-\beta\cos\theta)\right]^{-(3-\alpha)}, \qquad (2)$$

where $\beta=(1-\Gamma^{-2})^{1/2}$, $\nu'=\nu/[\Gamma(1-\beta\cos\theta)]$, and α is the spectral index defined as $S\propto\nu^{\alpha}$. Now, radiation emitted in the plane of the shock whose normal makes an angle θ with the line-of-sight would appear, due to relativistic aberration, to arrive at the observer at an angle θ' given by (e.g. Cawthorne & Wardle 1988)

$$\cos\theta'=\frac{\cos\theta-\beta}{1-\beta\cos\theta}. \qquad (3)$$

The fractional polarization of such a shocked emission has the following dependence on the aberrated angle θ' (Laing 1980b; Hughes et al. 1985).

$$\Pi=\frac{1-\alpha}{5/3-\alpha}\,\frac{(1-\kappa^2)\sin^2\theta'}{2-(1-\kappa^2)\sin^2\theta'}, \qquad (4)$$

where κ is the factor by which the jet plasma is conpressed by the shock. The dependence on θ' is exact only for $\alpha=-1$ but the variations with α are negligible (Laing 1980b). Our simple picture also neglects the frequency-dependent effects related to enhanced optical depth resulting from shock compression and enhanced Faraday depth, both of which can subsequently reduce the polarization initially raised by the passage of the shock (e.g. Hughes et al. 1985; Jones 1988).

For the purpose of illustration we shall consider here only two simple cases: (i) the emitting plasma is approaching with the same Lorentz factor as the shock itself ($\Gamma_{em}=\Gamma_s$); and (ii) the Lorentz factor of the post-shock material is roughly approximated by (Peacock 1987)

$$\Gamma_{em}=\Gamma_{ps}\approx 2\,\Gamma_s(9-\beta_s^{-2})^{-1/2} \qquad (5)$$

if both the unshocked and shocked materials have relativistic equations of state. This Γ_{ps} is used in Eqs. (2) and (3) and can be treated as an effective Lorentz factor for the shocked plasma, as far as both Doppler boosting and relativistic aberration are concerned. In reality a range of Lorentz factors would characterize the shocked material, particularly if the jet itself is conical, and strictly speaking, the boost is a composite of that associated with the shock front and the motion of the flow in the frame of the shock (Lind & Blandford 1985; Björnsson 1985).

Figure 1a shows the dependence of the Doppler boosting factor on the viewing angle for 3 different values of Γ_s and taking 2 representative values of α for each of the cases (Eq. 2). Figure 1b gives the corresponding results where we have used the post-shock Lorentz factor, Γ_{ps} [Eq. (5)], in place of Γ_s in Eq. (2). The apparent transverse velocity, β_{app}, depends only on Γ_s and is displayed as a function of θ in Fig. 2. The observed fractional polarizations (Π) are plotted for the same values of Γ_s, Γ_{ps} and for two values of κ as functions of θ in Fig. 3. The corresponding relations for the polarized flux P (instead of fractional polarization) are displayed in Fig. 4 for $\kappa=0$ (i.e. maximal compression).

It is worthwhile to explicitly display the forms of changes in β_{app} and Π/Π_{max} as functions of changes in the flux density, at least for case (i). Differentiating Eq. (1) and using Eq. (2) we find

$$\frac{d\beta_{app}}{d(S/S_{em})}=\frac{\Gamma^{4-\alpha}(\beta-\cos\theta)}{(3-\alpha)\sin\theta}(1-\beta\cos\theta)^{2-\alpha}. \qquad (6)$$

If we write $\Pi_{max}=(1-\alpha)/(5/3-\alpha)$ and consider the case $\kappa\ll 1$

