RAPID VARIABILITY IN THE SOUTHERN BLAZAR PKS 0521–365

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Abstract. We present an intrinsic interpretation for the recently reported radio variability in the southern blazar PKS 0521–365. A shocked jet model can account for the quasi-periodical variations in the flux density of the source by means of inhomogeneities in the electron density with a quasi-periodic distribution along a jet in which a relativistic strong shock is propagating. These inhomogeneities are naturally produced by the effects of Kelvin–Helmholtz instabilities in the hypersonic parsec scale jet. The quasi-linear evolution of the polarization position angle can be understood as an effect of the "illumination" of successive cross sections with different mean field orientation or as a consequence of the shock propagation through a turbulent region in the jet. The high brightness temperature problem introduced by the short timescale varibility is solved invocating relativistic boosting with a moderately small viewing angle in agreement with the known structure of the source. In this context, several parameters are estimated.

1. Introduction

Variations in flux density and polarization of compact extragalactic radio sources at millimeter and centimeter wavelengths on timescales from months to years are well known. The first detections of flux density variability in these objects were reported by Sholomintskii (1965) and by Dent (1965). Variability in the radio polarization was first reported by Aller and Haddock (1967). An extensive review of the main observational characteristics of the phenomenon is given by Altschuler (1989). For southern sources just a few observations are available. In particular, Giacani and Colomb (1988) monitored weekly all known BL-Lac objects of the southern hemisphere during two years, finding out strong variability in several sources.

Recent observations have shown the existence of variability in extragalactic radio sources on timescales of days or less with amplitudes up to 25% or even more (Simonetti *et al.*, 1985; Heeschen *et al.*, 1987; Quirrenbach *et al.*, 1989a; Romero *et al.*, 1994). The origin of this rapid variability may be intrinsic to the sources or caused by propagation effects occurring along the line of sight, such as interstellar scintillation or gravitational microlensing. To this respect, variations in the degree of polarization and the polarization position angle can be used to enlighten the matter, especially if they are correlated. Despite extrinsic models can

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be invocated successfully to account for the rapid low amplitude variations in most of the flat spectrum sources (Quirrenbach *et al.*, 1992), there are some peculiar objects which seem to require a different approach as it is suggested, for instance, by the correlated radio-optical variations observed by Quirrenbach *et al.* (1991) in the BL-Lac object 0716+714.

Recently Quirrenbach *et al.* (1989b) and Luna *et al.* (1993) have reported quasi-periodical variations in the flux density and the degree of polarization of the active radio sources 0917+624 and PKS 0521−365. Both sources displayed large swings (or rotations) of the polarization position angle which are difficult to explain by extrinsic factors.

In this paper we propose an intrinsic interpretation for the rapid variability observed in the southern blazar PKS 0521−365 in terms of a relativistic shocked jet model. Details of the observations and data analysis are described in the paper by Luna *et al.* (1993) (hereafter Paper I).

2. Source and Observations

The active radio source PKS 0521−365 has an optically variable continuum which has resulted in its classification as a BL-Lac object. The spectrum contains diluted stellar absorption features and weak emission lines which agree with a redshift of $z = 0.055$ (Searle and Bolton, 1968). The host galaxy seems to be a normal elliptical one (Eggen, 1970), with a jet resembling in several aspects that of M 87 (Danziger *et al.*, 1985; Keel, 1986; Cayatte and Sol, 1987). The large-scale radio structure has been investigated by Danziger *et al.* (1979) and Keel (1986), and it presents several interesting features. In a quiet state the emission is dominated by the core and a single lobe opposite to the jet. The jet is detected at 2 cm up to a projected distance of 6.8 kpc from the nucleus. No counterjet has been observed connecting the nucleus and the hotspot opposite to the jet. This seems to suggest a small-moderate angle between the hotspot-nucleus-jet axis and the line of sight, in such a way that the relativistic beaming magnifies the jet emission and attenuates the emission from the counterjet. Relativistic velocities are assumed to be usual in BL-Lac objects (e.g. Bregman, 1990).

The integrated radio spectrum of the source is shown in Figure 1 (data from Kühr *et al.*, 1981). The spectrum is clearly nonthermal with a spectral index $\alpha_{408}^{1410} = \alpha_{1410}^{2650} = -0.5$ ($S \propto \nu^{\alpha}$). The radio spectral index for the jet probably shares this value (Cayatte and Sol, 1987).

Recently, Sparks *et al.* (1990) measured the optical polarization of the jet and nucleus confirming the expected high polarization if the optical emission is interpreted as due to synchrotron mechanism. This fact, together with the radio polarization measurements by Keel (1986), shows the absence of Faraday rotation in the source. Optical polarization variability has been reported by Luna (1990) during a quiet period of the source. The Faint Object Camara on the Hubble Space Telescope has revealed an apparent optical extension of the jet towards the nucleus

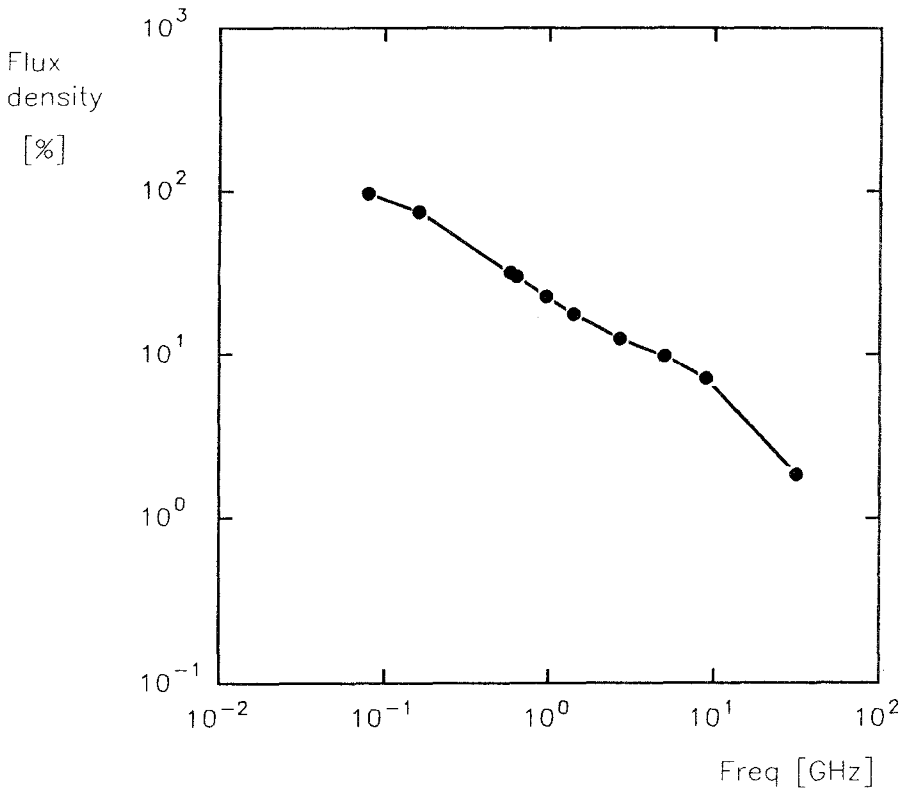

Fig. 1. Radio spectrum of PKS 0521−365 in log-log scale (data from Kühr *et al.*, 1981).

(Macchetto *et al.*, 1991). This extension falls within the VLA radio core at a projected distance of 300 pc from the nucleus and, if real, it could be interpreted as a site of electron acceleration along the jet by transverse shocks (Macchetto *et al.*, 1991). PKS 0521−365 has been also detected as a high-energy γ-ray source by the Compton Gamma Ray Observatory (Fitchel *et al.*, 1994). The γ-ray luminosity in this and other sources seems to be largely greater than the observed at other wavebands. Marscher and Bloom (1994) have recently discussed the relation between γ-ray and lower frequency emission in the context of shocked jet models.

