EVIDENCE FOR HIGHLY RELATIVISTIC VELOCITIES IN THE KILOPARSEC-SCALE JET OF THE QUASAR 3C 345

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ABSTRACT

In this paper we use radio polarimetric observations of the jet of the nearby bright quasar 3C 345 to estimate the fluid velocity on kiloparsec scales. The jet is highly polarized, and surprisingly, the electric vector position angles in the jet are “twisted” with respect to the jet axis. Simple models of magnetized jets are investigated in order to study various possible origins of the electric vector distribution. In a cylindrically symmetric transparent jet a helical magnetic field will appear either transverse or longitudinal due to partial cancellations of Stokes parameters between the front and back of the jet. Synchrotron opacity can break the symmetry, but it leads to fractional polarization less than that observed and to strong frequency dependence that is not seen. Modeling shows that differential Doppler boosting in a diverging jet can break the symmetry, allowing a helical magnetic field to produce a twisted electric vector pattern. Constraints on the jet inclination, magnetic field properties, intrinsic opening angle, and fluid velocities are obtained and show that highly relativistic speeds ($\beta \gtrsim 0.95$) are required. This is consistent with the observed jet opening angle, with the absence of a counter-jet, with the polarization of the knots at the end of the jet, and with some inverse-Compton models for the X-ray emission from the 3C 345 jet. This model can also apply on parsec scales and may help explain those sources where the electric vector position angles in the jet are neither parallel nor transverse to the jet axis.

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

1. INTRODUCTION

An important question about extragalactic radio jets is whether or not the highly relativistic velocities often present on parsec scales continue to kiloparsec scales. Here we discuss a novel piece of information suggesting that this is indeed the case in at least one quasar jet.

3C 345 is a superluminal quasar with inferred Lorentz factor $\Gamma$ up to at least 20 on parsec scales (Lister et al. 2009). In a companion paper (Roberts et al. 2012, hereafter RWM), we present detailed Very Large Array observations of the kiloparsec-scale jet of 3C 345. Its most surprising feature is a “twist” to the electric vector distribution, suggesting a helical magnetic field. This was first seen by Kollgaard et al. (1989) and is unlike the jets in other Fanaroff–Riley Type II radio sources, where the electric vectors are typically transverse to the jet axis, suggesting a longitudinal magnetic field (Bridle & Perley 1984). In this Letter, we examine possible origins of this unusual electric vector distribution. Section 2 summarizes the relevant data on the 3C 345 jet. Section 3 describes simple models for the polarization of the jet, and Section 4 presents our conclusions.

2. KEY DATA ON THE KILOPARSEC-SCALE JET OF 3C 345

Here we summarize the key features of the 3C 345 jet as determined by RWM. (1) The fractional polarization in the jet is high, ranging from 0.2 to 0.5, and is systematically greater at the edges. (2) Unusually, the inferred magnetic field direction in the main body of the jet is neither longitudinal nor transverse, but makes an apparent helix (Figure 1(a)). At the center of the jet the twist is about $35^\circ$. (3) The “twist” in the apparent magnetic field is not due to Faraday rotation, which is a few degrees or less (Figure 1(b)). (4) The jet diverges slightly with an apparent semi-opening angle of about $\phi_d = 9^\circ 4$. (5) The mean spectral index of the jet is $0.85$ ($I_\nu \propto \nu^{-0.85}$). (6) There is no counter-jet to a limit of 5% of the brightness of the main jet.

In Figure 2, we show cross-sectional slices of the Stokes parameters $I$, $Q$, and $U$ for six positions in the jet. The purpose of this Letter is to use these data to constrain fluid velocities on kiloparsec scales in 3C 345.

3. MODELS FOR THE TWISTED POLARIZATION OF THE 3C 345 JET

Is the magnetic field in 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 and suggest instead that the twisted electric field pattern is the result of relativistic effects. A truly helical 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 a horizontal jet this means that $U$ is identically zero). Two possibilities suggest themselves: either the symmetry through the jet is broken by opacity or it is broken by relativistic effects. In the latter case, the gentle divergence in the profile of the jet demonstrated by RWM suggests a similarly diverging velocity field. In such a 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. Here we show that this is sufficient to produce the twist seen in 3C 345 and use it to determine important physical parameters of the jet.

