Multiwaveband polarimetric observations of NRAO 530 on parsec-scale

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ABSTRACT
We report on Very Long Baseline Array polarimetric observations of NRAO 530 at 5, 8, 15, 22 and 43 GHz made during one week in 1997 February. We present the total intensity, the fractional polarization and the electric vector position angle (EVPA) distributions at all these frequencies. A model fitting has been performed to the full polarization visibility data. From this, the fitted southernmost component A is confirmed as the core of the radio structure with relatively high brightness temperature and hard spectrum between 15 and 43 GHz in comparison with the central component B of dominant flux. The relatively high degree of polarization for the component A may arise from its complex radio structure, which can be resolved at 86 GHz. In contrast, the component B shows a well-fitted power-law spectrum with a spectral index of about −0.5 (f ∝ ν^α), and a linear correlation between EVPAs and wavelength square with an observed rotation measure of about −1062 rad m^−2, indicating its structural singleness. Assuming that the component B has a comparable degree of polarization without depolarization at these frequencies, the decrease in fractional polarization with wavelength mainly results from opacity and Faraday rotation, in which the opacity plays quite a large role. A spine-sheath-like structure in fractional polarization (m) is detected, covering almost the whole emission region at 5 and 8 GHz, with a degree of polarization relatively low along the jet spine, becoming higher towards two sides of the jet. The linear polarization at 5 GHz shows three separate polarized emission regions with alternately aligned and orthogonal polarization vectors down the jet. The polarization goes to zero between the top two regions, with the highest polarization level occurring at the top and bottom. The 5- and 8-GHz images show EVPA changes across the width of the jet as well as along the jet. These complex polarimetric properties can be explained in terms of either the presence of a large helical magnetic field or tangled magnetic fields compressed and sheared down the jet. These can be further determined by multifrequency polarimetric very long baseline interferometry observations with sufficient high resolution and sensitivity spanning an appropriate frequency range.

Key words: polarization – galaxies: active – galaxies: jets – quasars: individual: NRAO 530 – radio continuum: galaxies.

1 INTRODUCTION
In the leading model for jet production, acceleration and collimation in blazars, the magnetic field plays an important role (e.g. Meier, Koide & Uchida 2001; McKinney 2006). Poloidal magnetic fields are supposed to be wound up by the differential rotation of a rotating disc or ergosphere surrounding a central supermassive black hole, propagating outward in the polar directions with a tight helical pattern. On parsec scale or beyond the jet acceleration region, the magnetic fields within a jet might maintain a tight helical pattern (Lyutikov, Pariev & Gabuzda 2005), become chaotic, or possibly become compressed and sheared (Jorstad et al. 2007). The degree of order and geometry of the magnetic field will differ from case to case, and therefore can help us to better understand the physical conditions in a jet.

Because the jet emission is mainly synchrotron radiative, and hence linearly polarized with an electric vector perpendicular to the projection on the sky of the magnetic field (Begelman, Blandford & Rees 1984), the magnetic geometry and order of degree can be revealed to some degree through polarimetric very long baseline interferometry (VLBI) observations. The dominant transverse magnetic field is often ascribed to shock compression, and the dominant longitudinal one to the effect of shear or interaction with the surrounding medium (e.g. Laing 1980; Hughes, Aller & Aller 1989). However, both cases can also be interpreted in terms of intrinsic
helical magnetic fields, which appear more natural and simpler (e.g. Gabuzda, Murray & Cronin 2004). It is difficult to distinguish between transverse magnetic fields resulting from a toroidal field component and those resulting from shock compression. Under the circumstances, the measurement of the rotation measure (RM) gradient across the jet is proposed to test the magnetic helicity within or wrapping around the jet (Blandford 1993), which has been detected in some sources such as 3C 273 (Asada et al. 2002; Zavala & Taylor 2005) through multiband polarimetric VLBI observations with sufficiently good visibility data.

