THE STRUCTURE AND LINEAR POLARIZATION OF THE KILOPARSEC-SCALE JET OF THE QUASAR 3C 345

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ABSTRACT

Deep Very Large Array imaging of the quasar 3C 345 at 4.86 and 8.44 GHz has been used to study the structure and linear polarization of its radio jet on scales ranging from 2 to 30 kpc. There is a 7–8 Jy unresolved core with spectral index $\alpha \simeq -0.24$ ($I_\nu \propto \nu^{\alpha}$). The jet (typical intensity 15 mJy beam$^{-1}$) consists of a 2.5 straight section containing two knots, and two additional non-co-linear knots at the end. The jet’s total projected length is about 27 kpc. The spectral index of the jet varies over $-1.1 \lesssim \alpha \lesssim -0.5$. The jet diverges with a semi-opening angle of about 9$^\circ$, and is nearly constant in integrated brightness over its length. A faint feature northeast of the core does not appear to be a true counter-jet, but rather an extended lobe of this FR-II radio source seen in projection. The absence of a counter-jet is sufficient to place modest constraints on the speed of the jet on these scales, requiring $\beta \gtrsim 0.5$. Despite the indication of jet precession in the total intensity structure, the polarization images suggest instead a jet re-directed at least twice by collisions with the external medium. Surprisingly, the electric vector position angles in the main body of the jet are neither longitudinal nor transverse, but make an angle of about 55$^\circ$ with the jet axis in the middle while along the edges the vectors are transverse, suggesting a helical magnetic field. There is no significant Faraday rotation in the source, so that is not the cause of the twist. The fractional polarization in the jet averages 25% and is higher at the edges. In a companion paper, Roberts & Wardle show that differential Doppler boosting in a diverging relativistic velocity field can explain the electric vector pattern in the jet.

Key words: galaxies: active – galaxies: jets – quasars: individual (3C 345)

1. INTRODUCTION

The compact radio source 3C 345 (J1642+3948) is a 16th magnitude quasar at a redshift of $z = 0.593$ (6.5 kpc arcsecond$^{-1}$ in concordance cosmology, $h = 0.73$). This is one of the best studied quasars over a wide range of wavelengths and angular resolutions because it is nearby and bright. The source is variable in X-ray, optical, and radio bands on timescales ranging from minutes to months, and it is highly bright. The source is variable in X-ray, optical, and radio bands on timescales ranging from minutes to months, and it is highly

2. OBSERVATIONS AND DATA REDUCTION

Interferometer data from 1989 January 7–8 (epoch 1989.02) were obtained from the VLA data archive (experiment code AR196). The array was in the A configuration with 27 working antennas. The frequencies used were 4.86 GHz (C band, $\lambda = 6.2$ cm) and 8.44 GHz (X band, $\lambda = 3.6$ cm), with a bandwidth of 50 MHz for each of the two intermediate-frequency systems at each band. The data were edited and calibrated in AIPS (NRAO 2011). The nearby source 1635+381 was used for primary flux calibration, and the primary flux calibrator 3C 286 was used for secondary calibration. To obtain the maximum dynamic range in the images a baseline-dependent calibration was executed with the task BLCAL. The baseline calibration tables were determined from the data for 3C 286 and its AIPS CLEAN component models. The tables were then attached to the data files of 3C 345 for their respective frequency bands. It was found that making a baseline correction using an image of the bright source 3C 84 made from data collected about 12 hr earlier produced essentially the same results at 5 GHz, but was superior at 8 GHz. Hence this correction was used at the higher frequency. Baseline-corrected images had signal to noise about a factor of two better than those made without baseline correction, and were judged to have higher image fidelity. Compared to the images of Kollgaard et al. (1989), the present images are of somewhat higher resolution and have a second frequency. Polarization calibration was done with the phase calibrator using the task PCAL. The position angle of linear polarization on the sky was set by 3C 286. We estimate that the absolute polarization of 3C 345. The observations and data reduction are described in Section 2, the properties of the jet are described in Section 3, we discuss the results in Section 4, and our conclusions are presented in Section 5. The data in this paper are used by Roberts & Wardle (2012) to produce strict limits ($\beta \gtrsim 0.95$) on the fluid velocity in the jet on kiloparsec scales.