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3.1. Synchrotron Opacity

We have made simple radiative transfer calculations using the equations in Pacholczyk (1970) that show that adding some synchrotron opacity can produce an apparently helical field, but that the fractional polarization is reduced well below the $\sim 25\%$ typical of the 3C 345 jet, and that the polarization structure would be a strong function of frequency, which is not the case here. Thus we reject this explanation.

3.2. Differential Doppler Boosting

In order to assess the effects of differential Doppler boosting in a slightly conical jet, we have investigated the following model. The jet is taken to be a uniform-density axisymmetric cylinder filled with relativistic electrons with energy index $1+2\alpha$ containing a helical magnetic field made up of two parts. The first is a toroidal component generated by a uniform current density and the second component is a uniform longitudinal field; we parameterize the helicity of the field by the ratio $b$ of longitudinal component to the toroidal component at the surface. The effect of Doppler boosting is included in an ad hoc manner by superimposing a diverging velocity field whose outer profile is constrained by the observed opening angle of the jet. The angle of the velocity vectors to the jet axis varies with normalized radius $r$ as

$$\eta(r) = \phi_i r^\epsilon,$$

where the radial parameter satisfies $0 \lesssim r \lesssim 1$, $\phi_i$ is the intrinsic half-opening angle of the jet, and $\epsilon$ is an adjustable parameter that we take to be unity. The radiative transfer was done in

Figure 1. Linear polarization of the kiloparsec-scale jet of 3C 345 at 5 GHz (from RWM). (a) The contours are linearly polarized intensity, and the ticks show the orientations of the electric vectors. Note the unusual twist of the electric vectors in the main body of the jet. (b) The contours are linearly polarized intensity, and the ticks display the differences between the electric vector orientations at 5 and 8 GHz as position angle. Vertical lines indicate no Faraday rotation. These figures have been rotated by $-50^\circ$. 
Figure 2. Slices of $I/I_{\text{peak}}$ (black solid), $Q/I_{\text{peak}}$ (red dashed), and $U/I_{\text{peak}}$ (blue dotted) across the 3C 345 jet at 5 GHz. The interval between slices, which range from 0.75 to 2.00 from the core, is 0.25. These data were derived from Figures 2 and 9 in RWM.
the observer frame using the equations in Pacholczyk (1970),
incorporating the relationship between the source magnetic field and radiation electric vectors in a relativistically moving medium (Lyutikov et al. 2003).

If the fluid speed is $\beta c$ and the inclination of the jet axis to the line of sight is $i$, in the fluid frame the photon paths make an angle $\theta'$ with the jet axis, where

$$\cos \theta' = \frac{\cos i - \beta}{1 - \beta \cos i}.$$ 

The computations show that the symmetry of the profiles of $I$, $Q$, and $U$ across the jet constrain the angle $\theta'$ to be very close to 90°. This means that $\sin i \simeq 1/\Gamma$, so $\beta$ and $i$ cannot be chosen independently. The intrinsic opening angle of the jet $\phi_i$ and the apparent opening angle $\phi_a$ are related by geometry according to

$$\tan \phi_i = \tan \phi_a \sin i,$$

which means that increasing the speed of a model jet reduces the intrinsic opening angle of the jet for a given observed opening angle, partially counteracting the increased differential Doppler effect. One upshot of this is that the maximum $U/I$ that can be generated is sensitive to $\beta$ only linearly, and is not explicitly a function of $\Gamma$.