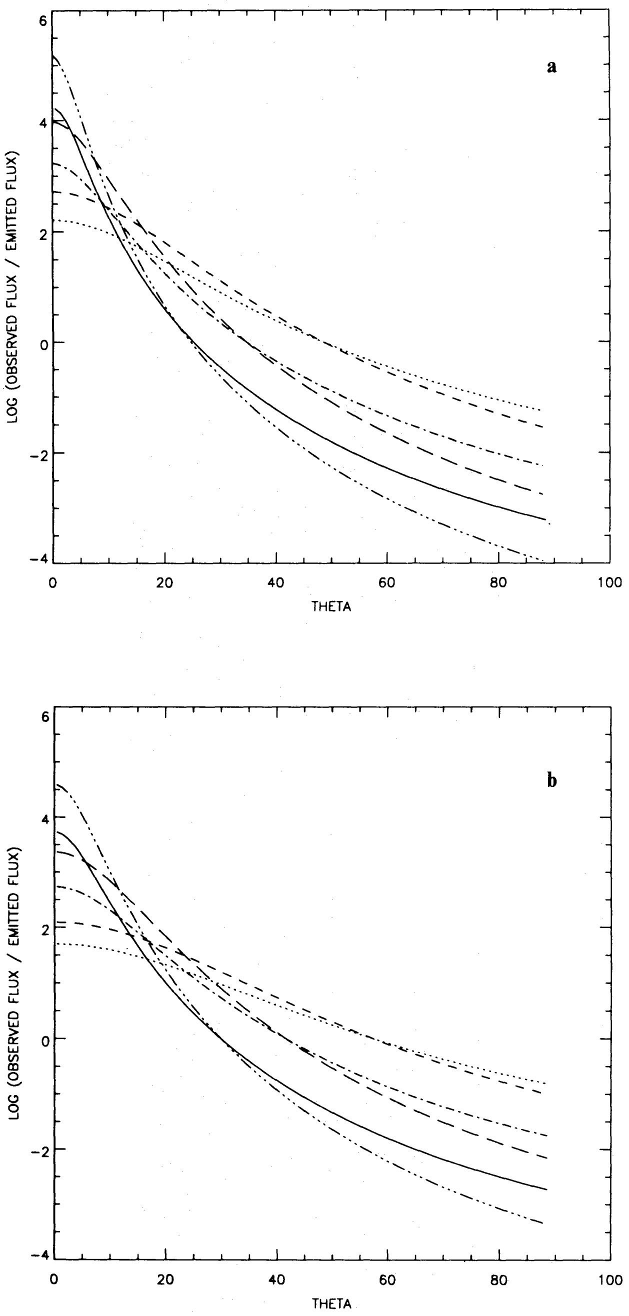

Fig. 1a and b. The observed flux, S (on a logarithmic scale), as a function of viewing angle for **a** $\Gamma_{em}=\Gamma_s$ and **b** $\Gamma_{em}=\Gamma_{ps}$. The dotted curves correspond to $\Gamma_s=2.5$, while $\alpha=-0.25$; the short-dashed curves to $(\Gamma_s, \alpha)=(2.5, -1.0)$, the dot-dashed curves to $(5.0, -0.25)$, the long-dashed curves to $(5.0, -1.0)$, the solid curves to $(10.0, -0.25)$, and the dash-dot-dot-dotted curves to $(10.0, -1.0)$

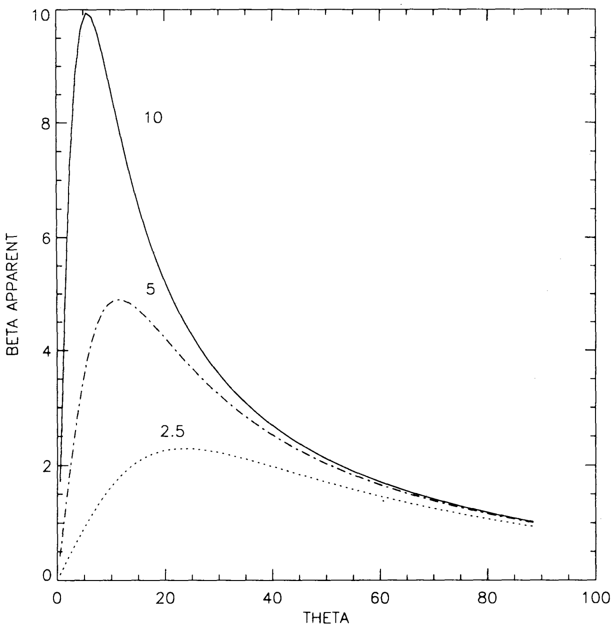

Fig. 2. The apparent transverse speed, β_{app}, as a function of θ for $\Gamma_s=2.5$ (dotted curve), 5.0 (dot-dashed curve), and 10.0 (solid curve). In this, and the following figures, the labels refer to the value of Γ

(very strong compression), the derivative of Eq. (4), using Eqs. (2) and (3) becomes

$$\frac{d(\Pi/\Pi_{max})}{d(S/S_{em})}=\frac{4\Gamma^{2-\alpha}}{(3-\alpha)\beta}\,\frac{(\beta-\cos\theta)(1-\beta\cos\theta)^{5-\alpha}}{\{(1-\beta\cos\theta)^2+(\cos\theta-\beta)^2\}^2}\,. \tag{7}$$

Figure 5 illustrates the dependences between the normalized changes in flux and polarization against viewing angle θ for several values of Γ. Consider the first case ($\Gamma_{em}=\Gamma_s$) where the observed orientation towards a jet changes from $\theta\approx0°$ to $\theta>\theta_c=\sin^{-1}(1/\Gamma_s)$. Unitl $\theta=\theta_c$ the decline in flux is accompanied by a rise in Π and in β_{app}. So the swings in this regime would yield a Π–S anti-correlation, accompanied by an increasing β_{app}. However, beyond $\theta=\theta_c$, the decline in flux will be accompanied by a drop in Π, P, as well as β_{app}. This regime is characterized by S–P and Π–S correlations. For small variations in θ around the critical angle, Π varies little but substantial variations in S occur. Thus, this single component model allows the wide range of dependences between Π, P and S as reported in multiband observations; quantitative fits can be obtained for small swings ($\delta\theta<10°$), adopting reasonable values for α, κ, θ and Γ_{em}. While this picture is certainly an oversimplification, it leads to a straightforward observational prediction, namely, *the sense of temporal variations of β_{app} and Π should always be the same, even though the sense of the Π–S correlation flips across the critical angle*. Current data do not permit testing of this hypothesis, but sufficiently frequent monitoring of blazars using the VLBA (and other dedicated VLBI arrays) should allow this test to be performed in the near future.

