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An Intrinsic Model for the Polarization Position Angle Swing Observed in QSO 1150+812

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Abstract The rapid polarization position angle swing of $\sim 180^\circ$ observed in QSO 1150+812 at 2 cm by Kochenov and Gabuzda is quite a regular event. One interesting property of the event is that, during the time of the swing the polarized flux density remained almost constant. We suggest that such an event can be explained in terms of a relativistic thin shock propagating through a uniform helical magnetic field, giving rise to relativistic aberration effects as the transverse field component rotates. The model may also be applicable to other similar events in which variations in polarization are not accompanied by variations in total flux density.

Key words: radio continuum: galaxies — polarization — quasars: individual: QSO 1150+812

1 INTRODUCTION

In the study of compact extragalactic radio sources, variability in linear polarization has been observed for more than 20 years, especially for the so-called violently variable radio sources (blazars). The timescale of the variability ranges from weeks (even days) to years, and it usually appears during radio outbursts (Aller 1999). Radio outbursts are believed to be synchrotron radiation by shocks in relativistic jets. Relativistic shocks (transverse and oblique) have been suggested to explain the polarization variations (Aller et al. 2002; Hughes et al. 1989; Qian et al. 1992, 1993).

Very short timescales of polarization variability are observed ranging from $\sim$ 1 day to less than an hour (called intraday variability (IDV hereafter, Wagner & Witzel 1995; Kedziora-Chudzcer et al. 1997) and intraday polarization variability (Gabuzda & Kochenov 1997)). The characteristics of the polarized radiation can provide important information about the physical processes in the emitting region. Although the observed properties of intraday polarization variations are complicated and erratic to some extent, the relationship between the variabilities in the flux density and in the polarized flux density is most informative for understanding the physics of IDV (Qian et al. 2002). The rapid polarization angle swing events observed in a few blazars may belong to this kind of very special phenomenon. Both intrinsic (Qian et al. 1991, 2002; Marscher et al. 1992, 1996; Quirrenbach et al. 1989; Gopal-Krishna & Wiita 1992) and extrinsic mechanisms (especially refractive scintillation; Rickett et al. 1995, 2002; Qian et al. 2001a, 2001b) have been suggested for explaining the rapid polarization variations. For example, in QSO 0405–385, polarization variability on timescales from $\sim$ 1 day to less than one hour was observed (Kedizora et al. 1997). These variations in polarization were associated with variations in total flux density and were interpreted by Rickett et al. (2002) in terms of combined scintillation of three compact polarized components. For QSO 0917+624 multifrequency intraday polarization variations (from 2 cm to 20 cm) were observed. From an analysis of the 20 cm light-curves and by subtracting out the polarization variation due to scintillation, Qian et al. (2001a) isolated some significant features in the 20 cm polarized flux light curve. It was shown that these features are significantly correlated with the polarization variations at the short wavelengths (2–6 cm) and have similar timescales. This broad-band behavior seems to show that in this source some intrinsic polarization variations was at work. More simultaneous polarization observations at long (20 cm) and short wavelengths (2 cm) are needed to confirm this phenomenon.

VLBI polarization observations of IDV sources are important for studying the origin of IDV, because these observations can locate the VLBI components that are responsible for the intraday polarization variations. Gabuzda et al. (2000a, 2000b) have made VLBI polarization observations to study several IDV sources. They found that in several cases substantial variations in polarization were not accompanied by substantial variations in the total flux density. These cases can not be explained in terms of refractive scintillation, because in the scintillation mechanism polarization variations are caused by flux density variation of polarized components. They argued that while there are a few cases in which observed IDV can be clearly adequately explained as the effect of scintillation (Dennett-Thorpe & de Bruyn 2000; Kedziora-Chudczer et al. 2000; Jauncey et al. 2000), there is mounting evidence that a sizeable fraction of IDVs include an appreciable, or even a dominant, intrinsic component.

Therefore, from available observational facts and theoretical arguments, both intrinsic mechanisms (including coherent emission mechanism) and refractive scintillation need to be further developed in the study of intraday variation of polarization.

In this study, rapid polarization angle swings of $\sim 180°$ on time scales of $\lesssim$ 1 day may be of particular interest. Such swing events have a regular pattern, which should imply some kind of regularity in the responsible physical process. Their study may be helpful to the further understanding of the physics of IDV. Up to now, two such events have been observed: one in QSO 0917+624 (Quirrenbach et al. 1989) at 6cm and the other in QSO 1150+812 (Kochenov & Gabuzda 1999) at 2 cm. Both intrinsic and extrinsic (scintillation) mechanisms have been proposed for their explanation.

Quirrenbach et al. (1989) suggested that the polarization angle swing event observed in 0917+624 might be caused by a relativistic shock propagating along the jet and illuminating a helical magnetic field. This is an 'intraday version' of the model proposed by (Königl & Choudhouri 1985a; Qian 1992) for interpreting polarization angle swing events with time scales of months or years observed in blazars. This interpretation is based on the relativistic aberration effects when the transverse field component rotates. The model suggests that a relativistic shock propagating along a magnetized jet with a non-axisymmetric equilibrium field configuration (force-free field, mode $m = 1$; Königl & Choudhouri 1985b) would 'light up' the different field orientations in successive cross sections, leading to an apparent rotation of the synchrotron polarization position angle, when viewed from a small angle to the jet axis. In the model the apparent rate of change of the polarization position angle is highly non-uniform when θ is close to $\cos^{-1}(\beta_{\rm ps})$, even when the velocity of the shock is constant (Here $\beta_{\rm ps}$ representing the velocity of the post shock. See below). That is, a step-like variation of polarization angle can occur in this case.