As a typical blazar, NRAO 530 (J1733–1304) is strong and variable in almost all the wavebands from radio to γ-ray. Long-term monitoring at cm wavelengths from 1967 to 2003 shows a bright outburst peaking around 1997 (Pyatunina et al. 2006), which is almost coincident with our VLBI observations. In this paper, we present the polarimetric VLBI observational results of NRAO 530 at five frequencies. Model fitting has been carried out to the full polarization data. The physical properties of the southernmost component A and the central component B are analysed and discussed in more detail. Because the total intensity structures have been reported in Feng et al. (2006), here we focus more on the polarimetric properties of the source on parsec scale.

In Section 2 we present the whole process of data reduction. The results are given in Section 3, followed by a discussion in Section 4. A summary is given in Section 5. Throughout this paper, we take the cosmological parameters of $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\Lambda} = 0.73$ when calculating the angular distance, with 1 mas of angular size corresponding to 7.8 pc for NRAO 530 with a redshift of 0.902.

2 OBSERVATIONS AND DATA REDUCTION

We observed NRAO 530 at 5, 8, 15, 22 and 43 GHz in 1997 February with the Very Long Baseline Array (VLBA) plus one Very Large Array (VLA) antenna. Three separate observations were made within an interval of 7 d, with the first observation at 5 and 8 GHz made on 7 February, the second at 15 and 22 GHz on 12 February, and the third at 43 GHz on 14 February. Some other specific observational information can be found in Feng et al. (2006). Based on the University of Michigan Radio Astronomy Observatory (UMRAO) data during the observational period, the largest flux density variation at 5, 8 and 15 GHz is about 4 per cent. The observations at 15, 22 and 43 GHz were made within an interval of 2 d. The total flux density available at 15 GHz remained almost constant within the observational error of about 2 per cent from 8 to 10 February. This means that a 2-d interval between observations has almost no impact on the following analysis of the resultant spectral indices and RMs derived from the three high-frequency observations.

The data reduction and imaging were carried out in the AIPS and DIFMAP packages, respectively, using standard techniques, as described in Zavala & Taylor (2004). Careful data editing was first carried out to flag those obviously bad data points, including all the visibility data to antenna MK at 5 and 8 GHz, those visibilities to BR at 15 and 22 GHz because of the correlation failure, and some other points because the elevation angle was too low. The standard amplitude and phase calibration were performed subsequently. Here, we would like to stress that we make antenna gain(s) calibration with ‘CLCOR’ to one or more antennas in AIPS before imaging because at least one antenna gain is required to be adjusted at all but 43 GHz.

NRAO 530 was observed as a calibrator during the observations. It is very strong and compact, and hence the fringes can be easily detected on almost all the baselines. Because of its relatively complex radio structure, the task ‘CCEDIT’ in AIPS was used to separate the total intensity distribution into several point sources by hand in order to calibrate the instrumental polarization (‘D-terms’) of each antenna with the AIPS task ‘LCAL’. To ensure that the D-term solutions were acceptable, we checked the distribution of the normalized cross visibilities in the complex (real and imaginary) plane, with and without instrumental calibration. We found that it becomes well clustered after the instrumental calibration is performed. We also tried to obtain an independent set of D-terms from another calibrator OV-236, which was observed for about half of the on-source time on NRAO 530. These solutions are consistent at 5 and 8 GHz. At 15 GHz and higher frequencies, there are some differences. The distribution of the normalized visibilities in the complex plane becomes better clustered, and the final results have a better dynamic range, especially at 15 and 22 GHz when using the D-terms from NRAO 530 alone. Therefore, in this paper, we have adopted the D-term solutions derived from NRAO 530 alone.

The absolute EVPA calibrations at 5, 8 and 15 GHz were performed using the integral EVPA within 5 d of our observations from the UMRAO (cf. Aller et al. 1985). The absolute EVPAs are 52.8 ± 2.7 at 5.0 GHz, 73.4 ± 2.2 at 8.0 GHz and 70.8 ± 2.0 at 15.4 GHz. At 22 and 43 GHz, no absolute EVPAs are available. Thus, the true EVPAs at the two frequencies are estimated by using the RM of about −109 rad m$^{-2}$ obtained at lower frequencies. The resultant values at the two frequencies are about 75:5 and 76:6, respectively. Corrections to the EVPA are obtained by doubling the difference between the integral EVPA from the UMRAO and the observed integral EVPA at each frequency, and by then applying to the visibility data with the AIPS task ‘CLCOR’. In comparison to the UMRAO data, about 83, 86 and 76 per cent of polarized flux at 5, 8 and 15 GHz is recovered, respectively, in our observations. That is to say, the adopted EVPA corrections are roughly reasonable with the corresponding uncertainties of 0.4, 2.2 and 0.3 as a result of the missing flux. Table 1 lists the reference antenna and corresponding EVPA correction at each frequency. The final images, including the total intensity, fractional polarization, linear intensity and EVPA distributions are shown in Figs 1 and 2. These are analysed and discussed in Sections 3 and 4, respectively.