If, in reality, the shock's Lorentz factor does not closely characterize the effective Lorentz factor of the emitting material, then these neat correlations become somewhat diffuse. We then also have to consider an additional critical angle, $\tilde{\theta}_c=\sin^{-1}(1/\Gamma_{ps})$. Assuming $\Gamma_{ps}<\Gamma_s$, it can be seen that for θ approaching θ_c from below, the decline in flux is still accompanied by increase in both Π and β_{app}. However for $\theta_c<\theta<\tilde{\theta}_c$, β_{app} has begun to decline while Π and S are still anti-correlated. Only for $\theta>\tilde{\theta}_c$ do we recover the concomitant decline of S, Π and β_{app}. But for reasonable values of Γ_s and Γ_{em}, the variation in β between the two critical angles would be quite small and difficult to measure.

In either of the two cases, one expects a statistical preponderance of Π–S anti-correlation among the very flat-spectrum

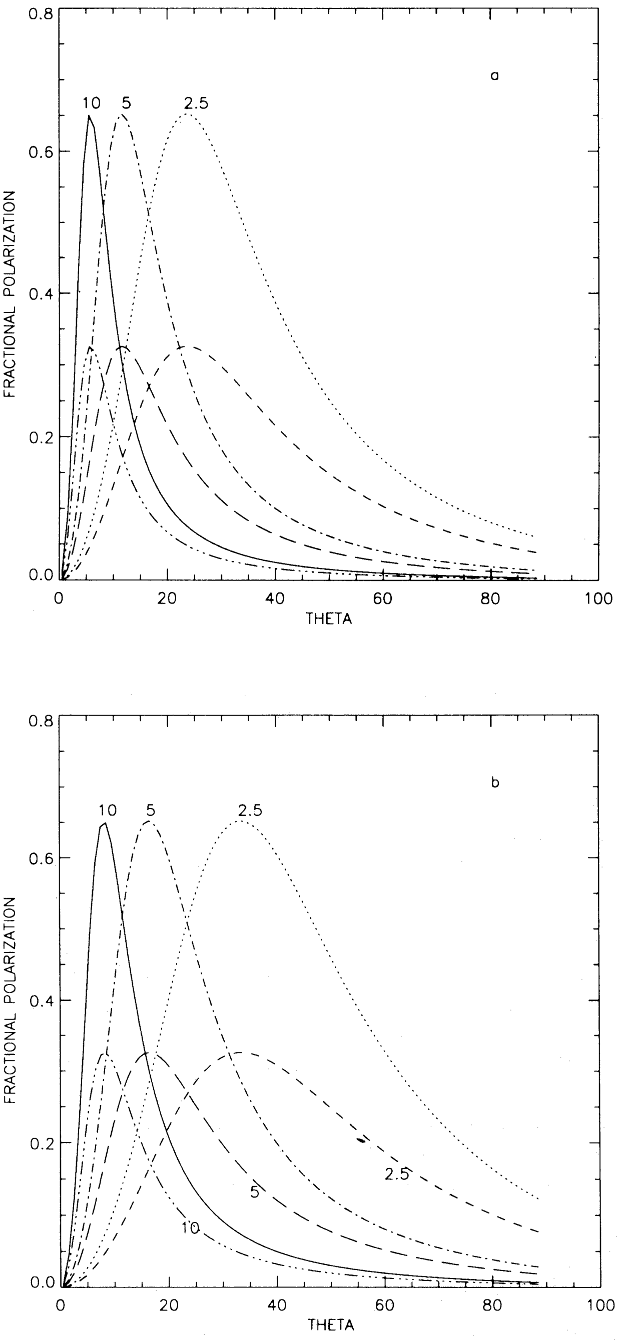

Fig. 3a and b. The fractional polarization, Π (assuming $\alpha=-0.25$) against θ for **a** $\Gamma_{em}=\Gamma_s$ and **b** $\Gamma_{em}=\Gamma_{ps}$. The dotted curves correspond to $\Gamma_s=2.5$, while $\kappa=0$; the short-dashed curves to $(\Gamma_s, \kappa)=(2.5, 1/\sqrt{3})$, the dot-dashed curves to (5.0, 0), the long-dashed curves to $(5.0, 1/\sqrt{3})$, the solid curves to (10.0, 0), and the dash-dot-dot-dotted curves to $(10.0, 1/\sqrt{3})$