Qian et al. (1991, 2002) considered a two-component model, in which a relativistic shock propagates along a jet, producing variations in the degree of polarization and the position angle of its synchrotron radiation and its vector combination with the steady polarized component leads to a swing of the resultant polarization angle. Generally, the shock component and the steady component have polarizations approximately perpendicular to each other. The main characteristic of the shock model is that both the degree and angle of polarization of the shock component are variable. Thus, in addition to being able to interpret rapid polarization angle swings, this model can also explain the general behavior of intraday variations in the polarized and total flux density: e.g., the complicated relationship between the variations in the total and polarized flux densities (correlation, anti-correlation and rapid transition between the two). It was shown that the degree and angle of polarization of the shock component were required to vary only in a narrow range.

Gopal-Krishna & Wiita (1992) suggested that the relationship between the total flux and polarized flux observed in IDV sources (correlation and anti-correlation) could be explained by the relativistic thin shock moving along slightly curved trajectories. In their model the degree of polarization of the shock component varies due to relativistic aberration (i.e., the change of the viewing angle with respect to the shock compression plane).

Rickett et al. (1995) has proposed a scintillation model to explain the intraday variability (in total flux and polarization) observed in QSO 0917+624. However, it could not explain the polarization angle swing of ∼ 180° observed by Quirrebach et al. (1989). They suggested that it could be due to low level intrinsic activity. This suggestion implies that intrinsic activity could temporarily dominate over scintillation during the polarization angle swing. However, they did not clarify how this could happen: why is it that the intrinsic activity played its role only during the swing, not during the entire IDV event. This problem may be regarded as one of the main shortcomings of the scintillation model, which significantly limited its application to intraday polarization variations. The problem seems to be related to the fact that in the case of refractive scintillation any individual scintillating component keeps its degree and angle of polarization constant while its total and polarized fluxes fluctuate due to refractive scattering. In this case two or more scintillating components could not 'vary in concert' to produce a continuous polarization angle swing of ∼ 180°, because refractive scattering is a random process.

Simonetti (1992) suggested that the polarization angle swing event observed in 0917+624 could be interpreted in terms of refractive focusing – defocusing by an interstellar shock if the source is compact enough. Two polarized components (say, A and B) are assumed in the source, having their polarizations differing approximately by 90°, but only one component (say, A) is affected by the shock. As the shock propagates across the line of sight, the pre-shock first makes component-A strongly focused, causing a rapid increase of its intensity and polarized flux. At this stage the polarization angle of the source will approach that of component-A alone. Afterwards, when the post shock propagates across the line of sight it makes component A sharply defocused, causing a rapid decrease of its intensity and polarized flux. At this stage the source polarization angle approaches that of the component-B. In this interpretation the variation of the polarization angle is discontinuous (a 'jump'). If, however, one branch of the position angle curve is moved by 180°, we would then see an 'apparent' continuous swing. In order to explain the observed polarization angles near the middle of the continuous swing, Simonetti (1992) suggested that some other mechanisms are needed, including an intrinsic mechanism or an additional focusing – defocusing process by another cloud. Thus problems arise similar to those for the scintillation model proposed by Rickett et al. (1995), as we already discussed above. Moreover, we would point out here that, for the model suggested by Simonetti (1992), there should be a rapid and large amplitude 'jump' of flux density during the polarization angle swing, but this was not observed. So from the above description it is clear that until now there is no satisfying interpretation in terms of scintillation for the intraday polarization angle swings of $\sim 180°$.

2 POLARIZATION ANGLE SWING IN 1150+812: OBSERVED PROPERTIES

In this paper we intend to propose a new intrinsic model for explaining the rapid polarization angle swing of $\sim 180°$ observed in QSO 1150+812.

The event of polarization angle swing of $\sim$ 180° observed at 2 cm in QSO 1150+812 (Kochenov & Gabuzda 1999) is shown in Fig. 1. The event was observed during an observational run of about 24 hours. The most rapid polarization angle swing occurred during a