We monitored the source searching interday polarization variability during four months, spanning from December 13, 1989 to April 26, 1990, with the 30 m continuum antenna of the Instituto Argentino de Radioastronomía at 1435 MHz, as a part of an extensive variability project (see Paper I for details). The main results of these observations of PKS 0521−365 are illustrated in Figure 2, where variations in flux density, degree of polarization and polarization position angle are displayed against the Julian Date of the observations. The presence of variability over the given error bars in both flux density and linear polarization light curves can be

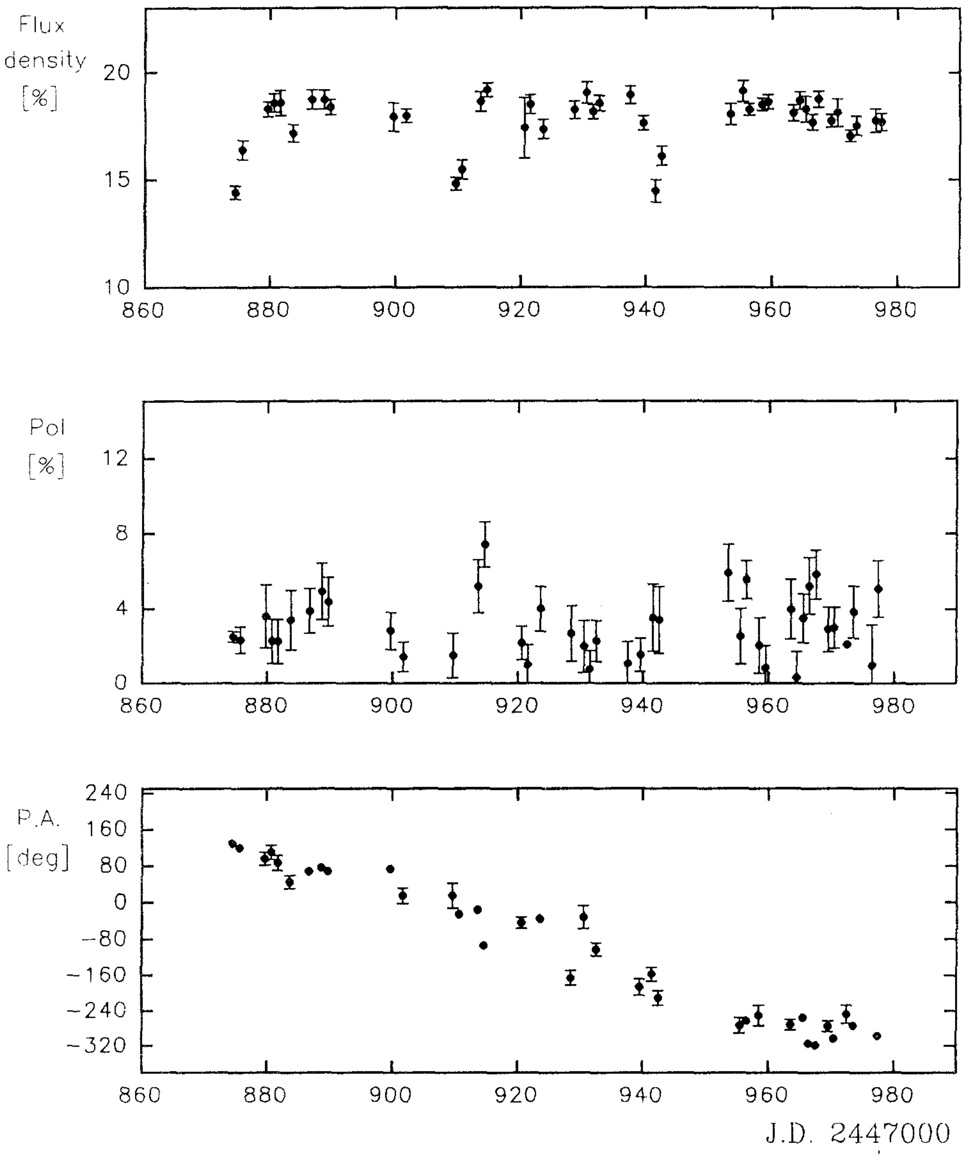

Fig. 2. Flux density, degree of linear polarization, and polarization P.A. of PKS 0521−365 against Julian Date.

tested with the criterion of Kesteven *et al.* (1976), which is used by several authors in variability data analysis (e.g. Altschuler, 1982, 1983; Giacani and Colomb, 1988; Romero *et al.*, 1994). According to this criterion, a source is classified as variable in the observable A if the probability of exceeding the value of

$$y^2 = \sum_{i=1}^{n} \epsilon_i^{-2}(A_i - \langle A \rangle)^2 \tag{1}$$

by chance is $< 0.1\%$, and as nonvariable if this probability is $> 0.5\%$. In Equation (1) n is the number of measurements, ϵ_i is the error corresponding to the measured value A_i, and $\langle A \rangle$ is the mean weighted value of A given by:

$$\langle A \rangle = \frac{\sum_{i=1}^{n} \epsilon_i^{-2} A_i}{\sum_{i=1}^{n} \epsilon_i^{-2}}. \tag{2}$$

If errors are random, y^2 should be distributed as χ^2 with $n-1$ degrees of freedom. Both light curves of PKS 0521−365 satisfy $p(y^2) \ll 0.1\%$. This fact, together with the flat light curves registered for calibration sources (see Paper I), indicates that the variability is real and not an instrumental effect (additonal information about the receiver and error analysis can be found in Romero *et al.*, 1994). The variability in the polarization angle is quite pronounced and can be appreciated even without computational tests.

The most remarkable features observed can be summarized as follows:

- The flux density S had a fluctuation index $\mu_S = \sigma_S/\langle S \rangle = 0.06 \pm 0.01$, with variations of $\Delta S \sim 4$ Jy in $\Delta t \sim 20$ days. A quasi-periodicity of $\sim$ 34.3 days can be detected. The mean weighted flux density $\langle S \rangle = 17.9$ Jy was 9.8% above the stable value of the last years (Giacani and Colomb, 1988).
- The degree of polarization P displayed regular variations, reaching a maximun value of P=7.4% in J.D. 2447914. The mean weighted value was $\langle P \rangle = 2.9\%$. There is a weak anticorrelation with the light curve, the minima of flux density being near in time with the maxima of P.
- The polarization position angle (P.A.) of the source showed a regular (quasi-linear) rotation during all four months of observation. The rate of rotation was $4.8^\circ \pm 0.2^\circ$ per day. Three jumps were detected, two of them being coincident with minima of P. This rotator event is one of the most rapid and linear ones ever reported for an extragalactic radio source, and is far larger than the 180° allowed by the relativistic aberration model (Björnsson, 1982). The rotation is similar to, but faster than, the one discovered by Ledden and Aller (1979) in the blazar 0235+164.

The observed polarization behaviour seems to rule out an extrinsic origin for the variations based on gravitational microlensing or refractive interstellar scintillation

(RISS). According to the gravitational interpretation of the rapid variability of blazars (e.g. Gopal-Krishna and Subramanian, 1991), the existence of a constant association between variations and sources is assumed every time the latter are looked at, as the variability is linked to the presence of a foreground lensing object. This is not the case of PKS 0521−365, which has been in a quiet state during the latter years (Giacani and Colomb, 1988). In addition, it seems to be no simple way of reconciling the observed polarimetric evolution of the source with microlensing because of the anticorrelation, the quasi-periodicity and the large swing in the P.A.. RISS (Rickett, 1986) is a more attractive hypothesis to account for quasi-periodical flux density variations. Strong local fluctuations in the electron density of the interstellar medium can produce multiple imaging and focusing events which may result in apparent flux density variations of compact extragalactic radio sources (e.g. Fiedler *et al.*, 1987). Even variations in the degree of polarization could be explained assuming a two component model for the source: if each component has a dominant magnetic field perpendicular to the other one, the scattering could preferentially magnify the smaller component and produce an anticorrelated variability in S and P by cancellation of P during the maximum amplification. However, the rotation in P.A. remains without explanation so as the correlation between the jumps in P.A. and the minima in P.

Hereafter we will concentrate in an intrinsic interpretation of the reported radio variability of PKS 0521−365. Intrinsic models must face several problems related with the fast rate of variation, but if they are solved, these models can provide a powerful tool to explore the inner region of blazars.

3. Interpretation

Variable radio emission from compact extragalactic sources on timescales of months can successfully be explained by adiabatically expanding synchrotron "clouds" of relativistic electrons (e.g. Rees, 1967). These clouds are initially assumed opaque to long wavelengths but by expansion they become optically thin at successively longer wavelengths producing flux density variations (Kellermann and Pauliny-Toth, 1968).