We searched for solutions in the $b$-$\beta$ plane using contours of constant $Q/I$ and $U/I$ at the center of the jet, where the values should be approximately 0.05 and 0.22, respectively, prior to convolution with the beam (see Figure 3). The nominal model without convolution with the observing beam is shown in Figure 4; its parameters are $\beta = 0.97$, $i = 14^\circ$, $\phi_i = 2^\circ 3$, and $b = -0.19$. Figure 5 shows the average observed profiles of $I$, $Q$, and $U$, each normalized by the peak of $I$, as functions of distance across the jet versus the predictions of this model when it is convolved with the observing beam of RWM. We find the following. (1) It is possible to choose parameters $\beta$ and $b$ for the jet that produce Stokes parameters that closely match those of the 3C 345 jet. (2) The ratio of surface longitudinal to toroidal magnetic field strength in the observer frame must satisfy $-0.3 \lesssim b \lesssim -0.1$. (3) The inclination of the jet to the line of sight is $8^\circ \lesssim i \lesssim 16^\circ$. (4) The fluid speed is $\beta \gtrsim 0.95$.

We also did numerical and analytic calculations in the plasma frame that were consistent with these results when transformed to the observer frame (see Cocke & Holm 1972). For example, in the special case of a spectral index of $\alpha = 1$ and $\theta' = 90^\circ$, it
can be shown that the normalized profiles of $I$, $Q$, and $U$ are

$$\frac{I(x)}{I(0)} \simeq \frac{3b^2 - 1 + x^2}{1 + 3b^2}(1 - x^2)^{3/2} + O((\phi_0 \beta)^2),$$

$$\frac{Q(x)}{I(0)} \simeq \frac{3b^2 - 1 + x^2}{4(1 + 3b^2)}(1 - x^2)^{1/2} + O((\phi_0 \beta)^2),$$

$$\frac{U(x)}{I(0)} \simeq \frac{9b^2 \phi_0}{2(1 + 3b^2)}(1 - x^2)^{3/2} + O((\phi_0 \beta)^3).$$

Here $-1 \leq x \leq 1$ is normalized position across the jet and $b' = T b$ is the pitch angle parameter in the frame of the fluid. These profiles agree very well with numerical integrations for $b$. Here $\phi_0$ is the pitch angle parameter in the frame of the fluid.

For such a simple model the success is gratifying. All of the essential features of the linear polarization of the jet are reproduced within the observational uncertainties. Models without highly relativistic bulk flows are unable to reproduce the twist of the electric vectors, and we regard the fit of data and model to be strong evidence for such flows on kiloparsec scales. All of this assumes that the apparent semi-opening angle to the line of sight is proportional to $b \beta$ and $b$ is constrained by the observed values of $Q/I$, even a 20% reduction in $\phi_0$ renders the models untenable.

If 3C 345 is typical, and helical magnetic fields are present in all kiloparsec-scale jets, we must explain why we do not see twists in other highly polarized FR II jets. One possibility is that 3C 345 is core-dominated and thus is inclined near the line of sight, while those observed by, e.g., Bridle et al. (1994) are lobe-dominated and their jets are inclined at much larger angles to the line of sight. When we apply our model for 3C 345 to such jets the result is apparently longitudinal magnetic fields.

The symmetry of $I$, $Q$, and $U$ across the jet means that it is seen at an angle $\theta' \simeq 90^\circ$ in the frame of the fluid. If a counterjet existed on kiloparsec scales. Acceptable models have speed $\beta \gtrsim 0.95$, intrinsic jet opening angle $\phi_i \lesssim 2^\circ$, and inclination to the line of sight $i \lesssim 16^\circ$. Models with $\beta \lesssim 0.95$ are unsuccessful, so we conclude that the fluid speeds in the kiloparsec-scale jet of 3C 345 are highly relativistic. This is in agreement with the conclusions drawn from inverse-Compton models of the X-ray emission seen from 3C 345 by Chandra (Kharb et al. 2012). This model can also apply on parsec scales and may help explain those sources where the electric vector position angles in the parsec-scale jet are neither parallel nor transverse to the direction of the jet (Cawthorne et al. 1993; Gabuzda et al. 2000; Pollack et al. 2003; Lister & Homan 2005).

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