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2 There are over 1000 references to 3C 345 in the NASA Extragalactic Database (http://nedwww.ipac.caltech.edu/), to which we refer the reader for further information.
position angle calibration is good to within $\pm 3^\circ$ at 5 GHz and
$\pm 5^\circ$ at 8 GHz.

Images were made using AIPS and the Caltech difference
imaging package DIFMAP (Shepherd et al. 1994) as follows. Using
DIFMAP, at each step in the SELFCAL–CLEAN cycle, a tight CLEAN box was placed around the brightest remaining
flux and purely positive CLEAN components were removed un-
til the process ended. Then a 15 minute phase-only SELFCAL
was done, and the boxing-CLEANing-SELFCAL resumed. The $u-v$ weighting was changed and $u-v$ tapers applied as required
to recover more flux. Only when this process terminated was an
amplitude SELFCAL used, with a 60 minute timescale. Phase-
only SELFCAIsLs were resumed until the process terminated. Fi-
ally, the self-calibrated visibilities were moved into AIPS and
the final images made with the task IMAGR using the restoring
beams listed in Table 1. To create images that could be com-
pared at the two frequencies, uniform weighting (ROBUST = −5) was used for 5 GHz and natural weighting (ROBUST = 5)
for 8 GHz, a $u-v$ taper with parameters (850, 800) k$\lambda$
was used at both frequencies, and identical circular restor-
ing beams of full width at half-maximum 0.30 were ap-
plied. To study the divergence of the jet, full-resolution im-
ages were made from the data at 8 GHz; it was judged that
“optimum weighting” (ROBUST parameter 0) and a CLEAN
beam of 0.20 gave the best compromise between resolution
and signal to noise. To simplify the analysis and image dis-
play, most of the images were rotated by $-50^\circ$ in position
angle.
Figure 2. Total intensity images of the quasar 3C 345 made from (a) 5 and (b) 8 GHz VLA A-array data. The images are the means of those made by two of the authors, and have been rotated by $-50^\circ$ in position angle. See Table 1 for image data and figure details.

Figure 3. VLA image of 3C 345 at 8 GHz made with “optimum” weighting (ROBUST = 0). The image is the mean of those made by two of the authors, and has been rotated by $-50^\circ$ in position angle. See Table 1 for image data and figure details.
Figure 4. Comparison of the ridge-line brightness in images made independently by two of the authors from the same 5 and 8 GHz data (Figure 2). The black lines are at 5 GHz, the red lines are at 8 GHz. Note the logarithmic intensity scale.

In Table 1 we give the parameters of the images and the figures. The root-mean-square (rms) noise reported is from a $5'\times5'$ box centered 7.5 southeast of the core, and is reasonably representative of the uncertainties in the images (see below). Because of the presence of the bright core the noise levels are dominated by residual calibration errors, and exceed the theoretical rms for the parameters of the observations by about a factor of 10.

3. PROPERTIES OF THE 3C 345 JET AT 5 AND 8 GHz

3.1. Total Intensity Structure

A 20'-wide field of 3C 345 at 5 GHz at its correct orientation on the sky is shown in Figure 1. The detailed total intensity structures at 5 and 8 GHz are shown in Figure 2. At the epoch of observation (1989.02), the core of 3C 345 was essentially unresolved, and had flux densities of 8.1 and 7.1 Jy at 5 and 8 GHz, respectively. Figure 3 shows a full-resolution image of 3C 345 at 8 GHz.

Since the jet is weak compared to the core, we examined the reliability of the images by comparing those made independently from the same data by two of the authors (D.H.R. and V.V.M.). The rms difference between the pairs of images was about 0.5 mJy beam$^{-1}$ at each frequency, consistent the rms noise in the images. Ridge-line intensities at 5 and 8 GHz are compared in Figure 4, and are consistent with an rms difference of $\sim$0.5 mJy beam$^{-1}$. This gives an idea of the dependence of the intensity levels in this faint jet on the personal equation in the hybrid imaging technique. This of course does not mean that the absolute intensity levels are reliable at that level because any calibration uncertainties cancel in this comparison.