Rapid variability introduces severe constraints to intrinsic models because of the high brightness temperatures implied from the short timescales. In a synchrotron source, the brightness temperature should not exceed 10^{12} K in order to avoid the so-called "inverse Compton catastrophe" (i.e. the rapid loss of energy by the domineering inverse Compton process).

From the light travel time argument, the linear size of the variable radio emission region l must satisfy:

$$l \leq \frac{2ct_{\rm v}}{(1+z)}, \tag{3}$$

where the variability timescale is:

$$t_v = S\left(\frac{dS}{dt}\right)^{-1} \approx S_{max}\left(\frac{\Delta S}{\Delta t}\right)^{-1}. \tag{4}$$

The linear size l is related with the angular size θ by:

$$l = D_a\theta \tag{5}$$

with

$$D_a \approx \left(\frac{2c}{H_o}\right)[1 + z - (1+z)^{1/2}] \tag{6}$$

for $q_o = 1/2$.

The brightness temperature of the source will be:

$$T_B = 1.22\,[S/\mathrm{Jy}][\nu/\mathrm{GHz}]^{-2}[\theta/\mathrm{mas}]^{-2}(1+z) \times 10^{12}\,\mathrm{K}. \tag{7}$$

In the case of PKS 0521−365 we obtain from Equations (3)–(5) and (7) $T_B = 5.5 \times 10^{14}$ K, quite above the Compton limit (we adopt $H_o = 100$ km s^{-1}Mpc^{-1} throughout the paper).

In order to solve the high temperature problem, many authors have proposed models involving bulk relativistic motion in jets (Blandford and Königl, 1979, Marscher, 1980). In these models, the observed flux density S_{ob} is related to the flux density S in the comoving frame of the source by:

$$S_{ob}(\nu) = S(\nu)D^{3-\alpha}, \tag{8}$$

where $\alpha = d(\ln S)/d(\ln \nu)$ is the spectral index, and $D = [\gamma(1 - \beta\cos\psi)]^{-1}$ is the Doppler factor. The observed timescale t_{v_o}, and the intrinsic timescale t_{v_i} are related by $t_{v_o} = t_{v_i}(1+z)D^{-1}$.

Writing the flux density from a synchrotron radio source in the Rayleigh–Jeans approximation as:

$$S(\nu) = \pi k T_B \nu^2\theta^2/2c^2 \tag{9}$$

and using Equations (7) and (8) we obtain, after some algebra, the Doppler factor as a function of the brightness temperature:

$$D^{5-\alpha} = \frac{2c^2 S_{ob}(\nu)}{\pi k H_o^2 \nu^2 T_B t_{v_o}^2}\{1 + z - (1+z)^{1/2}\}^2(1+z)^4. \tag{10}$$

Adopting $T_B = 10^{12}$ K as an upper limit, we get the minimum value of D which is necessary to avoid the inverse Compton catastrophe. For PKS 0521−365 ($\alpha = -0.5$) the minimum Doppler factor is $D \approx 3.3$. Doppler factors of $\sim$ 2–10 have been derived from direct VLBI observations of superluminal bulk motion in other radio sources (e.g. Porcas, 1987).

3.1. Flux Density Variations

The observed quasi-periodicity in the flux density variability of PKS 0521−365 can be interpreted in terms of a relativistic strong shock propagating along the underlying stable jet (Marscher and Gear, 1985; Hughes *et al.*, 1985, 1989; Marscher, 1990; Qian *et al.*, 1991). In this context, the total flux density is the superposition of two components:

$$S(t) = S_s(t) + S_j, \tag{11}$$

where S_j is the stable contribution of the jet, and $S_s(t)$ is the variable shock component. If we include in S_j all stable contribution to the flux, we may take S_j as the lowest flux density observed, i.e. $S_j = 14.4$ Jy (J.D. 2447874). The variability timescale is related to the distance l along the jet travelled by the shock between two extreme points of the light curve by:

$$t_{v_o} = \frac{l(1+z)}{c\beta_s D_s \gamma_s}, \tag{12}$$

where $\gamma_s = (1-\beta_s^2)^{-1/2}$ and D_s is the Doppler factor of the relativistic shock. We adopt a Doppler factor $D_s \approx 4$, close to the lower value permitted by Equation (10), and a value $\psi \approx 10°$ for the viewing angle, according to the radio map by Keel (1986) and the considerations of the previous section. With these values we obtain $\gamma_s \approx 14.1$, and then $l \approx 3.6$ pc. Following to an original proposal by Marscher (1990), we interpret this spatial scale as the linear size of inhomogeneities in the electron density along the jet, in the region where the shock was propagating during the period of observation. Inhomogeneities in jets have been reported for many sources. For instance, the jet of M87 seems to contain six knots with a quasi-periodic spacing (Arp and Lone, 1976; Owen *et al.*, 1980). A strong knot similar to knot A in the M87 jet is located at 1.7" from the nucleus of PKS 0521−365 (Keel, 1986; Cayatte and Sol, 1987).

A strong freely propagating shock may "illuminate" (by enhanced synchrotron radiation due to particle acceleration and magnetic field amplification) successive transverse cross sections of the jet with different electron density, producing a variable component in the flux density. The shock is said to be strong in the sense that the random kinetic energy per particle behind the shock is much greater than ahead. The thickness of the shocked region must be small in comparison with the spatial scale of the inhomogeneities, and these must be spaced quasi-regularly along the jet in order that $S_s(t)$ be a quasi-periodical well-defined function of t, with $T \approx 34$ days. If we adopt an electron energy distribution (valid for $E < E_h = \gamma_{max} mc^2$) given by:

$$N(E) = NE^{-p} \tag{13}$$

with $p = 1 - 2\alpha$, and assume a magnetic field B_{ps} uniform in strength for the postshock region, the incoherent synchrotron optically-thin flux density from the shock will be:

$$S_\nu \propto N B_{\rm ps}^{1-\alpha} V D_{\rm s}^{3-\alpha} \nu^\alpha. \tag{14}$$

If the volume V of the shocked gas has no significant variations in short timescales, expansion losses are negligible and then the temporal behaviour of the flux density is dominated by the changes in N produced by the motion of the shock through the inhomogeneities spaced along the jet:

$$S_{\rm s}(t,\nu) \propto N(t) B_{\rm ps}^{1-\alpha} \Delta x_{\rm s} R_{\rm j}^2 D_{\rm s}^{3-\alpha} \nu^\alpha, \tag{15}$$

where $\Delta x_{\rm s}$ is the thickness of the shocked region and $R_{\rm j}$ is the jet radius. The number of electrons with energy $E_1 < E < E_2$ in the shocked region is given by $n(t) = N(t) \int_{E_1}^{E_2} E^{-p} dE$, with the function $N(t)$ determined by the electron density distribution along the jet and the shock velocity $c\beta_{\rm s}$.

A high-energy cutoff will appear in the spectrum of the shocked component at a frequency:

$$\nu_{\rm oh} = 6.3 \times 10^{18} (1+z)^{-1} D_{\rm ps} B_{\rm ps} E_{\rm h}^2. \tag{16}$$

For frequencies $\nu < \nu_{\rm oh}$ the flux density will be $S_{\rm s}(\nu) \propto \nu^\alpha$, according to Equation (14). Below the synchrotron self-absorption turnover frequency $\nu_{\rm om}$, the shocked component will become optically-thick, and then $S_{\rm s} \propto \nu^{5/2}$. The transition frequency $\nu_{\rm m}$ (in the postshock frame) is defined by the condition $\tau(\nu_{\rm m}) \sim 1$, where

$$\tau(\nu) = \int_{x_0}^{x_1} \kappa(\nu)\, {\rm d}x \propto N \Delta x_{\rm s} B_{\rm ps}^{(p+2)/2} \nu^{-(p+4)/2} \tag{17}$$

is the optical depth, $\kappa(\nu)$ is the absorption coefficient, N and p are defined by Equation (13). Then:

$$\nu_{\rm m} \propto N^{2/p+4} B_{\rm ps}^{(p+2)/(p+4)} (\Delta x_{\rm s})^{2/p+4} \tag{18}$$

and

$$\nu_{\rm om} \propto N^{2/p+4} D_{\rm ps} B_{\rm ps}^{(p+2)/(p+4)} (1+z)^{-1} (\Delta x_{\rm s})^{2/p+4} \tag{19}$$

in the observer frame. The turnover frequency has not been observed in the steady jet, probably because its value lies below the lowest used observing frequency, which is ~ 0.1 GHz.