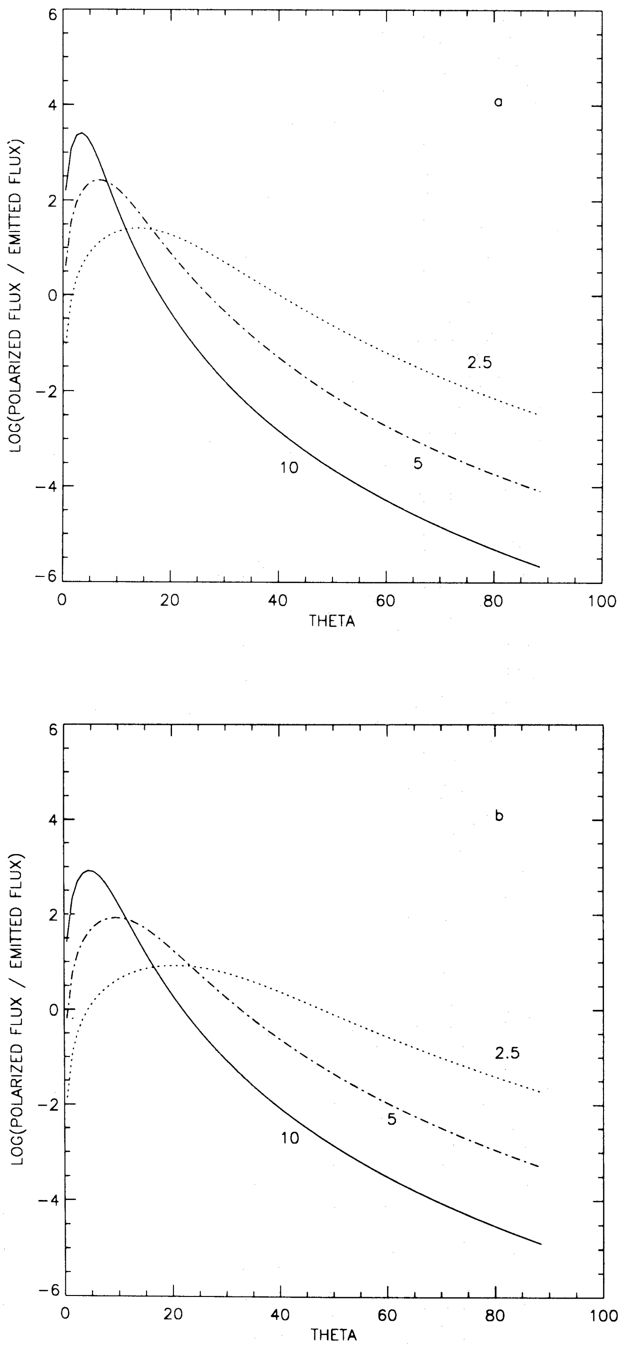

Fig. 4a and b. The polarized flux, P (on a logarithmic scale), against θ for $\alpha=-0.25$ and $\kappa=0$ and for **a** $\Gamma_{em}=\Gamma_s$ and **b** $\Gamma_{em}=\Gamma_{ps}$. Here $\Gamma_s=2.5$ (dotted curve), 5.0 (dot-dashed curve), and 10.0 (solid curve)

radio sources for which θ is expected to be very small. The values of Γ_s used by us span most of the range inferred from VLBI data from which it appears that lower values of Γ_s are more common (Cohen 1989).

Another important measurable quantity in such sources is the angle of polarization χ. If the shocked component, representing a compressed, initially random field, continues to move in the same direction, with fixed velocity, its polarization would always appear to be perpendicular to the shock for all except extremely small values of θ. If the shock front is seen essentially face-on, the very low Π due to the random component of the compressed field would be overwhelmed by the polarization expected from the plausible non-random residual component of the magnetic field in the shocked region. Within our picture, where changes in the jet direction would continuously alter the aspect of the shock front