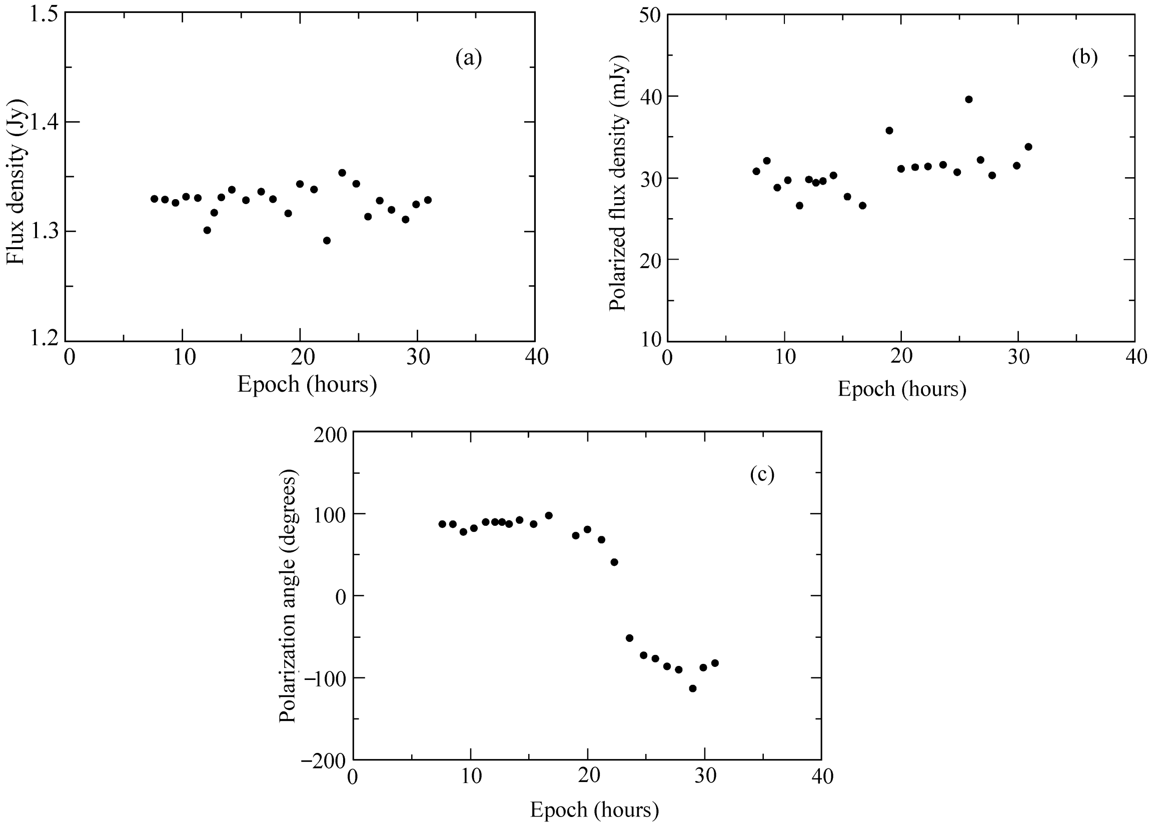

Fig. 1 Polarization angle swing event observed at 2 cm in QSO 1150+812. (a) total flux density, (b) polarized flux and (c) polarization angle. Data points are reproduced from Kochenov & Gabuzda (1999).

very short period of ~5 hours (from ~20h to 25h). The light curves of the Stokes parameters Q and U, and the $Q-U$ track are shown in Fig. 2, which shows the rapid variations in Q and U during the time of the swing. From Fig. 1 it can be seen that this event has some distinctive properties.

1) The most interesting behavior is that, during the time of rapid polarization angle swing (a swing of $\sim 150°$ from ~20h to 25h), the polarized flux density was observed to be almost constant: the average polarized flux density (for the five observational points) is 31.4 mJy with a standard deviation of 0.4 mJy (1σ). For the entire observation, the average polarized flux density is 30.92 mJy with a standard deviation of 2.87 mJy (1σ). Therefore, most of the variations occurred outside the period of rapid polarization angle swing, and the fluctuations in the polarized flux density (for example, the largest fluctuations at ~19h and ~25.8h) are not related to the rapid variations in the polarization angle.

2) Similarly, during the entire event, the total flux density did not vary substantially. The average of the flux density is 1.327 Jy with a standard deviation of 0.014 Jy (1σ). The largest variations occurred during the rapid polarization angle swing period. From ~21h to ~24h, the flux density first decreased by ~50 mJy and then increased by ~60 mJy, forming a minimum at ~22.3h. However, this variation in flux density did not cause any noticeable variations in the polarized flux density. This fact seems to imply that this largest variation in flux density occurred in a non-polarized component, distinct from the polarized component responsible for the variability in polarization and without any association with the polarization angle swing.