3.2. Total Intensity Properties of the Jet

The jet consists of a westward straight section$^3$ of approximate projected length 2.25 (16 kpc), with two “knots” that we will call “K1” and “K2,” and two additional bright spots at the west end of the jet that do not lie on the same east–west line. To avoid confusion with K1 and K2, we will refer to the first of these spots as the “knob,” denoted “KB,” and the final one as the “hotspot,” or “HS”; see Figure 2(a). Examination of the polarization images below suggests that we further subdivide the knob into a northern piece that we will refer to as “KBN” and a southern piece, “KBS.”

3.2.1. Spectral Index

Figure 5 shows a spectral index image in color over total intensity contours, made from the images in Figure 2. The

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$^3$ In those images that have been rotated in position angle by $-50^\circ$ we will refer to directions on the sky as they appear in the rotated images; note that the true position angles are “West” = $-40^\circ$, “East” = $+140^\circ$, “North” = $+50^\circ$, and “South” = $-130^\circ$.
core has a rather flat spectrum with \( \alpha = -0.24 \), while the spectral index of the jet along the ridge line ranges over \(-1.1 \lesssim \alpha \lesssim -0.5 \) \( (I_{\nu} \propto \nu^{\alpha}) \). The spectrum is significantly steeper along the south edge of the jet yet flatter on the north side, and flatter between K2 and KB, and between KB and HS. The spectral index and intensities along the ridge line are plotted in Figure 6. The error bars for \( \alpha \) were determined from the estimate of the systematic uncertainties in the intensities derived by comparison of pairs of independent images made from the same data.

3.2.2. Is There a Counter-jet in 3C 345?

Kollgaard et al. (1989) detected a possible counter-jet with (true) position angle \( \sim 55^\circ \). In the naturally weighted image (Figure 1) we see the same feature in essentially the same location. Is this feature a counter-jet? In our images it is not as “jet-like” as in Figure 2 of Kollgaard et al. (1989), and it does not meet the criteria of Bridle & Perley (1984). Nonetheless, the feature is real; at a distance of 1" from the core the intensity is about 1 mJy beam\(^{-1}\), a factor of about 20 fainter than the main jet at the same core distance, and so we take \( J = 20 \) as a lower limit on the jet–counter-jet ratio. For continuous jets, assuming that the jets and counter-jets are identical and lie along the same line, the jet–counter-jet ratio due to Doppler boosting is given by

\[
J = \left( \frac{1 + \beta \cos i}{1 - \beta \cos i} \right)^{2-\alpha}.
\]

In Figure 7 we show theoretical curves of constant jet–counter-jet ratio in the \((\beta, i)\) plane, taking \( \alpha = -0.85 \). Examination of the curves shows that the fluid speed must be \( \beta \gtrsim 0.48 \) (for \( i = 0 \)). Thus our images support the conclusion of Kollgaard et al. (1989) that at least mildly relativistic fluid speeds are required on kiloparsec scales in 3C 345. We also show the curve \( \beta = \cos i \) that expresses the constraint that the photons we observe are emitted perpendicular to the jet axis in the frame of the fluid that follows from the symmetry across the jet of the polarization profiles (Roberts & Wardle 2012). If we adopt this constraint, the lower limit on jet speed becomes \( \beta \gtrsim 0.69 \). In all cases this is rather insensitive to the value of \( \alpha \). More stringent constraints are derived by Roberts & Wardle (2012) from a model of the polarization.

3.2.3. Jet Opening Angle

The shape of the jet may play an important role in understanding the peculiar electric vector configuration in this object (see Section 4.2 below). We examined the divergence of the main jet body width using a set of transverse slices taken from the image in Figure 3. We estimated the half-width at half-maximum of the jet in two ways, by fitting Gaussian profiles to the slices, and by searching for the location of the half-maxima on each side of the peak, and subtracting the beam quadratically. The results are shown in Figure 8, which shows deconvolved half-widths and fits. The linear least-squares fits yield half-opening angles of \(9.31\) and \(9.43\), depending on whether or not the fit is forced to go through the origin. We adopt an apparent half-opening angle of \( \phi_a = 9.4^\circ \).