3 RESULTS

3.1 Total intensity distribution and model fitting to the full visibility data

The results and analysis of the total intensity distributions have been presented in Feng et al. (2006), where spectral fits to some of the components and the radiative mechanism are investigated in detail. Here, we reproduce the intensity distributions at all five frequencies as contour profiles in the left panel of each map in Figs 1 and 2. We calibrate the antenna gains to those antennas of unreasonable magnitude by checking the amplitude versus distance plots at all but 43 GHz before imaging this time (e.g. Zavala & Taylor 2004). This gives rise to small differences in the amplitude of the resultant components in the model fitting. In terms of the recovered proportion

| Obs. freq. (GHz) | 5   | 8   | 15  | 22  | 43  |
|------------------|-----|-----|-----|-----|-----|
| Reference antenna| FD  | FD  | PT  | PT  | LA  |
| χ (deg)          | −33.6 | 156.6 | −16.4 | 19.1 | 77.6 |

Table 1. Reference antenna and corresponding EVPA correction at each frequency.
and increase by a factor $\theta$ at lower frequencies.

3.2 Fractional polarization distribution

The polarization imaging results are shown in Figs 1 and 2, with fractional polarization superposed by the total intensity contours, and the EVPAs superposed by linearly polarized intensity contours at all five frequencies. The 5-GHz imaging result is shown alone for more discussion later. At this frequency, the total and polarized intensity distributions show a typical core–jet structure with the jet roughly extending to north. Small fluctuations of the jet orientation occur down the jet, which can be more clearly seen by comparing radio structures at different frequencies. In Table 2 it can be seen that the component $A$ lies at the extreme end of the radio structure, and has a relatively high brightness temperature in comparison to the component $B$, although its flux density is relatively low. This may imply that it is component $A$ that represents the radio core of the source. To produce more evidence for this hypothesis, we fitted power-law spectra to both components from 15 to 43 GHz, as shown in Fig. 3. The spectral indices for components $A$ and $B$ are estimated to be $0.08 \pm 0.11$ and $-0.52 \pm 0.03$, respectively. Obviously, the power-law spectrum for component $A$ is fitted badly, but surely harder, while component $B$ exhibits a spectrum of quite a good power-law form. This argues for the core hypothesis of component $A$, as suggested in Jorstad et al. (2001) and Feng et al. (2006).

\[ T_B = 1.77 \times 10^{22} \left( \frac{f_\nu}{Jy} \right) \left( \frac{\nu}{GHz} \right)^{-2} \left( \frac{\theta_d}{mas} \right)^{-2} (1 + z). \]  

Here, $f_\nu$ is the flux density at frequency $\nu$ and $\theta_d$ is the angular size $\theta_d = \sqrt{\theta_{maj}\theta_{min}}$, with $\theta_{maj}$ and $\theta_{min}$ being the major and minor axes, respectively. Because of the large differences in resolutions, we cannot separate the southernmost component $A$ at lower frequencies 5 and 8 GHz. The central component $B$ at these two frequencies therefore probably contains a larger emission region in comparison to that at higher frequencies. This is investigated separately from the other frequencies later.