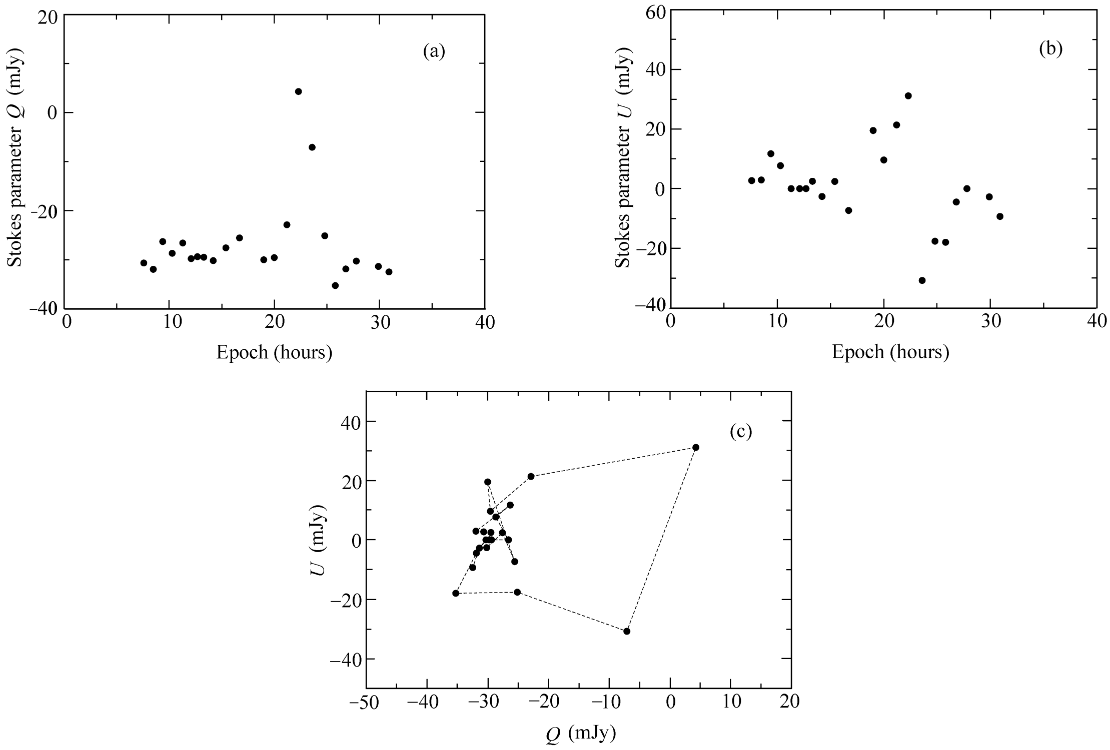

Fig. 2 Variations of Stokes parameters Q and U during the polarization angle swing event.

3) There are other pieces of evidence for this supposition. For example, during the period ∼12h–14h, the total flux density increased monotonically from 1.30 Jy to 1.34 Jy (by an amount of 40 mJy), but the polarized flux density and the polarization angle changed only a little. Similarly, the largest deviations observed at ∼19h and ∼25.8h in the polarized flux density did not have remarkable variations in the total flux density.

From the above description it is clear that, in order to understand the polarization angle swing observed in 1150+812, some special mechanism is required, in which the polarized flux density remains constant while the polarization angle swings. There may be two possibilities: (a) the apparent constancy of the polarized flux density during the polarization angle swing might be due to the vector combination of the variations in two or more polarized components. Each component could vary with a large amplitude, but of their polarized fluxes cancel out on vector addition resulting in the observed constancy; (b) The constancy of the observed polarized flux density was really occurring in a single polarized component. In this paper, we discuss the second possibility and propose a new model to explain the polarization angle swing event.

We assume that there are two components in the source, one unpolarized and the other polarized, that vary independently of each other. The unpolarized component is responsible for the variations in the flux density, and the polarized component, for the variations in the polarized flux density and for the polarization angle swing. We find that a relativistic shock propagating through a helical magnetic field with uniform strength may be taken as the polarized component.

3 MODELLING OF POLARIZATION ANGLE SWING

From the previous theoretical study of polarization position angle swing events with long timescales in extragalactic radio sources, we find that the properties of polarization angle swing and its relationship to the variations of polarized flux and total flux density are critically dependent on the configuration of the magnetic field and the dynamical behavior of the source. Blandford & Königl (1979) proposed a cloud model (an accelerating cloud with a uniform magnetic field within the jet) to explain the polarization angle swing of $\sim 130^\circ$ observed in AO 0235+164 by Ledden & Aller (1978). This model exemplifies the aberration effect in a source in relativistic motion: when a synchrotron source accelerates the aberration angle changes and causes rotation of the observed polarization angle. However, the model could not explain the observed variation in the degree of polarization which showed a maximum during the swing.

Björnson (1982) also considered polarization angle swings caused by a synchrotron radiating source in relativistic motion (or caused by the change of the aberration angle) and studied the ‘single vector’ model (i.e., model of a uniform magnetic field). The author pointed out that a relativistically moving source exhibits two qualitatively different polarization behaviors depending on the degree of asymmetry in the magnetic field distribution: (1) if the field has a high degree of rotational symmetry around some direction, it can be characterized by an average direction, i.e., the “single–vector” model can be applied; (2) in the case of significant asymmetry in the magnetic field distribution, then the polarization properties are very similar to a two-component model, in which the changes in polarization are solely due to changes in the relative flux of the two components. A common property of both models is that rapid polarization angle swings occur close to the minimum of the degree of polarization. The best way to distinguish between the relativistic motion model and the two-component model is to study the relationship between the variabilities in the polarization and in the associated flux density.

In contrast, Königl & Choudhouri (1985a) considered polarization angle swing in the case where a relativistic shock propagates along the jet and illuminates a helical field. Relativistic effects can cause rapid polarization angle swings of ∼ 180° due to rotation of the transverse component of the field. They applied a force-free field configuration to explain the polarization angle swing observed in the source 0727–115 by Aller et al. (1981). As in the case studied by Björnson (1982) this model also predicts that the swing should occur close to the minimum of the degree of polarization, but not accompanied by substantial variations in flux density.

From the above description it can be seen that none of the previously suggested models can explain the properties of the polarization angle swing observed in QSO 1150+812: a swing occurring without a substantial variation in the polarized flux density.

Recently, Qian & Zhang (2003) studied polarization angle swings caused by relativistic effects for two field configurations (uniform helical field and force-free field) and found that, in contrast to the case of force-free field, in the case of uniform helical field polarization angle swing events can occur with the polarized flux density varying only a little. In this paper we will apply the results obtained in the above paper to propose a plausible model for the polarization angle swing observed in 1150+812.