3.3. Polarization Structure

The linear polarization\(^4\) structures at 5 and 8 GHz are shown in Figure 9, and the fractional polarization is illustrated in Figure 10. We confirm the discovery by Kollgaard et al. (1989)

\(\text{Figure 6. Intensity (5 GHz in black, 8 GHz in red) and spectral index (blue) along the ridge line as a function of distance from the core, derived from the images in Figure 2. The error bars correspond to an rms uncertainty of 0.5 mJy beam}^{-1} \).
Figure 8. Deconvolved half-widths and fits at 8 GHz; the data come from Figure 3. The data points are the means of Gaussian fits and simple searches for the half-power points, and the error bars are standard errors using these two estimates. The linear least-squares fits yield half-opening angles of about 9°.

that the electric vectors in the jet are not transverse to the jet but twisted at a significant angle. Here we are able to resolve the polarization of jet in the transverse direction, and find that the twist is greatest, about 35°, down the center of the jet and vanishes at both edges. The fractional polarization of the jet is about 25% down the center of the main part of the jet, greater at the edges, and varies strongly with position in KB and HS.

We first address the possibility that the twist in electric vector position angles is due to Faraday rotation in the jet. This is ruled out as it is apparent from Figure 9 that the electric vector distributions at the two frequencies are nearly identical. Polarization angle differences $\Delta \chi = \chi_5 - \chi_8$ across 3C 345 are shown in Figure 11, where $\Delta \chi$ is displayed as position angle. Any deviations from the vertical indicate Faraday rotation. Everywhere in the source except the edges, $|\Delta \chi| \lesssim 10^\circ$, corresponding to a rotation measure of $|RM| \lesssim 70 \, \text{rad} \, \text{m}^{-2}$. To produce a 35° twist at 8 GHz would require $RM = 400 \, \text{rad} \, \text{m}^{-2}$, which would produce a 92° twist at 5 GHz, clearly incompatible with the data. We conclude that Faraday rotation is not the cause of the twist in the $E$ vector directions in the main body of the jet.

Rudnick & Jones (1983) found an integrated RM of $29 \pm 7 \, \text{rad} \, \text{m}^{-2}$ for 3C 345, but our measurement at the core yields $\Delta \chi = 14.6^\circ$ for a rotation measure of $RM = 100 \, \text{rad} \, \text{m}^{-2}$.

Figure 9. Linear polarization images of the quasar 3C 345 with ticks showing the direction of the observed $E$ vectors, made from (a) 5 and (b) 8 GHz VLA A-array data. The contours are of linearly polarized intensity. These images have been rotated by $-50^\circ$ in position angle. See Table 1 for image data and figure details.
$-17 \text{ rad m}^{-2}$. Our absolute position angle calibration uncertainty of $\pm 5^\circ$ corresponds to an RM uncertainty of about $\pm 30 \text{ rad m}^{-2}$, marginally incompatible with the integrated measurement. We have examined data at 5, 8, and 15 GHz from the University of Michigan Radio Astronomy Observatory for this epoch, and they are compatible with our measurement of negligible Faraday rotation. The source is highly variable and this is the likely cause of the disagreement with the Rudnick & Jones (1983) measurement.

In highly luminous radio sources with FR II structure such as 3C 345 the inferred magnetic field in the jets is typically longitudinal (Bridle et al. 1994), as evidenced by $\mathbf{E}$ vectors orthogonal to the jet ridge-line direction, while in low-luminosity FR I sources the inferred field is transverse (Bridle & Perley 1984). Thus the linear polarization distribution in the straight portion of the 3C 345 jet is unusual in that the $\mathbf{E}$ vectors are neither longitudinal nor transverse to the jet axis.
4. DISCUSSION

4.1. Does the Jet in 3C 345 Precess?

The non-co-linear I structure of the jet seems to suggest that the jet was pointed in different directions at different times in the past (Kollgaard et al. 1989). But the polarization structure strongly suggests that this is not the case, and instead that KB contains two impact points of a jet that is twice re-directed by interactions with the external medium, and that comes to an apparent end at the hotspot. We interpret the electric vector configurations at KBS, KBN, and HS as indicating compressed sheets of magnetic field seen roughly edge-on (Laing 1980). In KBS and KBN the jet is re-directed by interaction with the ambient medium, and at HS the jet ends in a hotspot. This interpretation is consistent with a jet inclined at a small angle to the line of sight that is seen roughly from the side due to aberration because its fluid speed is highly relativistic. Based on X-ray observations of 3C 345, Kharb et al. (2012) have recently suggested that the jet is deflected at KB, consistent with our interpretation of the polarization structure there.