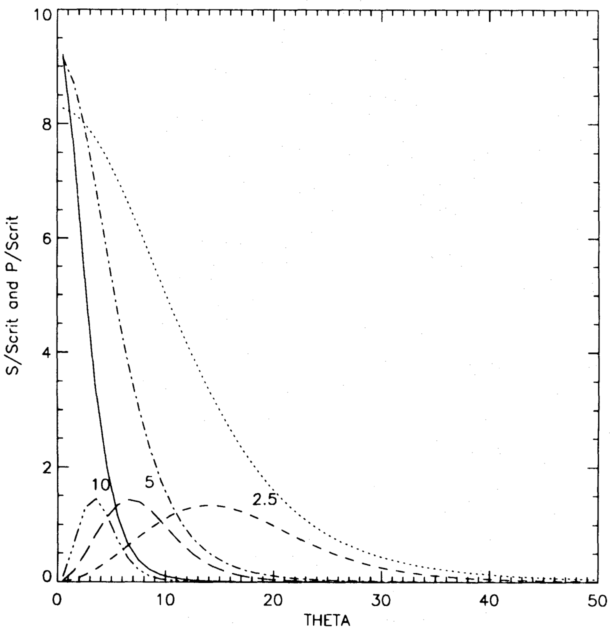

Fig. 5. S and P, both divided by S_{crit} (S evaluated at θ_c) for the case where $\Gamma_{em}=\Gamma_s$, $\alpha=-0.25$ and $\kappa=0$. The dotted curve corresponds to S, while the short-dashed one corresponds to P for $\Gamma_s=2.5$; the dot-dashed curve is S and the long-dashed one is P for $\Gamma_s=5.0$; the solid curve is S and the dash-dot-dot-dotted one is P for $\Gamma_s=10.0$

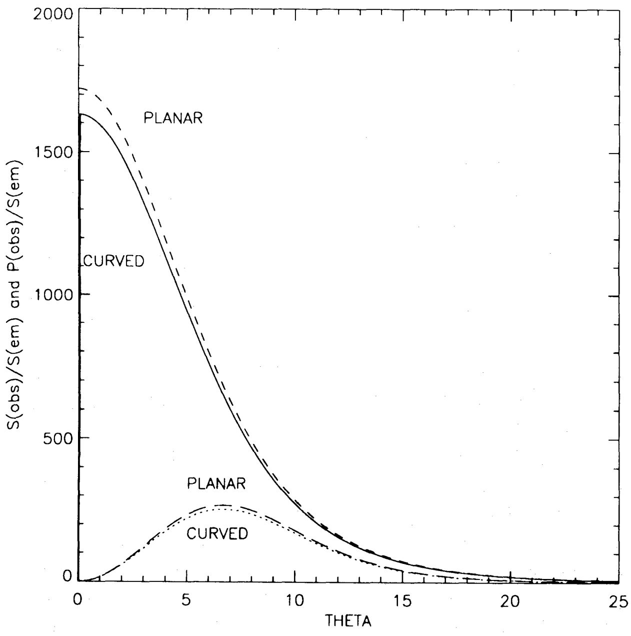

Fig. 6. The short-dashed curve reproduces the values of S, and the long-dashed curve the values of P as functions of viewing angle for $\Gamma_{em}=\Gamma_s=5$, $\alpha=-0.25$, and $\kappa=0$ for our standard model where the shock front is assumed planar. The solid curve gives S and the dotted curve gives P for the same parameters, but assumes the shock front is a spherical cap over an opening angle of 1° with the same total S_{em}

and, hence, the amount of aberration, one expects a general correlation between changes in χ and the amount of flux variability, as is generally seen in the long-term radio monitoring programs (Aller et al. 1985). However, if the changing direction of the jet is such that for a period the flow moves predominantly near the plane of the sky (as could be expected for helical motion, or for a shock passing across a helix) then during that period a substantial change in χ could be observed without much change in Π or S. However, any simple relativistic beaming or two-component models are restricted to swings in χ smaller than 180° (Björnsson 1982), although a few events of larger swings may have been observed (Quirrenbach et al. 1989b; Kikuchi et al. 1988; Aller et al. 1981). If not due to the inherent ambiguity in the interpretation of the polarization measurements, such large swings may arise from shock illuminating structures with a rotating magnetic field, as in the model of Königl & Choudhuri (1985), but they could also be explained by chance random walks around the origin of the Q–U (Stokes parameters) plane produced by cells with randomly oriented B fields (Jones et al. 1985).

3. Discussion

The occurrence of oscillations or wiggles in jets are perhaps most commonly evident on the VLA maps of many kpc-scale jets and are therefore likely to be a common phenomenon (Bridle & Perley 1984; also, Zaninetti & van Horn 1988 and references therein). The advance of jets has, in fact, been likened to a dentist's drill (Scheuer 1982). If the kpc-scale oscillations are due to the growth of instabilities (e.g. Hardee & Norman 1988; Saikia et al. 1987), they may be negligible on sub-parsec scales. But, if they are due to beam precession (Gower et al. 1982; Roos & Meurs 1987) then the wiggling will extend into the core. The limited available VLBI evidence (Sect. 1) shows that in a few best-resolved sources, prominent wiggly structures exist on the sub-parsec scale. If these features have larger Doppler factors, intrinsically minute wiggles can also appear greatly exaggerated. Taking a jet opening angle of say 1° (Biretta & Cohen 1987), a planar shock at a distance of, say 1 light-year from the engine, would have a size of ≈1 light-week; therefore, a bending by a few degrees within about a day in the observer's frame involves only non-relativistic physical movements in the frame of the emitting material, which are easily attainable.