3.1 Magnetic Field Configuration

We first introduce the results given in Qian & Zhang (2003). We consider a helical magnetic field with a uniform strength. The geometry for the magnetic field and the relativistic jet flow is sketched in Fig. 3.

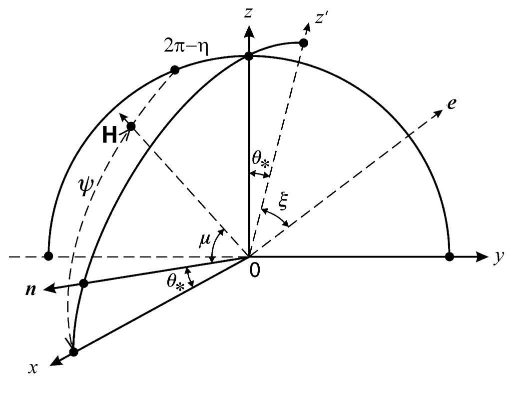

Fig. 3 Geometry of the magnetic field configuration.

The jet flow with velocity $c\beta_j$ is assumed to be along the x-axis. Let $\boldsymbol{n}$ be the unit vector directed to the observer located in the plane (x, z) at a viewing angle θ (corresponding to an aberration angle θ_*). The magnetic field in the jet flow frame can be described as:

$$H_x = H_0 \cos\psi, \tag{1}$$

$$H_y = H_0 \sin\psi \cos\eta, \tag{2}$$

$$H_z = H_0 \sin\psi \sin\eta, \tag{3}$$

H_0 – the strength of the magnetic field defined in the rest frame of the jet flow, ψ – the polar angle (or pitch angle in our case) measured from the x-axis; $\eta = 2\pi x/\lambda$ – the azimuthal angle measured clockwise in the yz plane; x coordinate denotes the distance along the jet axis; λ – the wavelength through which the magnetic field rotates by 2π.

3.2 Magnetic Field of the Post-shock

We consider a relativistic shock propagating along a cylinder shaped jet. The speed of the jet flow is $c\beta_j$ (Lorentz factor γ_j). The magnetic field is assumed to be frozen into the jet plasma and is given by Eqs. (1)–(3). The speed of the shock is $c\beta_s$ (Lorentz factor γ_s). Then the velocity of the shock relative to the jet plasma, ($c\beta_{sj}$), and the corresponding Lorentz factor (γ_{sj}) are given by the following equations:

$$\beta_{sj} = \frac{\beta_s - \beta_j}{1 - \beta_s \beta_j}, \tag{4}$$

and

$$\gamma_{sj} = \gamma_s \gamma_j (1 - \beta_s \beta_j). \tag{5}$$

For an extremely relativistic shock ($\gamma_{sj} > 1$), $\gamma_{sj} \approx \frac{\gamma_s}{2\gamma_j}$, and the Lorentz factor of the post-shock plasma $\gamma_{\rm ps} \approx \gamma_s/\sqrt{2}$ (Blandford & Mckee 1976; Königl 1980). The transverse field component of the post-shock is amplified by compression and the amplification factor is $\sim 2\sqrt{2}\gamma_{sj} \approx \sqrt{2}\gamma_s/\gamma_j$.

The longitudinal field component remains unchanged. Therefore, the magnetic field components in the region (in the comoving frame) can be expressed as

$$\begin{aligned} H_{{\rm ps},x} &= H_x, & (6) \\ H_{{\rm ps},y} &= \frac{\sqrt{2}\gamma_s}{\gamma_j} H_y, & (7) \\ H_{{\rm ps},z} &= \frac{\sqrt{2}\gamma_s}{\gamma_j} H_z. & (8) \end{aligned}$$

In the observer's frame the magnetic field components of the post-shock are

$$\begin{aligned} H_{{\rm obs},x} &= H_{{\rm ps},x}, & (9) \\ H_{\rm obs,y} &= \gamma_{\rm ps} H_{{\rm ps},y}, & (10) \\ H_{{\rm obs},z} &= \gamma_{\rm ps} H_{{\rm ps},z}. & (11) \end{aligned}$$

3.3 Polarization Position Angle

As shown by Björnson (1982) (also see Blandford & Königl 1979; Königl & Choudhouri 1985a), for a relativistically moving synchrotron source with its magnetic field configuration as shown in Fig. 3, the observed polarization position angle ξ can be written as

$$\tan \xi = \cot \eta_{\rm ps} (-\cos\theta_* + \cot\psi_{\rm ps} \sec\eta_{\rm ps} \sin\theta_*), \tag{12}$$

where $\eta_{\rm ps}$ and $\psi_{\rm ps}$ are, respectively, the polar angle and azimuthal angle of the magnetic field in the post-shock frame, θ_* is the aberration angle, satisfying

$$\cos\theta_* = \frac{\cos\theta - \beta_{\rm ps}}{1 - \beta_{\rm ps}\cos\theta}\,, \tag{13}$$

and

$$\sin\theta_* = \frac{\sin\theta}{\gamma_{\rm ps}(1 - \beta_{\rm ps}\cos\theta)}\,, \tag{14}$$

where $\gamma_{\rm ps}=(1-{\beta_{\rm ps}}^2)^{-\frac{1}{2}}$. Using the expression of the magnetic field in the observer's frame, we obtain

$$\tan\xi=\frac{\cot\eta_{\rm obs}}{(1-\beta_{\rm ps}\cos\theta)}(-\cos\theta+\beta_{\rm ps}+\cot\psi_{\rm obs}\sec\eta_{\rm obs}\sin\theta)\,. \qquad (15)$$