4.2. Origin of the “Twist” in the 3C 345 Electric Vectors

Is the magnetic field in the 3C 345 helical, as it appears to be? There are few similar examples in the literature, the best observed one being M 87. There the well-resolved jet shows a twisted filamentary structure in the radio (Owen et al. 1989) that has been ascribed to a Kelvin–Helmholtz instability (Hardee & Eilek 2011), and the magnetic field structure seems to follow the filaments. Optically it looks quite similar to the radio image (Fraix-Burnet et al. 1989). In 3C 345 we see no filamentary structure in the jet,6 and suggest instead that the twisted electric field pattern is the result of relativistic effects. A helical magnetic field in a transparent homogeneous cylindrical jet would appear either transverse or longitudinal, not helical, due to cancellations between the back and the front (in an east–west jet this means that Stokes U is identically zero). Two possibilities for producing a twist in the electric vector pattern suggest themselves; either the symmetry through the jet is broken by opacity or it is broken by relativistic effects. The former would produce frequency dependence of the complex polarization that is not present in the data. In the latter case, the gentle divergence in the jet width demonstrated in Section 3.2.3 suggests a similarly diverging velocity field. In such a velocity field, differential Doppler boosting due to differing line-of-sight velocity components in the front and back of the jet will break the symmetry, permitting there to be non-zero U, and thus creating a twist to the observed electric vectors if the underlying magnetic field is helical. It is shown in Roberts & Wardle (2012) that simple models for the magnetic field in 3C 345 coupled with differential Doppler boosting in a gently diverging jet can produce the “twist” seen in the electric vectors in the main body of the jet. This model requires that the fluid speed in the jet be at least $\beta = 0.95$, and an intrinsically helical magnetic field.

5. CONCLUSIONS

We have made sensitive VLA Array A-array images of the nearby bright quasar 3C 345 in total intensity and linear polarization at 5 and 8 GHz. The principal results of the analysis of these images are the following.

1. 3C 345 has a bright $7–8$ Jy unresolved core with spectral index $\alpha \simeq -0.24 (I_\nu \propto \nu^\alpha)$.
2. The jet consists of a straight section of projected length about $2.3$ (15 kpc), and two bright knots at the end of the jet that do not lie on the same line.
3. The spectral index of the jet ranges over $-1.1 \lesssim \alpha \lesssim -0.5$.
4. The jet diverges slightly with an apparent half-opening angle of about $9^\circ$. De-projected, the jet opening angle is significantly smaller (Roberts & Wardle 2012).
5. There is a faint near-core feature whose base extend from the core at (true) position angle $\sim 55^\circ$. This feature does not appear to be a true counter-jet, but instead is part of

6. Note that 3C 345 is 75 times as distant as M 87, which is an FR I radio source.
an extended lobe seen in projection. The lack of a true counter-jet requires fluid speeds \( \beta \gtrsim 0.5 \).

6. The fractional polarization in the jet is high, ranging over \( 0.2 \lesssim m \lesssim 0.5 \), and is systematically greater at the edges.

7. The non-co-linearity of the main body of the jet and the knots at its end seems to indicate that the jet was pointed in different directions at different times in the past. However, the polarization structure suggests instead that the knots represent three impact points with the external medium of a jet that is twice re-directed by interactions.

8. The polarization behavior in the knots at the apparent end of the jet is consistent with the possibility that the jet, despite being at a small angle to the line of sight, is seen effectively from the side due to relativistic effects for a fast-moving flow.

9. Unusually, the electric vector directions in the main body of the jet are neither longitudinal nor transverse, but are twisted by about 35° from orthogonal to the jet axis at both 5 and 8 GHz.

10. The “twist” in the electric vectors is not due to Faraday rotation, which is a few degrees or less everywhere, and is significantly less in the core, the brightest parts of the jet, and the knots at the end.

In Roberts & Wardle (2012) it is demonstrated that these data suggest that the fluid velocity on kiloparsec scales in 3C 345 is highly relativistic (\( \beta \gtrsim 0.95 \)) and that the magnetic field is indeed helical.

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