The total intensity distributions show a typical core–jet structure with the jet roughly extending to north. Small fluctuations of the jet orientation occur down the jet, which can be more clearly seen by comparing radio structures at different frequencies. In Table 2 it can be seen that the component $A$ lies at the extreme end of the radio structure, and has a relatively high brightness temperature in comparison to the component $B$, although its flux density is relatively low. This may imply that it is component $A$ that represents the radio core of the source. To produce more evidence for this hypothesis, we fitted power-law spectra to both components from 15 to 43 GHz, as shown in Fig. 3. The spectral indices for components $A$ and $B$ are estimated to be $0.08 \pm 0.11$ and $-0.52 \pm 0.03$, respectively. Obviously, the power-law spectrum for component $A$ is fitted badly, but surely harder, while component $B$ exhibits a spectrum of quite a good power-law form. This argues for the core hypothesis of component $A$, as suggested in Jorstad et al. (2001) and Feng et al. (2006).
Figure 2. The same as Fig. 1, but at four different frequencies: (a) 8 GHz; (b) 15 GHz; (c) 22 GHz; (d) 43 GHz. (a) The restoring beam is $4.2 \times 1.2$ mas$^2$ at $20.0^\circ$, and contours start at 3.5 mJy beam$^{-1}$ for total intensity and 6.0 mJy beam$^{-1}$ for linearly polarized intensity. (b) The restoring beam is $1.5 \times 0.5$ mas$^2$ at $-7.7^\circ$, and contours start at 3.5 mJy beam$^{-1}$ for total intensity and 6.0 mJy beam$^{-1}$ for linearly polarized intensity. (c) The restoring beam is $1.3 \times 0.3$ mas$^2$ at $-10.9^\circ$, and contours start at 4.2 mJy beam$^{-1}$ for total intensity and 9.5 mJy beam$^{-1}$ for linearly polarized intensity. (d) The restoring beam is $0.55 \times 0.17$ mas$^2$ at $-8.6^\circ$, and contours start at 7.5 mJy beam$^{-1}$ for total intensity and 10.5 mJy beam$^{-1}$ for linearly polarized intensity. A and B indicate the locations of the fitted Gaussian components A and B, as listed in Table 2.

Table 2. Model parameters to components A and B.

| Component ID | Freq. (GHz) | $f_\nu$ (Jy) | $m$ (per cent) | $\chi$ (deg) | $\theta_{\text{maj}}$ (mas) | $\theta_{\text{min}}$/$\theta_{\text{maj}}$ | $T_B$ (10$^{12}$ K) |
|--------------|-------------|---------------|----------------|-------------|-----------------|-----------------|-----------------|
| A            | 15          | 1.01          | 4.97           | 49.9        | 0.046           | 1.0             | 6.86            |
|              | 22          | 1.74          | 5.45           | 56.0        | 0.052           | 1.0             | 4.30            |
|              | 43          | 1.30          | 5.22           | 21.8        | 0.035           | 1.0             | 1.87            |
| B            | 5           | 6.85          | 1.32           | 48.6        | 1.032           | 0.291           | 2.99            |
|              | 8           | 9.76          | 2.01           | 73.9        | 0.615           | 0.214           | 5.73            |
|              | 15          | 8.49          | 2.95           | 71.6        | 0.184           | 0.586           | 6.11            |
|              | 22          | 7.30          | 3.13           | 83.7        | 0.269           | 0.467           | 1.47            |
|              | 43          | 4.86          | 4.46           | 91.8        | 0.169           | 0.893           | 0.34            |

The overall polarization level (e.g. Taylor 1998). Also, the overall dependence of polarization level on frequency is probably because at a lower frequency, the depolarization by Faraday rotation is more severe, and the resolution is relatively low.

In the outermost region of the 5- and 8-GHz fractional polarization, there exists a prominent blob with extremely high fractional polarization. In contrast, the core region shows a lower polarization level, although the absolute linear intensity is relatively strong at all five frequencies. The relatively low polarization level in the core region in comparison with that in the jet is also observed in many other sources, such as 3C 273, 3C 279, 1803+784, etc. This may well be a result of the large opacity effect, considerable substructures...
in the core region and/or plasma in the immediate vicinity of the active galactic nucleus (e.g. Taylor 1998; Homan et al. 2009).