Here we note that the relativistic transformation of the magnetic field from the post-shock frame to the observer's frame is: $\tan\psi_{\rm obs}=\gamma_{\rm ps}\tan\psi_{\rm ps}$, $\eta_{\rm obs}=\eta_{\rm ps}$ (ξ is an invariant). We can also use the components of the field to write down these formulae: in the post-shock frame,

$$\tan\xi=\frac{H_{{\rm ps},y}}{H_{{\rm ps},z}}\Big(-\cos\theta_*+\sin\theta_*\frac{H_{{\rm ps},x}}{H_{{\rm ps},y}}\Big)\,, \qquad (16)$$

or in terms of the field components in the observer's frame

$$\tan\xi=\frac{H_{{\rm obs},y}/H_{{\rm obs},z}}{1-\beta_{\rm ps}\cos\theta}\Big(\beta_{\rm ps}-\cos\theta+\sin\theta\frac{H_{{\rm obs},x}}{H_{{\rm obs},y}}\Big)\,. \qquad (17)$$

Here we note that the relativistic transformation gives: $H_{x,{\rm obs}}=H_{x,{\rm ps}}$, $H_{y,{\rm obs}}=\gamma_{\rm ps}H_{y,{\rm ps}}$, $H_{z,{\rm obs}}=\gamma_{\rm ps}H_{{\rm ps},z}$.

3.4 Stokes Parameters

In order to study the polarization properties of a relativistically moving synchrotron source (shock) we need to use Stokes parameters to describe the radio emission of the post-shock. We will first calculate the Stokes parameters in the comoving frame and then transform them into the observer's frame through a Lorentz transformation (Björnson 1982; Königl & Choudhouri 1985a; Qian 1992). The Lorentz transformation involved is quite simple. What we should do is just to multiple each of the Stokes parameters by the factor $D_{\rm ps}^{3+\alpha}$. Here $D_{\rm ps}=[\gamma_{\rm ps}(1-\beta_{\rm ps}\cos\theta)]^{-1}$ is the Doppler factor of the emitting plasma, α is the spectral index ($S_\nu\propto\nu^{-\alpha}$). For simplicity we only consider optically thin radio frequencies. We will assume that the shock is thin in the sense that the magnetic field in the region is uniform, although the field rotates along the jet. We also assume that the energy distribution of the relativistic electrons is isotropic, and has a power-law of index 2α+1 ($N_{\rm ps}\propto E^{-(2\alpha+1)}$), but the number density may be distributed across the cross-section of the jet (see below). For an unresolved emitting region the Stokes parameters (I_o, Q_o, U_o) of the total radiation can be obtained by integrating over the whole cross section. So we have

$$I_o={D_{\rm ps}}^{3+\alpha}\int I_\sigma d\sigma, \qquad (18)$$

$$Q_o={D_{\rm ps}}^{3+\alpha}\frac{3+3\alpha}{5+3\alpha}\int I_\sigma\cos2\xi d\sigma, \qquad (19)$$

$$U_o={D_{\rm ps}}^{3+\alpha}\frac{3+3\alpha}{5+3\alpha}\int I_\sigma\sin2\xi d\sigma \qquad (20)$$

Here

$$I_\sigma(r)\propto(1+z)^{1-\alpha}C_5(2C_1)^\alpha\nu^{-\alpha}N_{{\rm ps},0}\times\exp\left[-(r/r_m)^2\right](H_{\rm ps}\sin\mu_{\rm ps})^{1+\alpha}{D_l}^{-2}\Delta x, \qquad (21)$$

$$\sin^2\mu_{\rm ps}=\cos^2\psi_{\rm ps}[\tan^2\psi_{\rm ps}(1-\sin^2\theta_*\cos^2\eta_{\rm ps})+\sin^2\theta_*-\sin2\theta_*\cos\eta_{\rm ps}\tan\psi_{\rm ps}], \qquad (22)$$

where z is the redshift, I_σ is the intensity of the synchrotron radiation emitted by a small element of the cross section (dσ), and θ_* is the aberration angle, Δx is the thickness of the post-shock, $\int d\sigma$ represents the integral over the entire cross-section of the post-shock, ν the observing frequency, ξ the polarization position angle of the emitting element as given above, $C_5 \equiv C_5\ (\alpha)$ and C_1 are constants (see Pacholzyck 1970). $N_{\rm ps,0}$ is the normalization of the density of relativistic electron energy distribution in the post-shock frame, which is assumed to be isotropic and has a power-law form ($N_{\rm ps} \propto N_{\rm ps,0}E^{-2\alpha-1}$, and is distributed across the jet according to $\exp[-(r/r_m)^2]$ (r_m is the radius of the jet). $H_{\rm ps}$ is the strength of the magnetic field of the post shock, $\mu_{\rm ps}$ is the angle between the magnetic field and the direction to the observer. We should point out that, when we calculate this angle, we need the relativistic transformation for an angle between two directions neither of which coincides with the direction of motion. So the angle $\psi_{\rm ps}$ in Eq. (22) for $\mu_{\rm ps}$ is given by

$$\cos\psi_{\rm ps} = \frac{\cos\psi_{\rm obs} - \beta_{\rm ps}}{1 - \beta_{\rm ps}\cos\psi_{\rm obs}}, \tag{23}$$

where $\psi_{\rm obs}$ is related to the polar angle of the magnetic field $\boldsymbol{H}_{\rm obs}$ (in the observer frame).