Returning to one of the approximations in our model, we consider the effect of our assumption that the shock front is planar, by also examining the situation where the shock front exhibits a range of Doppler factors because of the jet's conical shape. In Fig. 6 we display the difference in S and P for a planar shock and a curved shock (with an intrinsic opening angle of 1°) where all the parameters other than the geometry are held constant. It is clear that the differences are very small, except when viewing angles as small as the opening angle are considered, and even then, the deviations are not dramatic. However, the additional complications arising from more complex geometries, such as helical filamentary structures (e.g. Rosen 1990), demand a careful consideration which is beyond the scope of this paper.

The most dramatic event of rapid S and P variability at radio frequencies was reported for the quasar 0917+624 at 5 GHz (Quirrenbach et al. 1989b). It is also a striking example of large changes in the polarized flux, P, anti-correlated with the variations in S. Quantitatively, the decrease in S by ≈20% is accompanied by about sixfold increase in the polarized flux, P. Now, taking $\Gamma_{em}=\Gamma_s=5$, it is seen from Figs. 1 and 4 that a change in the viewing angle from $\approx 3°$ to $\approx 1.5°$, would essentially explain these observations in the limiting case where the entire emission is assumed to arise from the shocked material. For a more realistic situation where the shocked material contributes only a portion of the total flux but probably a majority of the polarized flux, large extreme anti-correlated variations could be understood with our framework if only somewhat larger values of Γ_{em} are adopted (Fig. 4).

An intriguing aspect of the radio variability of 0917+624 is that the extremas in the total (S) and polarized (P) flux densities, while generally anti-correlated, show significant offsets in time (Quirrenbach et al. 1989b). (Unfortunately, such detailed monitoring data is available for this source alone). To our knowledge, no explanations for these offsets have yet been proposed, but they follow naturally in our picture. Although, as illustrated above, no offsets are predicted between the extrema of S and Π, the relationship between S and the total polarized flux, P, is more complex for viewing angles smaller than θ_c, especially for large Lorentz factors. To illustrate this, we have plotted in Fig. 7 the prediction of our simple model for the variations of S and P for small oscillations of the viewing angle corresponding to even smaller wiggles in the shock's direction in its frame. Depending upon the range of viewing angle covered and the assumed value of the Lorentz factor, significant offsets are easily possible.

While the mildly wiggling relativistic jet invoked here seems to be able to account for the ultra-rapid variability, the changes on longer time scales would be modified by the evolution of the radiating plasma behind the shock (e.g. Marscher & Gear 1985; Hughes et al. 1985, 1989a). Even though the detailed modelling of such an evolution by these authors, based on a large set of input parameters, seems to provide remarkably good fits to the long-term S, P monitoring data (Aller et al. 1985), our simple picture involving only a few variables can still reproduce the qualitative behaviour of individual outbursts fairly well. The general trend of the polarized flux to vary faster than the total flux might be broadly understood in our model, as illustrated in Fig. 4, if the viewing angle is small.

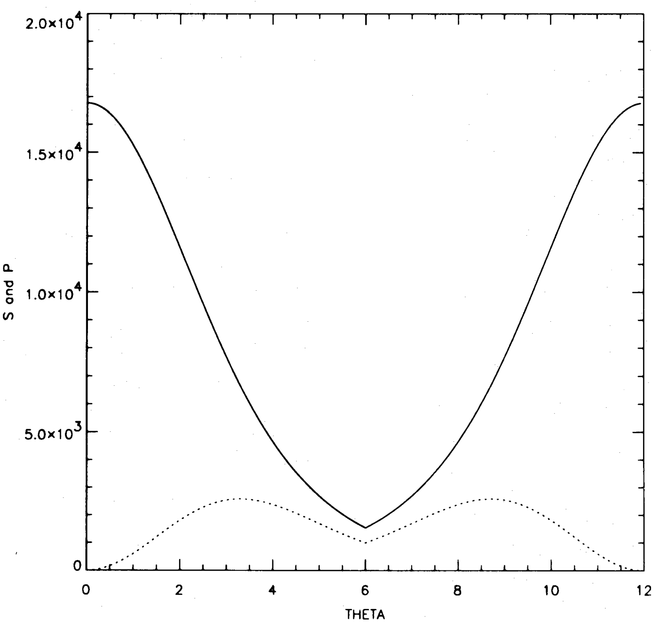

Fig. 7. Solid curves are S and dotted ones are P, for $\Gamma_{em}=\Gamma_s=10.0$, $\alpha=-0.25$ and $\kappa=0$. Here θ varies from 0 to 6°, but the labelled θ's continuing up to 12° actually shows the variations as θ decreases back to 0°, illustrating how maxima in P do not coincide with extrema in S. Note that reflecting Fig. 6 around a value of θ near 12.5° would yield very similar shaped curves for $\Gamma_s=5$