3.2.1 Transverse fractional polarization

It can be seen in Fig. 1 that the fractional polarization at 5 GHz is relatively low along the local jet spine, but becomes higher towards the jet edges beyond ~5 mas from the core region (referred to as a spine-sheath-like structure hereafter). At 8 GHz, although it is not so obvious, we can still find such a signature at about 5 and 25 mas from the core, the only two regions with polarization information available. However, at 15, 22 and 43 GHz, it is difficult to make sure that this feature exists for the current data. To have a quantitative idea of the polarization level across the jet, three slices perpendicular to local jet direction are selected for $m$ profiles, with the local jet direction defined to be that pointing from one component to the next down the jet at 5 GHz. The fitted component distribution at 5 GHz is shown in Fig. 4, with each component indicated as an elliptical form by the fitted position, size and orientation. We find that the radio structure is well reproduced with these components. In the core region containing four fitted components, we cannot definitely determine the local jet direction according to the component distribution. Thus, we choose the component’s moving direction with a positional angle (PA) of 25° as the local jet direction from Lister et al. (2009). The selected slices lie in three separate regions of detectable polarization emission with PAs of 115°, 54° and 118° from south to north, as indicated in Fig. 1. The $m$ profiles on these slices are shown in Fig. 5, displaying that the polarization level is relatively low in the jet spine, but becomes higher towards both sides of the jet. If we ignore the patch of extremely high fractional polarization at the bottom-right of the middle region, this trend would appear to be slightly more remarkable.

3.3 Projected polarization structure and Faraday rotation

The projected polarization structures throughout the five frequencies are shown in the right panel of each map in Figs 1 and 2, where the linearly polarized intensity distribution is superposed. As can be seen in all these images, the electric field is locally well ordered from the core to the outermost emission region. For the 5-GHz polarization image with high signal-to-noise ratio, the electric field information can be well extracted on a scale of more than 30 mas from the core, corresponding to a linear size of 240 pc. At this frequency, the electric vector is distributed with a PA of about 50° near the core, and then bifurcates apparently at a distance of about 5 mas north to the core (see also the polarization image at 8 GHz). When the jet reaches a distance of about 10 mas from the core, the electric field turns almost perpendicular to the overall jet direction with an overall PA of $\sim 78°$. At a distance of about 25 mas north to the core, the electric vector becomes roughly parallel to the north direction with an overall PA of $\sim 23°$. Such an orientation change down the jet may be attributed to magnetic fields that are ordered by local phenomena at various places in the jet. However, Gabuzda et al. (2004) have suggested that these alternating magnetic fields may indicate oscillations or instabilities of a global jet magnetic field.

Faraday rotation reveals some physical condition along the line of sight. When the polarized emission propagates through a magnetized plasma, the polarization plane will rotate with wavelength...
are fitted with equation (2). As a result, we find that component $\sigma_A$ in Table 2, we find that component $\Delta_1\chi$ is badly fitted, while the EVPAs for component $B$ is relatively hard for external Faraday rotation to result in depolarization (e.g. Burn 1966; Homan et al. 2009). Based on equation (2), the additional factors are obtained with values of 0.895, 0.975 and 0.998 at the corresponding frequencies of 15, 22 and 43 GHz, respectively. This means that even if all the observed rotation is completely internal to the jet, this rotation is not large enough to cause all of the decrease in fractional polarization observed, assuming that the component has a comparable degree of polarization without depolarization. Homan et al. (2009) argued that an alternative cause inducing depolarization is the opacity by the mediums in the passage, by which the depolarization also becomes worse with wavelength. This implies that both the opacity and internal Faraday rotation contribute to the decrease in fractional polarization with wavelength, in which the opacity plays quite a large role in the depolarization.