The high-energy portion of the shock spectrum may be steepened by synchrotron and inverse Compton losses which vary as the square of the electron energy. In the underlying jet there is an important change of the spectral index between radio and optical wavelengths. This change is produced around a frequency $\nu_{\rm bj} = (8 \pm 5) \times 10^{13}$ Hz (Cayatte and Sol, 1987), and it can be attributed to synchrotron losses. For the shocked component, a measure of the energy at which radiative losses become important is given by the energy $E_b = \gamma_b mc^2$ at which the loss time equals the expansion time. The corresponding break frequency is $\nu_{ob} \propto \gamma_b^2 D_{ps}(1+z)^{-1} B_{ps}$, where for a radiative shock is required that $\gamma_b < \overline{\gamma}_{ps}$ ($\overline{\gamma}_{ps}$ is the mean Lorentz factor of the electrons in the postshock region) (Blandford and McKee, 1977). A complete determination requires, of course, multifrequency observations.

Marscher (1992) has strongly emphasized the severe constraints introduced by phase effects on the applicability of shocked jet models in which the observed rapid variability is governed by Equation (12). Phase effects arise in the context of peculiar geometries that permit 'phase velocities' faster than c (Lynden-Bell, 1977). Such an effect can be produced when a shock strikes a feature (e.g. an inhomogeneity in density) that subtends an angle ζ within a jet. The variability produced by the event has a timescale given by (see Marscher, 1990 for details):

$$t_v = \left\{ \frac{x}{\beta_s c} \left[\beta_s \cos(\psi - \zeta) - \beta_s \cos(\psi + \zeta)\right] + \frac{x}{c} \sin\left(\frac{\zeta}{2}\right) \sin\left(\frac{\zeta}{4}\right) \right\} (1+z) \tag{20}$$

$$\approx \frac{r\psi}{c}(1+z) \qquad (\zeta \le \psi \le 1) \tag{21}$$

$$\approx \frac{r\zeta}{8c}(1+z) \qquad (\psi \le \zeta \ll 1), \tag{22}$$

where $r = x \sin\zeta \approx x\zeta$, and x is the distance along the jet where the variations occur.

As we shall discuss in the next subsection, the inhomogeneities in the case of PKS 0521−365 could be originated by Kelvin–Hemholtz instabilities, in which case the ratio ζ/ϕ between the angle subtended by the knot and the jet opening angle is of ~ 1. Considering the apparent angle in the map by Keel (1986) and a projection factor $\sin\psi \approx 0.17$, we have $\phi \approx 1°$, and then $\zeta \le \psi \le 1$ for this source. This implies that phase effects will be determined by Equation (21) (notice the difference with the case of the rapid variability reported for 0917+621 at 11 cm and discussed by Qian *et al.*, 1991, where Equation (22) should be considered). Using the observed timescale we derived the radius of the jet in the region where the shock interacts with the inhomogeneities obtaining $R_j \approx 0.37$ pc. Then, the distance x to the jet apex results $x \sim R_j\zeta^{-1} \approx 21.2$ pc. This introduces a constraint on the thickness of the shocked region. In fact, Blandford and McKee (1976) have shown that for strong relativistic shocks which are propagating through a continuous medium with decreasing density, the thickness of the shocked region is a linear function of the distance travelled by the shock. If Δx_s is the thickness of the region with shocked particles,

$$\Delta x_s \approx \frac{x}{\gamma_{sj}^2}, \tag{23}$$

where $\gamma_{sj} = \gamma_s\gamma_j(1 - \beta_s\beta_j)$ is the Lorentz factor of the shock in the jet-flow frame. In this expression the value of γ_j is unknown. Cruz-González and Carrillo (1991) have estimated a set of Lorentz factors of low luminosity jets in active radio sources, finding a range $1 < \gamma_{\rm j} < 12$. Because of the strength necessary for the shock and the low luminosity of the underlying jet, we adopt a value $\gamma_{\rm j} \approx 2 \ll \gamma_{\rm s}$. With this choice $\gamma_{\rm sj} \approx 3.8$, and the thickness of the shocked region results $\Delta x_{\rm s} \approx 1.5$ pc if the shock was produced near the jet origin. The ratio between the thickness of the relativistic shock and the distance travelled along the jet is $\Delta x_{\rm s}/x \sim 0.07$. This is more than three times higher than the most optimistic value derived from Qian *et al.* (1991) data for 0917+624, but small enough to produce the variability (a thicker shock could smeared out the variations).

Thinner shocked regions can be locally originated by relativistic collisions between plasma flows with very different velocities. If the velocity of a jet with Mach number $M_{\rm j}$ varies by a fractional amount $\delta\beta_{\rm j}/\beta_{\rm j} \geq M_{\rm j}^{-1}\gamma_{\rm j}^{-2}$ on a timescale δt, then the faster plasma flow will catch up with the slower one in a $t \sim \beta_{\rm j}(\delta t/\delta\beta_{\rm j})$, and a strong shock will be formed (Ress, 1978; Marscher, 1990). The energy released by the adiabatic impulsive explosion will be $E = \sigma w_{\rm j}\gamma_{\rm s}^2\beta_{\rm s}^2 V$, where V is the volume swept out by the shock, $w_{\rm j}$ is the relativistic enthalpy ahead the shock, and σ is a constant which value depends on the nature of the external medium and shock characteristics (see Blanford and McKee, 1977 for estimates). The fraction of the kinetic energy dissipated in the shock is $\sim \gamma_{\rm j}^2(\delta\beta_{\rm j}/\beta_{\rm j})^2$. The emitting electrons will be accelerated at the shock front and will be cooled behind it. If this is the formation mechanism for the shock, the thickness of the shock wave may be smaller than our previous estimate.

The volume of the shocked region will be $V \approx 0.64$ pc^3 for $\Delta x_{\rm s} \approx 1.5$ pc, assuming that the shock front extends over the entire section of the jet. In a rough estimate, we may expect an angular size $\theta \sim 2\phi R_{\rm j}(1+z)^2 D_{\rm a}^{-1}$, where the value of $D_{\rm a}$ is given by Equation (6), yielding $\theta \sim 0.02$ mas. This is below the best resolution available from earth-bound interferometers, which is $\theta \sim 1.6\,[\nu/\mathrm{GHz}]^{-1} \approx 1$ mas at 1.4 GHz.

From Equation (23) we can see that it is not possible to expect quasi-periodic variability during a long period from the shock propagation. The thickness of the shocked gas will increase with the distance travelled along the jet in such a way that it soon becomes comparable with the size of the inhomogeneities, preventing in this way to discriminate them in the resulting flux. Towards the last observation days a lesser definition in the flux density variability curve can be appreciated, an indication of the broadening of the shock. Recent observations (Romero *et al.*, 1994) show the source in a quiet period, with a mean flux density of 17.4 Jy at 1420 MHz. In general, we expect that the variability timescale range of this kind of shocked jet model spans from a few days to a few months, i.e. we are dealing with a model for *inter*day periodic variability.

Marscher (1990) and Marscher *et al.* (1992) have discussed the effects of bends in relativistic shocked jets. Some of their results have been recently applied by Gopal-Krishna and Wiita (1992) to develop a purely kinematic model for the rapid variability in flux density and degree of polarization in blazars. In this model, small amplitude swings in the jet direction produce changes in the trajectories of relativistic shocks modifying the Doppler factor, and consequently the observed flux density given by Equation (8). Variations in the polarized flux are also expected from the changes in the observed orientation towards the jet. For changes until a critical value $\psi_c = \sin^{-1}(1/\gamma_s)$ ($\approx 4°$ in the case of PKS 0521−365) the variations in S and P will be anticorrelated. A weaker anticorrelation is expected when the effects of the different Lorentz factor for the shocked material $\gamma_{ps} < \gamma_s$ are taken into account. This might explain the offsets in time presented by the $S-P$ variations in PKS 0521−365. The anticorrelation occurs for changes in the viewing angle below the critical value $\tilde{\psi}_c = \sin^{-1}(1/\gamma_{ps})$ ($\approx 5.7°$ for our case), with a change in the slope of the transverse apparent velocity $\beta_{app}(t)$ at ψ_c.