Our simple model is sufficiently flexible that significant changes in S without substantial changes in P are also possible for small viewing angles; e.g. for θ between 5° and 10° for $\Gamma_{em}=5$, as seen in Fig. 6. This type of variation has been found in 3C 273 at optical and near-IR wavelengths (Valtaoja et al. 1991b) and is difficult to understand within the framework of the frequently invoked two-component models comprising two synchrotron components with roughly orthogonal polarizations of similar magnitude, one of which is rapidly varying (e.g. Holmes et al. 1984; Qian et al. 1991; Valtaoja et al. 1990, 1991a, b). Since the degree of polarization of the "quiescent" component is usually believed to be much smaller, it must account for a majority of the flux, in order for this simple model to work. Usually, the light curves are decomposed into a variable component superposed on an underlying quiescent emission whose strength is determined by the minima in the light curve. Only if the underlying emission can be physically identified with either an extended feature ("jet"), or a self-absorbed "core", would it be safe to regard it as "quiescent" emission. There is little direct evidence for the putative "dominant quiescent polarized component" in blazars at centimetre (or optical) wavelengths. First, we are not aware of any VLBI map with good $u-v$ coverage that reveals significant emission in the form of an underlying continuous jet on a scale of less than about 1 pc. Further, estimating "quiescent" emission from intensity minima during brief periods of observation may be quite unrealistic, unless several periods of activity and inactivity have been monitored and the total flux is seen to return to the same level after the outbursts. Even when such a minimum appears to have been established through long-term monitoring, as in the case of BL Lac at 5 GHz (Hughes et al. 1989b), a VLBI map made during a quiescent phase (Gabuzda et al. 1989), shows that only ≈ 0.8 Jy out of the total ≈ 2.5 Jy is associated with the marginally polarized core; the rest is in the two polarized knots which cannot be regarded as quiescent. It is very likely that even this core will be further resolved into compact knots through VLBI at millimetre wavelengths (e.g. in 3C 273, Bååth et al. 1991). Thus, at most $\approx$ 0.8 Jy out of the peak flux of ≈ 10 Jy at 5 GHz could be ascribed to a quiescent component. To examine this point further, it is important to obtain VLBI maps of polarized and total intensity during the quiescent phases. In order to minimize the ambiguity in the polarization data observations must be made at high frequencies, where Faraday effects can be largely neglected, and which also provide a higher resolution.

Two-component models have also been applied to the optical–infrared monitoring data to blazars, especially for explaining their frequency-dependent polarization (e.g. Holmes et al. 1984; Ballard et al. 1990; Valtaoja et al. 1991a). One postulates different spectral slopes for the two polarized components, one of which is rapidly variable (probably the shocked material), so that the total emission displays a net polarization which changes with frequency and time. Prominent contaminating features include the thermal contributions from the galactic stars and the putative accretion disk, which cause additional uncertainities to the interpretation at these wavelengths. While some authors (e.g. Valtaoja et al. 1991a; Ballard et al. 1990) claim that the data are best understood if the "steady" component is a few percent polarized, others seem to associate the steady component with unpolarized emission (e.g. Impey et al. 1991).

A limitation of the simple two-component model is the difficulty in explaining the extremely large (>180°) swings in χ (Björnsson 1982; Qian et al. 1991) that have been occasionally reported (Sect. 2). Usually, such rare swings have been interpreted in terms of a rotating magnetic field structure along the jet (Königl & Choudhuri 1985). For highly core-dominated sources, which are presumably viewed end-on, the wiggling beam model proposed here could also account for such large swings in χ. As the aberrated viewing angle to the shock $\theta' \to 0$, the polarization vector would swing from its initial direction aligned with the shock to the new direction of reduced polarization determined by the vector sum of the individual magnetic cells within the shocked material (e.g. Jones et al. 1985; Jones 1988), which can be arbitrarily oriented. The dramatic swings of χ occurring during weakly polarized states, as noted observationally, can also naturally follow from this picture (Sect. 2); two-component models also predict such occurrences, in that all substantial polarization swings should occur when the two orthogonal polarizations nearly cancel each other.

Some of the radically different proposals for explaning rapid flux variability rely on extrinsic effects such as RISS at centimeter wavelengths (Heeschen & Rickett 1987) and superluminal gravitational microlensing (Gopal-Krishna & Subramanian 1991; Subramanian & Gopal-Krishna 1991). As noted by Witzel & Quirrenbach (1992) and others, refractive scintillations fail to account for the similar, correlated variations across the radio band observed for the source 0917+62, not to mention the correlated radio–optical variations seen in OJ 287 (Kikuchi et al. 1988) and 0716+714 (Quirrenbach et al. 1991). In the microlensing picture, the rapid variations could be imposed when the apparently superluminal emission knots pass behind planets or brown dwarfs within an intervening galaxy which acts as a gravitational lens. Gravitational lensing being achromatic (Einstein 1936), one can expect similar variations at different wavelengths provided the source remains transparent throughout the wavelength range and is not appreciably resolved by the lens. Microlensing can provide an explanation for the S–P correlation or anti-correlation in practically the same manner as does the two-component picture, since the lens can preferentially magnify the smaller component. An attractive feature of this model is that it provides a fairly natural explanation for the preferred day-like time scales (Gopal-Krishna & Subramanian 1991) observed at centimetre wavelengths (Heeschen et al. 1987; Krichbaum et al. 1991). This model shares many of the advantages and disadvantages of the two-component models, and despite the merits of the microlensing scenario, we have restricted our discussion here to possible intrinsic origins of rapid variability.