4 DISCUSSION

4.1 Core identification

In general, the core component in blazars lies at the extreme end of the jet, which is usually optically thick, and highly Doppler boosted with dominant flux density, a relatively hard spectrum and high brightness temperature. By comparing the physical quantities of components $A$ and $B$ in Table 2, we find that component $A$ has a higher brightness temperature and a harder spectrum, both of which are indicators of a radio core (e.g. Shen et al. 2005). However, component $B$ exhibits higher flux density and lower fractional polarization, which are also taken as the features of a radio core (e.g. Bower et al. 1997; Cotton et al. 1997). This apparent contradictory observational evidence for core identification exists in both components, which increases the difficulty of core identification.
Because of the large Doppler boosting effect present in NRAO 530 (Bower et al. 1997; Jorstad et al. 2001), it is impossible for the jet structure to be two-sided. Therefore, regardless of which is the core component, the jet direction changes down the jet to connect the north–north-west structure (Jorstad et al. 2001). This will lead to changes of the Doppler boosting effect down the jet. Assuming that component A is the core of the object, the adverse condition of relatively high fractional polarization and low flux density in core identification may be explained as follows. Component B has a relatively high flux density, mainly because of the strong outburst occurring 2 yr before (Jorstad et al. 2001). Possibly, the larger Doppler effect may also have contributed to it, because of the change of jet viewing angle, which requires further confirmation. As for its relatively high polarization level, this is because component A itself consists of at least two components (as shown in the radio structure of higher resolution at 86 GHz; Bower et al. 1997), of which the jet component enhances the overall fractional polarization of the fitted component A. For the same reason, component A cannot be fitted well with a single power-law spectrum (see Fig. 3), and also the EVPAs do not obey the wavelength square law (see Table 2; Taylor 1998). If, on the contrary, component B is the core, it is not only hard to explain its relatively soft spectrum and low brightness temperature, but also the trajectories are required to bend by nearly 180° to connect the north–north-west structure; it would be quite unnatural to interpret this logically. Combining all the above reasons, plus component A lying at the south end of its radio structure, we conclude that it is component A that is the true core of the object. This is consistent with the argument suggested in Jorstad et al. (2001) and Feng et al. (2006).

4.2 Magnetic geometry in the jet

As mentioned earlier, the magnetic geometry is crucial in determining what role the magnetic field plays in the dynamics and emission of relativistic jets in active galactic nuclei, which may be helical because of the differential rotation of the central engine (e.g. a Meier et al. 2001), transverse because of shock compression, longitudinal because of the effect of shear or interaction with an external medium (e.g. Laing 1980), or chaotic. Through polarimetric observations, the helical magnetic fields may manifest as a spine-sheath polarization structure (the polarization electric vectors predominantly aligned with the jet in the jet spine and perpendicular to the jet at one or both edges; e.g. Pushkarev et al. 2005), fractional polarization relatively low in the jet spine and increasing towards the jet edges (Lyutikov et al. 2005) and/or the exclusive feature of RM gradient across the jet (Blandford 1993; Asada et al. 2002).

4.2.1 Interpretation with magnetic compression and shear

As mentioned earlier, NRAO 530 shows a transverse m profile relatively low along the jet spine, and progressively increasing toward the jet edges. This suggests that the integrated magnetic field along the line of sight becomes better ordered toward the jet edges (Gómez et al. 2008). One possible reason for the presence of the spine-sheath-like structure as well as the magnetic bifurcate configuration might be related to the combination of shocks and flow shears (Laing 1980; Laing, Canvin & Bridle 2006). The shocks compress and partially order an initially tangled magnetic field, and the flow shear across the jet stretches the magnetic field along the jet (Wardle et al. 1994). The combination of shock compressions and flow velocity gradient across the jet may well reproduce the magnetic bifurcate configuration and the spine-sheath-like m profiles (e.g. Laing 1980; Laing et al. 2006), which are found in the m and polarization structure of NRAO 530.

Another important observational feature for magnetic shock compression in active galactic nuclei is that the magnetic field projected on the sky plane is transverse to the local jet axis. This is because the relativistic shocks enhance the magnetic component in the plane of compression, perpendicular to the direction of propagation of the shock (Laing 1980; Hughes et al. 1989). From the polarization structures at 5 and 8 GHz, the overall magnetic field directions in the bottom and top regions are roughly perpendicular to the local jet directions, which agrees well with the shock compression model. Furthermore, for the top two regions with detectable linear polarization at 5 GHz, we find that the largest variation in fractional polarization appears north to south, where the polarization goes to zero between the two regions. The highest levels of fractional polarization are at the top (north) and bottom (south). It is likely that these two regions belong to a bigger bright shocked region, where the roughly transverse shocked field has cancelled a roughly longitudinal field in the underlying jet. This will produce the effect that the middle of the structure appears to have the lowest polarization as a result of cancellation, as is predicted by shock in jet models (e.g. Gabuzda & Gómez 2001; Homan et al. 2009). Similar cases have also been reported in some other sources (e.g. Gabuzda & Gómez 2001) with alternating aligned and orthogonal polarization vectors down the jet, where the longitudinal magnetic field is mainly ascribed to the flow shear, oblique or conical shocked.