The kinematic model is a very attractive one due to its extreme simplicity. However, it is not possible to explain large rotations (> 180°) in the polarization position angle using aberration effects (Björnsson, 1982). In order to account the large swing in P.A. for PKS 0521−365 in this context, it is neccessary to resort to casual random walks around the origin of the Stokes parameters space produced by cells with randomly orientated magnetic fields as Jones *et al.* (1985) have suggested. Future frequently VLBA observations can yield evidence to decide between these two intrinsic models by means of measurements of β_{app} during the $S-P$ variations, according to the observational test proposed by Gopal-Krishna and Wiita (1992).

3.2. Jet's Inhomogeneities

Our shocked jet model for PKS 0521−365 requires the presence of small (~ 3.6 pc) regularly spaced inhomogeneities in the electron density of the jet in order to reproduce the quasi-periodic flux density variability. The spatial regularity of nonuniform structures on parsec-scales in jets may be the result of the interaction between the jet and the interstellar or intergalactic medium. The problem to be consider is the stability of a relativistic jet of compressible fluid moving through an environment of also compressible fluid. In this context, the development of Kelvin–Hemholtz instabilities on the interface between the jet and the external medium can lead to a quasi-periodic spacing of density inhomogeneities.

Kelvin–Helmholtz instabilities arise in the vortex sheet between two fluids with different velocities, e.g. a beam and its environment. Hardee (1979) has studied how these pertubations can modify the structure of extragalactic jets. He found that on the surface of a cylindrical jet there is an unstable pinching mode ($n = 0$) peculiar to the cylindrical geometry. Fluting modes ($n > 0$), similar to the unstable waves found on a plane-parallel velocity discontinuity, are also present. The $n = 0$ growing waves which lead to periodic pinching of the jet compete with the $n \geq 1$ growing fluting waves which do not change the cross section of the jet. The pinching is analogous to the sausage instability of current-carrying plasma columns and may produce variations in the electron density within the jet. When the Mach number is $M_j \geq 1$, and the wavelength of the pinching mode is related to the jet radius R_j by

$\lambda \sim 2\pi R_j$, the rate of growth of the fluting mode is exceeded by the rate of growth of the pinching one. In this case, perturbations are able to produce small, regularly spaced inhomogeneities in the jet structure. If pinches grow sufficiently fast, the unstable $n = 1$ mode will be stabilized by the variations in the jet density induced by the pinches. For a uniform external medium, a relatively uniform pinching might be expected to develop. Even the presence of the strong knot in the jet of PKS 0521−365 may be understood by an increment in the amplitud of the $n = 0$ mode due to a change in the Mach number or in the density of the external medium.

In the hypersonic regime (which applies for most parsec scale jets) the most unstable pinching mode has a spatial growth rate $k_g \approx (M_j R_j)^{-1}$ and a wavelength $\lambda \approx \pi M_j R_j$, where we have included the effects of the reflection modes (i.e. those modes that involve the resonant reflection of internal acoustic waves at the contact discontinuity defining the jet boundary, see Ferrari *et al.* (1981) for details). The expected wave packet length is of the order of the longest unstable wavelength, in such a way that the linear size of the inhomogeneities formed in the jet will be $l \sim \pi M_j R_j/2$. A Mach number $M_j \approx 6.2$ is required for the jet of PKS 0521−365 if we want to get by pinching nonuniform structures with the size scale implied by the observed flux density variability. Using $R_j \approx 0.37$ pc, we obtain $\lambda \approx 7.2$ pc and a growth length $k_g \approx 0.44$. Well-defined pinches will form with length $l \sim 3.6$ pc. The density ratio of the jet must satisfy $\eta \equiv n_j/n_{ex} \leq (M_j/2)^{3.3} \approx 20.56$ (Cohn, 1983), where n_j is the number density for $r < R_j$ and n_{ex} is the number density for $r \geq R_j$. The pressure and density in parsec scale jets do not seem to be very different from those encountered in the denser interestellar medium (Rees, 1982; Begelman *et al.*, 1984). Taking $n_j \approx 10^{-1}\text{cm}^{-3}$ as a reasonable mean value (Spitzer, 1978), we find that the confining medium around the jet of PKS 0521−365 must satisfy $n_{ex} \geq 2.4 \times 10^{-3}\text{cm}^{-3}$.

In this way, for a hypersonic ($M_j \sim 6$) jet propagating through an external medium with a density greater than 2.4×10^{-3} cm^{-3} in the region where the jet radius is ~ 0.37 pc (not too far from the nucleus), Kelvin–Helmholtz instabilities can yield density inhomogeneities with a spatial scale ~ 3.6 pc, which are required to interpret the flux density variations as originated by the shock propagation along the jet. For transonic jets ($2 \leq M_j \leq 5$) fluting modes are expected to be dominant in the relativistic jet (Ferrari *et al.*, 1981). 'Wiggles' are then produced by $n = 1$ modes resulting a parsec scale swinging jet. In such cases our model reduces to the swinging shocked jet model proposed by Gopal-Krishna and Wiita (1992).

3.3. Physical Parameters

The knowledge of the spectral features of the variations (self-absorption turnover frequency, flux density peak, etc) allows an estimate of the mean magnetic field and the mean electron density in the shocked gas by means of the standard formulae for flux density at optically-thin frequencies (Pacholczyk, 1970). Unfortunately, the available observations are restricted to the sole frequency of 1435 MHz. However, we shall estimate the physical parameters following a different approach based on a few simple physical assumptions.

In the case of a perpendicular, relativistic strong shock, the jump conditions can be written in the simple form derived by Blandford and McKee (1976):

$$\frac{e_{\rm ps}}{n_{\rm ps}} = 4\gamma'_{\rm ps}\frac{P_{\rm j}}{n_{\rm j}}, \tag{24}$$

$$\frac{n_{\rm ps}}{n_{\rm j}} = \frac{\hat{\gamma}\gamma'_{\rm ps}+1}{\hat{\gamma}-1}, \tag{25}$$

where e is the energy density related with the pressure by the relativistic equation of state $P = e/3$, $\hat{\gamma}$ is the adiabatic index, which has a value $\hat{\gamma} = 13/9$ for a gas with equal fractions of relativistic electrons and nonrelativistic protons (Königl, 1980), and $\gamma'_{\rm ps}$ is the Lorentz factor of the shocked gas measured in the frame of the unshocked gas:

$$\gamma'_{\rm ps} = \gamma_{\rm ps}\gamma_{\rm j}(1-\beta_{\rm ps}\beta_{\rm j}) \approx \frac{\gamma_{\rm s}}{\sqrt{2}}\gamma_{\rm j}(1-\beta_{\rm ps}\beta_{\rm j}). \tag{26}$$

Taking as before $\gamma_{\rm j} \sim 2$ we get $\gamma'_{\rm ps} \approx 2.8$, and the compression ratio is given by Equation (25):

$$\xi = \frac{n_{\rm ps}}{n_{\rm j}} \approx 11.3. \tag{27}$$

The magnetic field in the quiescent jet depends on the distance x according to

$$B_{\rm j} = B_0\left(\frac{x}{x_0}\right)^q, \tag{28}$$

where x_0 is the site of electron injection in the jet. Multifrequency and VLBI observations of individual components in compact radio jets seem to suggest that this site could be coincident with the broad line emission region in the sources (Marscher and Gear, 1985; Marscher, 1992). According to this, we shall assume $x_0 \sim 1$ pc. If the flow is adiabatic we expect $B_{\rm j\perp} \propto x^{-1}$ and $B_{\rm j\,||} \propto x^{-2}$. When a shock propagates along the jet, the component $B_{\rm j\perp}$ is amplified by a factor ξ in the postshock region. If $B_{\rm j\perp} \sim B_{\rm j\,||}$ in the quiescent jet (Jones *et al.*, 1985) the strength of the magnetic field in the shocked region will be:

$$B_{\rm ps} \approx (\xi^{1/2}+1)^{1/2}B_{\rm j\perp}, \tag{29}$$

where

$$B_{\rm j\perp} = B_0\left(\frac{x}{1{\rm pc}}\right)^{-1}. \tag{30}$$

B_0 can be estimated considering that the spectral break observed by Cayatte and Sol (1987) at $\nu_{bj} \sim 8 \times 10^{13}$ Hz is due to the effects of synchrotron losses (Königl, 1981). Then,

$$B_0 \approx 1.9 \times 10^3 \{D_j^{1/2} \gamma_j \, [\nu_{bj}/\text{Hz}]^{-1/2} (1+z)^{-1/2}\}^{2/3} \ \text{G}, \tag{31}$$

$$B_0 \approx 0.1 \ \text{G}.$$

With this value, the transversal component of the jet magnetic field in the region where the variability is produced is $B_{j\perp} \approx 4.7 \times 10^{-3}$ G, and from Equation (29) we obtain

$$B_{ps} \approx 0.05 \ \text{G}. \tag{32}$$

The energy density of the magnetic field in the shocked gas is $u_B \sim 10^{-4}$ erg cm^{-3}.