4. Conclusions

We have argued that a simple one-component model which allows for small variations in the direction of shocks occurring inside a relativistic jet can reproduce a wide range of the observed features of flux and polarization variability of blazars. We have specifically applied the model to the observed correlations of the flux density and polarized fraction of well-monitored blazars. In the simplest version of this kinematical model, when the viewing angle θ is greater than the critical angle $[\theta_c = (1/\Gamma_s)]$, the variations in S and Π are correlated, and in this case the apparent transverse velicity, β_{app}, would change in the same sense. Within the critical angle, however, changes in S and Π are anti-correlated and β_{app} varies in the same sense as Π. In a more general situation where the shocked material moves at a somewhat different speed from that of the shock itself, these correlations would break down for a limited range of viewing angles close to the critical angle (but the fractional change in β_{app} over this range is expected to be quite small). Our model also predicts a correlation between changes in χ, Π, and β_{app}. All these predictions can be tested by a dedicated VLBI monitoring program for blazars. Further, this model provides a natural explanation for the observed time offsets between the extrema of S and P. Note that while the correlations between S and Π can also be explained by the two component model, it makes no definite predictions about the likely variation of β_{app} and their correlations with S and Π.

A statistical trend predicted by our model is that the incidences of Π–S anti-correlation should be more common among the most core-dominated, flat-spectrum AGN, since we are more likely to be viewing them within the critical angle. Note that this model is designed to apply directly to BL Lacs, where the VLBI-scale polarization is observed to be prependicular to the structure (Gabuzda et al. 1989), presumably because of shock compression; but VLBI mapping of quasar knots indicates a magnetic field parallel to the axis (e.g. Roberts et al. 1990). It is possible that quasars involve more powerful jet sources with greater shear that generates parallel B fields and their knots are primarily an enhancement of the particle density or energy (Roberts et al. 1990; P.A. Hughes 1991, private communication), but it is clear that a simple shock model cannot explain all features of all types of AGN.

In the canonical two-component model, the fractional polarization of the knot and the orientation of its polarization vector are usually taken to remain steady even as the knot undergoes a rapid flux variation. In our picture we expect that the substantial changes in Π and β_{app} would accompany any large flux variations of the knot. This prediction is amenable to verification (or refutation) by means of polarization VLBI monitoring, which is an exciting possibility. Even if VLBI monitoring cannot be performed, the two schemes suggest different patterns of development of flares. In the two-component model, as a flare begins, the net polarization fraction of the source should decline, as the orthogonal polarization of the "quiescent" component begins to be cancelled. A sustained growth of the flare, and hence of S, would then lead to a positive correlation of Π with S and eventually to a saturation of Π and χ. However, in our one-component scenario, a vast majority of variations caused by changes in the viewing angle would produce either a positive or a negative correlation between S and Π and a concomitant small swing in χ. Only if θ crosses θ_c would a switch from positive to negative correlation (or vice versa) occur, and in this case the relative change in Π would be small, while S could change by a large amount.

Since very minor wiggles in the relativistic jets can lead to substantial measurable effects, one can speculate about their possible role in creating different classes of AGN. It is conceivable that a wiggling or twisting jet could more likely develop internal shocks leading to substantial flux and polarization variability (independent of any orientation effects), which are the principal characteristics of blazars. Such a scenario is consistent with the finding that the parsec- and kpc-scale radio structures are well aligned for low-polarization quasars, while misalignments are common for blazars (Impey et al. 1991; Saikia et al. 1991). In this context, it is also interesting that a few examples of highly variable BL Lacs have been found whose projected radio structures extend over several hundred kpc, thereby suggesting that these jets are unlikely to be pointing close to the line-of-sight (e.g. Strom & Biermann 1991; also, Mutel et al. 1990). However, superluminal motions for such non-aligned sources would require a non-standard model (e.g. Ekers & Liang 1990).

Our model is obviously over-simplified, and many of its predictions may be vitiated for individual sources where other factors we have ignored may play significant roles. But if the model is correct is essence, then studies of complete samples of radio sources should provide a statistical agreement with the above predictions. Currently available data are far too limited and sparse to allow such tests. But, with the quasi-continuous mapping of the fine structure and polarized emission of blazars that will become possible in the near future, these ideas can be tested.

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