4.2.2 Helical interpretation of the magnetic configuration

It is also possible that the emission occurs in a large scale of helical magnetic field with certain combinations of pitch and viewing angle, resulting in the spine-sheath-like m profiles in NRAO 530. For example, similar m profiles across the jet are presented with the viewing angle of 1/Γ or 1/2Γ in the observer’s frame and pitch angle of 45° in the rest frame shown in fig. 9 in Lyutikov et al. (2005) (here Γ is the Lorentz factor). The extremely high fractional polarization at 5 and 8 GHz in the outermost emission region from the core might also be a manifestation of such a structure.

In addition, about 5 mas away from the core at 5 and 8 GHz, the polarization vectors bifurcate obviously to opposite sides from the local jet axis, something like a spine-sheath structure. At distances of 12 and 25 mas from the core at 5 GHz, such a structure can also roughly be seen, although it is not very obvious. Synchrotron emission of relativistic particles in a helical magnetic field can naturally explain the polarization structure in the jet frame (e.g. Pushkarev et al. 2005).

It can be seen that the polarimetric properties of the object available for the current observations cannot exclusively make clear the magnetic configuration over the whole radio structure. Through multiband polarimetric VLBI observations of 3C 279 with the same three fitted components available at all six bands from 8 to 22 GHz, Homan et al. (2009) obtained a self-consistent picture for its magnetic configuration, particle population and low cut-off energy range using numerical simulations to the full polarization spectra. We cannot do this in our case mainly because of the limitations of the observational data and partly because of the source structure itself. Additionally, at 15 GHz and higher frequencies, the polarization structure cannot be resolved over the jet width, which prevents us obtaining the transverse RM variation down the jet for further analysis of the magnetic configuration. It is noticeable...
that large orientation changes of polarization structure down the jet have also been detected in PKS 1418+546 and OJ 287 (Gabuzda & Gómez 2001; Gabuzda & Chernetskii 2003). These both show a spine-sheath-like structure in fractional polarization at the same time. This probably implies that there exists a certain connection between the spine-sheath-like structure and the large orientation change of electric vectors down the jet. This is worth investigating further.

5 SUMMARY

We have performed polarization-sensitive VLBI observations at 5, 8, 15, 22 and 43 GHz during one week in 1997 February. We have presented the total intensity, fractional polarization, linear intensity and EVPAs distributions at all these frequencies. Model fitting has been carried out to the full polarimetric visibility data at all five frequencies, with the focus mainly on the two components A and B in the core region. Compared with component B, the southernmost component A shows relatively high brightness temperature and a hard spectrum, which is identified as the radio core of the object. The relatively high polarization level for the component is probably because it contains an additional jet component of high fractional polarization, which is resolved at 86 GHz with a VLBI observation of higher resolution (Bower et al. 1997). Component B of dominant flux density exhibits a good power-law spectrum with a steady increase in fractional polarization with frequency from 15 to 43 GHz. The observed EVPAs for component B are in good agreement with the $\lambda^2$ law, with the observed RM of about $-1062$ rad m$^{-2}$. Assuming that the component has a comparable degree of polarization without depolarization at these frequencies, both the opacity and internal Faraday rotation have an effect on the decrease in fractional polarization with wavelength, in which the opacity plays a large role.

The linear polarization shows a spine-sheath-like structure in some regions at 5 and 8 GHz with the degree of polarization relatively low along the jet spine, but becoming higher towards both edges. The largest variation in fractional polarization appears to be north to south, where the polarization goes to zero between the top two regions. The highest levels of fractional polarization occur at the bottom and top, while the lowest occurs in the middle. The polarization structure at 5 GHz shows that the magnetic fields appear alternately orthogonal and aligned down the jet, with a signature of bifurcating to the opposite sides from the local jet spine. All these radiative features can be explained either with a large scale of helical magnetic field present within the jet, or with tangled magnetic fields compressed and sheared down the jet. Further polarimetric VLBI observations are required with sufficient high resolution and sensitivity at multiple wavelengths to further determine if the magnetic field is helical or not.

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