From (27) we obtain the mean number density $n_{ps} \approx 1.1$ cm^{-3} of the electrons in the shocked gas, assuming as before $n_j \approx 0.1$ cm^{-3}. Equations (24) and (25) determine, together with the equation of state, the ratio between the gas pressure at both sides of the relativistic shock front:

$$\frac{P_{ps}}{P_j} = \frac{4}{3} \gamma'_{ps} \xi. \tag{33}$$

Using Equations (26) and (27) this leads to $P_{ps} \sim 42 P_j$. This jump pressure does not necessarily disrupt the flow if the jet is restmass dominated, which is the circumstance implied by the observed constancy of the superluminal velocity of a given component after it separates subtantially from the nucleus in many sources (e.g. Witzel, 1987).

We can also carry out a rough estimate of the intrinsic luminosity from the shocked region at the observing frequency. For a synchrotron source such as the shocked region observed at a frequency ν in a flat universe ($q_0 = 0.5$), the observed flux density $S_{ob}(\nu)$ and the intrinsic luminosity L_ν are related by:

$$S_{ob}(\nu) = 2.33 \times 10^{-62} L_\nu (1+z)^{1+\alpha_s} H_o^2 D_{ps}^{3-\alpha_s} \, [(1+z) - (1+z)^{0.5}]^{-2}, \tag{34}$$

where α_s is the spectral index for the shocked component, z is the observed redshift, D_{ps} is the postshock Doppler factor, and the numerical factor is for cgs units. Some multifrequency observations of radio bursts associated to shocks in flat spectrum radio sources (e.g. Holmes *et al.*, 1984, Qian *et al.*, 1991) show spectra for the shocked component which may be properly fitted by the spectrum of a homogeneous incoherent synchrotron source with optically-thin spectral index similar to that of the quiet underlying jet. If this is the case here, we may take $\alpha_s \sim \alpha$. Adopting $\overline{S_s} \sim 2$ Jy as the mean flux density from the shock, and using

TABLE I
Summary of assigned and derived values in the model

Parameter	Symbol	Value
Viewing angle	ψ	10°
Opening angle	ϕ	1°
Angle subtended by inhomogeneities	ζ	1°
Jet Lorentz factor	γ_j	2
Shock Lorentz factor	γ_s	14.1
Post-shock Lorentz factor	γ_{ps}	10
Linear size of inhomogeneities	l	3.6 pc
Distance from the jet apex to the shock	x	21.2 pc
Jet radius	R_j	0.37 pc
Thickness of the shock	Δx_s	1.5 pc
Volume of the shocked gas	V	0.64 pc^3
Jet Mach number	M_j	6.2
Jet number density	n_j	0.1 cm^{-3}
External medium number density	n_{ex}	$> 2.4 \times 10^{-3}$ cm^{-3}
Compression ratio	ξ	11.3
Post-shock number density	n_{ps}	1.1 cm^{-3}
Magnetic field at injection point	B_0	0.1 G
Jet magnetic field component	$B_{j\perp}$	4.7×10^{-3} G
Post-shock magnetic field	B_{ps}	0.05 G
Shock luminosity at 1435 MHz	L_{1435}	1.3×10^{34} erg s^{-1} Hz^{-1}

$H_o = 100$ km s^{-1}Mpc^{-1} we obtain $L_{1435} \approx 1.26 \times 10^{34}$ erg s^{-1}Hz^{-1}. Since the flux variations are not too dramatic, this value may yield a good estimate of the mean shock luminosity at 1435 MHz. Values of the several parameters are summarized in Table I.

3.4. Polarization Variability

Rapid variability of polarization in blazars has been recently reported by several authors (e.g. Kikuchi *et al.*, 1988; Quirrenbach *et al.* 1989b). Rotator polarization events seem to be very unusual phenomena observed in a few sources (see Sakia and Salter, 1988 for the list of objects and references). We shall discuss the polarization behaviour of PKS 0521−365 in the context of the shocked jet model of the previous subsections. At least two possibilities should be considered: the effect of turbulent fluctuations of the magnetic field and particle density, and the effect of a special geometry of the field in the parsec scale jet.

3.4.1. Turbulent Jet

Owing to the extremely large Reynolds numbers of relativistic jets the flows tend to be turbulent. When a shock propagates down in such a jet its emission is affected by the disturbances. The average synchrotron polarization from the shocked gas is (Hughes *et al.*, 1985; Jones, 1988):

$$P_{\rm ps} \approx 0.7\, \frac{g(\xi)\sin^2\overline{\psi}}{2 - g(\xi)\sin^2\overline{\psi}},$$
$$g(\xi) = \frac{\frac{128}{9}\,\gamma'^2_{\rm ps}\,\xi^2 - \frac{4}{3}\,\gamma'_{\rm ps}\,\xi - 1}{\frac{64}{9}\,\gamma'^2_{\rm ps}\,\xi^2 - \frac{4}{3}\,\gamma'_{\rm ps}\,\xi + 1}. \tag{35}$$

In these expressions $\overline{\psi}$ is the viewing angle corrected for aberration, $\gamma'_{\rm ps} \approx 2.8$ for our case, and ξ is the compression ratio. Turbulent fluctuations can locally modify the ratio ξ and consequently the degree of polarization of the shocked component. Variations in P.A. are produced by random fluctuations of Stokes vectors around a relatively steady component. Even apparent rotations can be originated by random walks around closed paths in the Q-U space. Jones *et al.* (1985) and Marscher *et al.* (1992) have carried out numerical simulations of such events, finding out apparent rotations up to 360° in P.A. (or a phase change up to 4π in the Stokes vector). The probability of exceeding a rotation of 180° is $p_{180^\circ} \sim 0.3$, which makes very probable such events. However, for rotations of 360° this probability drops to $p_{360^\circ} \sim 0.03$. In the case of PKS 0521−365 the observed value exceeds 480° having a probability of being originated by a 'phase diffusion' of the Stokes vector of $p_{480^\circ} \sim 7 \times 10^{-3}$. In addition to this low probability the event seems to be very linear while for a random process one would expect $\Delta(\mathrm{P.A.}) \propto t^{1/2}$ (see, for instance, Figure 7 in Marscher *et al.*, 1992).