4 MODEL FITTING RESULTS

Before making a model-fit for the observed polarization angle swing, we should mention that 1150+812 has been observed to be a superluminal source. The observed apparent speed is $4.1c\,h^{-1}$ ($h = H_0/100$, H_0 is the Hubble constant, usually taken to be between 50 and 100 km s^{-1} Mpc^{-1}; Zensus 1989; also Vermeulen & Cohen 1994, Ghisellini et al. 1993). 1150+812 was mapped at 5 GHz during the first Calteh–Jodrell Bank (CJ1) VLBI survey (Xu et al. 1995). The chart, shown in Fig. 4, clearly shows its compact core–jet structure within ~12 mas. The VLBI map reveals that the compact jet of 1150+812 gradually curves eastward: in the core the jet points at position angle $\sim 190^\circ$ and in the outer parts it is directed at $\sim 140^\circ$. The bending of the jet implies that different components along the jet could have different polarization angles. As shown in our previous paper (Qian et al. 2003; and also see Königl & Choudhouri 1985b) that for superluminal sources large–amplitude polarization angle swings can occur through relativistic aberration effects. In these cases the key conditions are: (1) the speed $\beta_{\rm ps}$ of the plasma is close to $\cos\theta$; (2) the helical magnetic field has a transverse component large relative to its longitudinal component, i.e., it has a large pitch angle.

A specific model was made to fit the observed polarization properties (polarization angle swing and the light curves of the total and polarized flux density). The chosen set of the parameters were: $\psi = 75^\circ$ (the pitch angle of the helical field); $\gamma_j = 2.0$ (the jet flow Lorentz factor); $\gamma_s = 10$ (the shock Lorentz factor); $\theta = 7.5^\circ$ (the viewing angle); $\alpha = 1.0$ (the spectral index of the synchrotron radiation); $r_m = 0.25\lambda$ (the jet radius). We do not specify the other parameters (e.g., $N_{\rm ps,0}$, $H_{\rm ps}$, μ, λ, Δx, etc.) and we use relative units in the computation of I_σ; but at the end we normalize the polarized flux density to the observed one for comparison.

We should point out that the selection of the set of the parameters is not unique, but the key conditions mentioned above must be satisfied, i.e., the parameters ($\beta_{\rm ps}$, θ and ψ), which are most sensitive for the occurrence of polarization angle swing, should be appropriately selected. For the set of parameters chosen above, we have the speed of the plasma $\beta_{\rm ps} = 0.9899$ ($\gamma_{\rm ps} = 7.07$), which is very close to $\cos\theta (= 0.9914)$. The apparent speed of its superluminal motion is correspondingly equal to $6.9c$, which is obviously consistent with the available VLBI observations. As required, a large value for the pitch angle of the helical field was taken.

The model-fitting results are shown in Fig. 5, where the modelled total flux density is obtained by adding 1.290 Jy to the flux density given by the model.

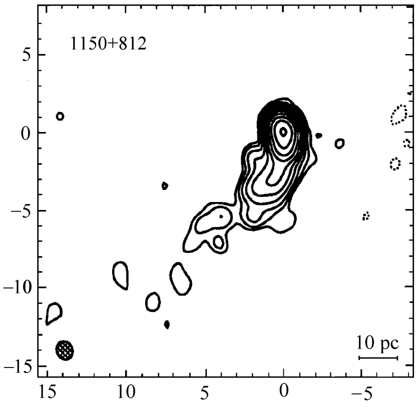

Fig. 4 VLBI map of 1150+812 at 5 GHz, showing the core–jet structure. Tick marks on the axes are in units of mas. (Adopted from Xu et al. 1995).