3.4.2. Force-free Jet

A quite different approach can be attempted considering that in the parsec scale jet the mean magnetic field satisfies the force-free equation (Königl and Choudhuri, 1985a):

$$\nabla \times \mathbf{B} = \mu \mathbf{B}. \tag{36}$$

In a force-free equilibrium the magnetic force upon the particles is zero owing that the movement is along the field lines. Under these circumstances, the jet is confined by the external particle pressure and no general MHD treatment is required. The general solutions of Equation (36) for μ constant and cylindrical coordinates are:

$$\mathbf{B} = \sum_{m,k} B_{mk}\mathbf{b}^{mk}(r,\ \theta,\ x), \tag{37}$$

$$b_r^{mk} = \frac{1}{(\mu^2 - k^2)^{1/2}}\left[kJ'_m(y) + \frac{m\mu}{y}J_m(y)\right]\sin\omega, \tag{38}$$

$$b_\theta^{mk} = -\frac{1}{(\mu^2 - k^2)^{1/2}}\left[\mu J_m'(y) + \frac{mk}{y} J_m(y)\right]\cos\omega, \tag{39}$$

$$b_x^{mk} = J_m(y)\cos\omega, \tag{40}$$

where $\omega \equiv (m\theta + kx)$, $y \equiv (\mu^2 - k^2)^{1/2} r$ and J_m are Bessel functions of kind m. The boundary condition that must be satisfied by the solution is $B_r(R_\mathrm{j}) = 0$. If the jet is super-Alfvénic (Alfvén Mach number $M_\mathrm{a} > 1$) and the flow is supersonic with respect to the ambient medium ($M_\mathrm{j} > 1$), then the resulting magnetic configuration will be a linear superposition of only two modes: an axisymmetric $m = 0$ mode which accounts for the net flux and axial current in the jet, and a helical $m = 1$ mode which varies along the jet with a wavelength $\lambda \simeq 5R_\mathrm{j}$. As before, the shock will illuminate successive transverse cross sections of the jet. The integrated polarized emission from each cross section has a well-defined position angle which is determined essentially by the nonaxisymmetric $m = 1$ field orientation. When the angle between the line of sight and the jet axis is small, the propagation of the shock will lead to an apparent very linear rotation of the polarization position angle (Königl and Choudhuri, 1985b). For a small-moderate viewing angle such as $\cos\psi \sim \beta_\mathrm{ps}$ (where β_ps is the normalized velocity of the postshock gas), the apparent swing will be a steplike variation. An additional feature predicted for sources that are viewed at an angle $\psi \sim \cos^{-1}\beta_\mathrm{ps}$ is an apparent oscillation of the degree of polarization. In particular, the model predicts that the minima of P will coincide with the jumps of the polarization position angle. From Figure 2 it may be seen that the P.A. rotation in PKS 0521−365 exhibits three jumps, two of them coincident with minima of P near the J.D. 2447899 and 2447931.

Since particles move along the helical field lines high circular polarization should be observed. This means that additional assumptions must be introduced in the model since no reliable measured values of circular polarization in compact extragalactic sources exceed 0.5% of the total flux density. One possibility is a flow composed by equal parts of electrons and positrons. Pelletier and Roland (1989) have developed a two-fluid model for superluminal radio sources where the relativistic beam is formed by a e^-–e^+ plasma which moves in a channel through the e^-–p nonrelativistic ($\beta_\mathrm{j} \sim 0.35$) jet. In this scenario the Kelvin–Helmholtz instabilities are produced in the interface between the jet and the beam. The jet provides the inertia necessary to keep confined the beam even under shock propagation, and the beam produces the observed variability in the way described in Section 3.1. Equal amounts of opposed circularly polarized radiation are produced resulting in a neglectable total contribution.

Other possibility to explain the low circular polarization in the context of a helical geometry for the magnetic field is the coherent emission model by Benford (1992). Collective emission emerges when the relativistic electron beam moves through a lower density plasma. Cavitons scatter coherently the electrons producing a collective power which exceeds the synchrotron power by a factor $\sim 10^5$. This kind of process makes unnecessary high Doppler factors to account for very rapid variability (e.g. 0917+624). The coherent spectrum resembles the synchrotron one, and linear polarization features do not change from those expected in the synchrotron regime. However, there is no circular polarization (Benford, 1984, 1992). So, if the field in the jet is helical, a large swing in P.A. and variations in P could be observed without significant values of circular polarizartion.

New polarimetric observations of PKS 0521−365 can provide additional evidence to support one of these models for the rotation in the polarization angle of the source. If the turbulent jet model is a faithful representation for the polarization variability in this object, future inverse rotations should be observed owing to both rotational directions are equally probable in this interpretation. VLBI polarimetry could give evidence about the geometry of the parsec scale magnetic field. Finally, we wish to point out that a mixed model can be also feasible: a weak helical component in the magnetic field can produce a 'directed phase diffusion' in the Q-U space in such a way that the movement in the polarization angle occurs along the preferential direction established by the helical component while turbulence can produce jumps superposed to the linear rotation.

4. Conclusions

The peculiar polarization variability observed in the blazar PKS 0521- 365 seems to rule out an interpretation based on extrinsic causes, i.e. interstellar scintillation or gravitational microlensing. Intrinsic models have to face successfully three problems: the high brightness temperature $T_{\rm B} = 5.48 \times 10^{14}$ K derived from the observed variability timescale, the observed quasi-periodicity in the flux density and polarization variations, and the quasilinear rotation displayed by the polarization position angle.

A shocked jet model can account for all these features. Relativistic beaming with a small viewing angle allows to reduce the brightness temperature below the inverse Comptom limit in the proper frame of the emitting region. The relativistic electrons responsible for the observed synchrotron emission are accelerated by a shock wave, which travels along the jet "illuminating" successive cross sections of inhomogeneous structures regularly placed, and produces an integrated quasi-periodical variable radio flux. These regular inhomogeneities can be originated by Kelvin–Helmholtz instabilities in the interface between the jet and the external medium. A Mach number $M_{\rm j} \sim 6$ is required in order to yield structures with a spatial scale of ~ 3.6 pc which are needed to reproduce the flux density behaviour.

The shocked jet model here outlined can explain the polarization variablity of PKS 0521−365 if it is assumed that the jet is force-free with a predominant nonaxisymmetric magnetic field configuration. The shock will induce an apparent rotation of the polarization P.A., with the observed jumps for a viewing angle $\psi \sim 10°$. Turbulence in the jet can give an alternative explanation for the rotational event. We have estimated, within the frame of our interpretation, the values of the jet radius $R_{\rm j}$, the distance x from the shocked region to the jet origin, the compression

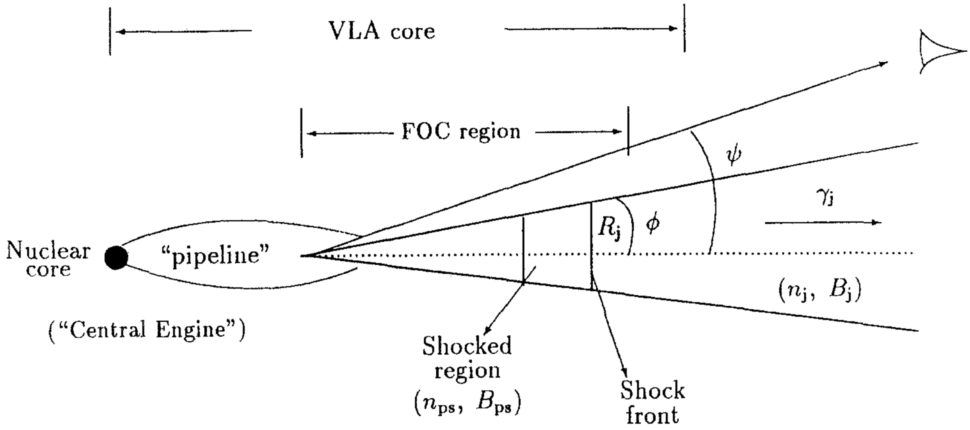

Fig. 3. Illustrative sketch of the source geometry. The existence of the "pipeline" is just hypothetical. Not drawn at any scale.

ratio ξ, the mean magnetic fields B_j and B_{ps}, the mean number density n_{ps}, and the intrinsic luminosity of the shocked region at 1435 MHz. All these values are very reasonable ones for an active extragalactic radio source, but it is important to remind that they are sensitive to the choice of certain unknown parameters such as γ_j, etc. To this respect, we have made a reasonable but not unique election.

The use of intrinsic models to account for the rapid variability in active extragalactic radio sources permits a comprehensive approach to the innermost regions of these objects, beyond the angular resolution of VLBI observations. The blazar PKS 0521−365 is an outstanding candidate for variability studies due to its proximity, the active nature of its nucleus and its well-defined jet. Future multifrequency radio observations and synchroneous radio and optical observations of this object may provide new keys to improve our understanding of the physical mechanisms that generate the amazing variability observed in some compact extragalactic radio sources.