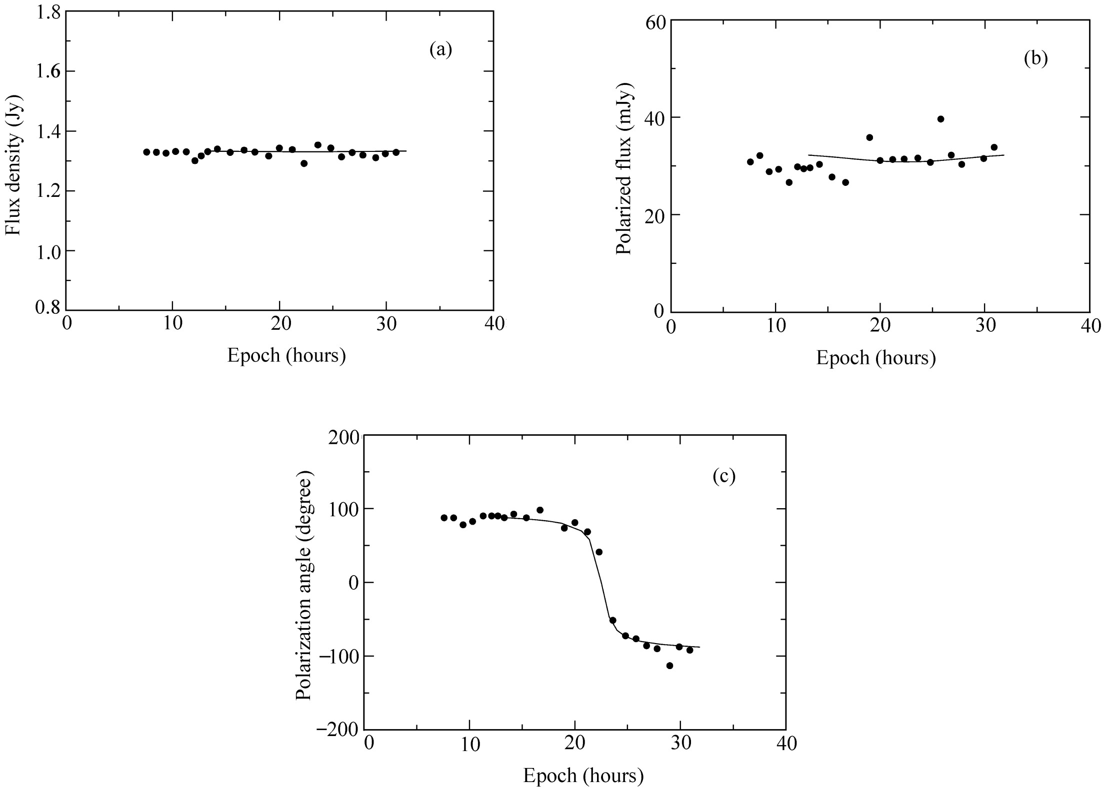

Fig. 5 Model fitting of the polarization position angle swing event observed in QSO 1150+812: (a) the light curves of total flux density, (b) polarized flux density and (c) the polarization position angle swing. The model only shows the result for one-half of the wavelength of the helical field.

5 DISCUSSION

1) It can be seen from Fig. 5 that the model fits the observed polarization angle swing very well. In addition, the modelled polarized flux density during the rapid swing period ($\sim$ 20h–25h) also agrees well with the observations. Our model shows that polarization angle swings of $\sim 180^\circ$ without substantial variations of polarized flux can be explained. A relativistic shock propagating through and illuminating a helical field with uniform strength is an adequate model: the rapid polarization angle swing occurs as the transverse field component rotates across the (x, z) plane. However, we should note that the fluctuations in the total and polarized flux density observed outside the period of the swing might be produced by other causes, if they are not due to observational errors. This property may be useful for understanding the polarization variability observed in extragalactic radio sources. Although the polarization angle swing event observed in 1150+812 is an intraday event, our model obviously can be applied to longer timescale swing events.

2) In the proposed model the timescale of polarization angle swing depends on the wavelength of the helical magnetic field and on the velocity of the shock. For the specific model, rapid swing occurs on the scale of $\sim 0.1\,\lambda$, thus the spatial scale of the swing event is very small and the shock should be very thin with respect to the wavelength of the field. This is similar to the model proposed by Spada et al. (1999) for 0716+714, where injection of electron sheets with very short timescales is required. As Qian et al. (2000) pointed out, these thin electron sheets might be formed in shock-fronts (like current sheets). Since in this model the flux density changes only by a very small amplitude, it would not give rise to the brightness temperature problem.

3) Since the modelled polarized flux density is almost constant during the entire event, the observed deviations (e.g., at $\sim$19h and $\sim$25.8h) could be due to changes in the structure of the magnetic field or the appearance of a random field component. As shown by Burn (1966), if the magnetic field of a synchrotron source consists of two components, one uniform and the other an isotropic random field, then the resultant degree of polarization will be reduced, but the angle of polarization is still determined by the uniform field. In other words, the fluctuation of the ratio of the energy of the random component to the uniform helical component could be responsible for the observed fluctuation of the polarized flux density.

4) We point out that the proposed model is a single-component model, i.e., the shock component is the only polarized emission region. If there exists another polarized component with a comparable polarization, then the resultant polarized emission should be determined by the vector combination of these two. In this case rapid polarization angle swing may not occur, but the rapid polarization angle swing of the shock component could still cause a rapid variation of the integrated polarization without substantial variation of the total flux density. This could be useful for explaining rapid polarization variations which are not accompanied by substantial variations of the total flux density. The intraday polarization variability observed in the BL Lac object 0716+714 (Gabuzda et al. 2000b) may belong to this kind of variability.

6 CONCLUSIONS

As shown above, the proposed model can well explain the main properties observed in QSO 1150+812: the polarization angle swing occurs when the polarized flux density remains almost constant. Such a type of variability in polarization may be rare, because usually there are two or more polarized components existing in compact radio sources. In these cases the shock component, as one of the polarized components, can only show its effect through the vector combination of the polarized radiation from all the components. However, the modelling of the polarization swing event demonstrates that such polarization angle swings can play significant role in polarization variability in extragalactic sources, even when only part of the swings could cause significant variability in the integrated polarization. These effects may more often be observed at shorter wavelengths (less than 2 cm), where scintillation could have little effects on the polarization. Since this kind of polarization variability does not involve substantial fluctuations in the total flux density, they may be applied to those events in which large amplitude polarization variability are not accompanied by substantial variability in the total flux density.

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