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References

Aller, H.D. and Haddock, F.T.: 1967, *Astrophys. J.* **147**, 883.
Altschuler, D.R.: 1982, *Astron. J.* **87**, 387.
Altschuler, D.R.: 1983, *Astron. J.* **88**, 16.
Altschuler, D.R.: 1989, *Fundam. Cosmic Phys.* **14**, 37.
Arp, H. and Lone, J.: 1976, *Astrophys. J.* **210**, 58.
Begelman, M.C., Blandford, R.D. and Rees, M.J.: 1984, *Rev. Mod. Phys.* **56**, 255.
Benford, G.: 1984, in: A. Bridle, and J. Eilek (eds.), *NRAO Proc. Physics of Energy Transport in AGNs*, NRAO, Green Bank, p. 18.
Benford, G.: 1992, *Astrophys. J.* **391**, L59.
Bergman, J.N.: 1990, *Ann. Rev. Astron. Astrophys.* **2**, 125.
Björnsson, C.I.: 1982, *Astrophys. J.* **260**, 855.
Blandford, R.D. and McKee, C.F.: 1976, *Phys. Fluids* **19**, 1130.
Blandford, R.D. and McKee, C.F.: 1977, *Monthly Not. Roy. Astr. Soc.* **180**, 343.
Blandford, R.D. and Königl, A.: 1979, *Astrophys. J.* **232**, 34.
Cayatte, V. and Sol, H.: 1987, *Astron. Astrophys.* **171**, 25.
Cohn, H.: 1983, *Astrophys. J.* **269**, 500.
Cruz-González, I. and Carrillo, R.: 1991, *Rev. Mex. Astron. Astrophys.* **22**, 217.
Danziger, I.J. and Fosbury, R.A.E. *et al.*: 1979, *Monthly Not. Roy. Astr. Soc.* **188**, 415.
Danziger, I.J., Shaver, P.A. and Moorwood, A.F.M. *et al.*: 1985, *The Messenger* (ESO) **39**, 20.
Dent, W.A.: 1965, *Science* **148**, 1458.
Eggen, O.J.: 1970, *Astrophys. J.* **159**, L95.
Ferrari, A., Trussoni, E. and Zaninetti, L.: 1981, *Monthly Not. Roy. Astr. Soc.* **196**, 1051.
Fiedler, R.L., Dennison, B., Johnston, K.J. and Hewish, A.: 1987, *Nature* **326**, 675
Fitchel, C. *et al.*, 1994, *Astrophys. J. Suppl.* **94**, 551.
Giacani, E.B. and Colomb, F.R.: 1988, *Astron. Astrophys. Suppl.* **76**, 15.
Gopal-Krishna and Subramanian, K.: 1991, *Nature* **349**, 766.
Gopal-Krishna and Wiita, P.J.: 1992, *Astron. Astrophys.* **259**, 109.
Hardee, P.E.: 1979, *Astrophys. J.* **234**, 47.
Heeschen, D.S., Krichbaum, T. and Schalinski, C.J. *et al.*, 1987, *Astron. J.* **94**, 1493.
Holmes, P.A., Brand P.W., Impey, *et al.*: 1984, *Monthly Not. Roy. Astr. Soc.* **211**, 497.
Hughes, P.A., Aller, H.D. and Aller, M.F.: 1985, *Astrophys. J.* **298**, 301.
Hughes, P.A., Aller, H.D. and Aller, M.F.: 1989, *Astrophys. J.* **341**, 54.
Jones, T.W., Rudnick, L. and Aller, H.D. *et al.*: 1985, *Astrophys. J.* **290**, 627.
Jones, T.W.: 1988, *Astrophys. J.* **332**, 678.
Keel, W.C.: 1986, *Astrophys. J.* **302**, 296.
Kellermann, K.I. and Pauliny-Toth, I.I.K.: 1968, *Ann. Rev. Astron. Astrophys.* **6**, 417.
Kesteven, M.J.L., Bridle, A.H. and Brandie, G.W.: 1976, *Astron. J.* **81**, 919.
Kikuchi, S., Inove, M. and Mikami, Y., *et al.*: 1988, *Astron. Astrophys.* **190**, L8.
Königl, A.: 1980, *Phys. Fluids* **23**, 1083.
Königl, A.: 1981, *Astrophys. J.* **243**, 700.
Königl, A. and Choudhuri, A.R.: 1985a, *Astrophys. J.* **289**, 173.
Königl, A. and Choudhuri, A.R.: 1985b, *Astrophys. J.* **289**, 188.
Kühr, H., Witzel, A., Pauliny-Toth, I.I.K. and Nauber, U.: 1981, *Astron. Astrophys. Suppl.* **45**, 367.
Ledden, J.E. and Aller, H.D.: 1979, *Astrophys. J.* **229**, L1.
Luna, H.G.: 1990, *Astron. Astrophys. Suppl.* **84**, 611.
Luna, H.G., Martínez, R., Combi, J.A. and Romero, G.E.: 1993, *Astron. Astrophys.* **269**, 77.
Macchetto, F., Albrecht, R., Barbieri, C. *et al.*: 1991, *Astrophys. J.* **369**, L55.
Marscher, A.P.: 1980, *Astrophys. J.* **235**, 386.
Marscher, A.P. and Gear, W.K.: 1985, *Astrophys. J.* **298**, 114.
Marscher, A.P.: 1990, in: J.A. Zensus and T.J. Pearson (eds.), *Parsec-Scale Radio Jets*, Cambridge University Press, Cambridge, p. 236.
Marscher, A.P.: 1992, in: W.J. Duschl and S.J. Wagner (eds.), *Physics of Active Galactic Nuclei*, Springer-Verlag, Heidelberg, p. 510.

Marscher, A.P., Gear, W.K. and Travis, J.P.: 1992, in: E. Valtaoja and M. Valtonen (eds.), *Variability in Blazars*, Cambridge University Press, Cambridge, p. 85.
Marscher, A.P. and Bloom, S.D.: 1994, in: J.A. Zensus and K.I. Kellerman (eds.), *Compact Extragalactic Radio Sources*, NRAO, Green Bank, p. 179.
Owen, F.N., Hardee, P.E. and Bignell, C.: 1980, *Astrophys. J.* **239**, L11.
Pacholczyk, A.G.: 1970, *Radio Astrophysics*, Freeman, San Fransisco.
Pelletier, G. and Roland, J.: 1989, *Astron. Astrophys.* **224**, 24.
Porcas, R.W.: 1987, in: J.A. Zensus and T.J. Pearson (eds.), *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 12.
Qian, S.J., Quirrenbach, A. and Witzel, A. *et al.*: 1991, *Astron. Astrophys.* **241**, 15.
Quirrenbach, A., Witzel, A. and Krichbaum, T.P. *et al.*: 1989a, *Nature* 337, 442.
Quirrenbach, A., Witzel, A. and Qian, S.J. *et al.*: 1989b, *Astron. Astrophys.* **226**, L1.
Quirrenbach, A., Witzel, A. and Wagner, S. *et al.*: 1991, *Astrophys. J.* **372**, L71.
Quirrenbach, A., Witzel, A. and Krichbaum, T.P. *et al.*: 1992, *Astron. Astrophys.* **258**, 279.
Rees, M.J.: 1967, *Monthly Not. Roy. Astr. Soc.* **135**, 345.
Rees, M.J.: 1978, *Monthly Not. Roy. Astr. Soc.* **184**, 61p.
Rees, M.J.: 1982, in: D.A. Heeschen and C. Wade (eds.), *Extragalactic Radio Sources*, D. Reidel Publ. Comp., Dordrecht.
Rickett, B.J.: 1986, *Astrophys. J.* **307**, 564.
Romero, G.E., Combi, J.A. and Colomb, F.R.: 1994, *Astron. Astrophys.* **288**, 731.
Sakia, D.J. and Salter, C.J.: 1988, *Ann. Rev. Astron. Astrophys.*.**26**, 93.
Searle, L. and Bolton, J.G.: 1968, *Astrophys. J.* **154**, L101.
Sholomintskii, G.B.: 1965, *Astron. Zh.* **42**, 673.
Simonetti, J.H., Cordes, J.M. and Heeschen, D.S.: 1985, *Astrophys. J.* **296**, 46.
Sparks, W.B., Miley, G.K. and Macchetto, F.: 1990, *Astrophys. J.* **361**, L41.
Spitzer, L.: 1978, *Physical Processes in the Interstellar Medium*, Wiley and Sons, New York, p.227.
Witzel, A.: 1987, in: J.A. Zensus and T.J. Pearson (eds.), *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 83.