MEASUREMENT OF THE ELECTRIC CURRENT IN A kpc-SCALE JET

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ABSTRACT

We present radio emission, polarization, and Faraday rotation maps of the radio jet of the galaxy 3C303. From these data we derive the magnetoplasma and electrodynamic parameters of this 50 kpc long jet. For one component of this jet we obtain for the first time a direct determination of a galactic-scale electric current (≈3 × 10^18 A), and its direction—positive away from the active galactic nucleus. Our analysis strongly supports a model where the jet energy flow is mainly electromagnetic.

Key words: galaxies: jets – galaxies: magnetic fields – plasmas

1. INTRODUCTION

A fundamental conundrum of astrophysical jet models is how energy is extracted from the accretion flow close to the black hole event horizon. The total energy carried by the jets of active galaxies is estimated to be a non-negligible fraction of the supermassive black hole formation energy, −0.1M_enc^2 (Kronberg et al. 2001). The jets are initially highly relativistic and low density, and for this reason are thought to be magnetically dominated or force-free with a negligible fraction of the power in particle kinetic energy. That is, the energy outflow from the accretion disk is in the form of a collimated “Poynting-flux jet” as proposed by Lovelace (1976) and Blandford (1976), and subsequently studied in many papers (Benford 1978; Lovelace et al. 1987, 2002; Lynden-Bell 1996; Li et al. 2001; Lovelace & Romanova 2003; Nakamura et al. 2008). The model has a current outflow (or inflow) I, along the spine of the jet of cylindrical radius r_j initially of the order of the Schwarzschild radius of the black hole. The associated toroidal magnetic field is responsible for collimating the jet. An equal but opposite “return current” flows inward (or outward) at much larger distances from the jet axis so that the net current outflow from the source is zero. Because the jet current and its return have opposite signs, they repel as a result of their magnetic interaction mediated by the toroidal magnetic field Bφ. This repulsion between the jet and its (more spatially distributed) return current has been demonstrated in MHD simulations (Ustyugova et al. 2000, 2006; Nakamura et al. 2008).

Rotation measure (RM) gradients observed on parsec scales close to the nuclear central black hole have provided evidence consistent with an electric current flow (Asada et al. 2002; Gabuzda et al. 2004; Zavala & Taylor 2005). Here, on a scale 10^3 times larger in a “mature” jet, we present a measured estimate of the jet’s net axial current and its sign.

2. BRIEF DESCRIPTION OF THE OBSERVATIONS

3C303 was observed in the Very Large Array’s (VLA) most extended “A” configuration in Stokes parameters I, Q, U in the 1.4, 4.9, and 15 GHz radio bands with maximal u − v coverage over an 11.5 hr observing period in 1981 April. Calibrated images have been discussed and analyzed in Kronberg (1986) and Lapenta & Kronberg (2005, hereafter LK05). In 2010 and 2011, the 1.4 and 4.9 GHz images were re-edited (flagged), recalibrated, and re-imaged using more updated AIPS imaging procedures, partly as a check of the earlier 1980s imaging procedures. We found excellent correspondence, though the more recent procedures permitted better imaging of the faintest structures. Due to the higher noise levels and sparser aperture plane (u − v) coverage of the 15 GHz data they are not presented here, though they are useful for confirming the main image features at a resolution of ≈0.15 and the lack of any detectable Faraday rotation between 15 and 4.9 GHz.

3. THE JET STRUCTURE AND KNOTS OF 3C303

The 3C303 radio source at z = 0.141 (Figures 1 and 2) has a one-sided prominent jet with regular repeating knot structures in both VLA radio (Kronberg 1976, 1986; Lapenta & Kronberg 2005 (LK05) and Chandra X-ray bands (Kataoka et al. 2003). It resides in a relatively sparsely populated intergalactic environment and at a high galactic latitude [l, b] = (+90.5, +57.5]. Being away from a galaxy cluster, it is well suited to an analysis of Faraday RM within the jet and lobes, since competing Faraday RM from an immediate cluster environment and the Galactic foreground are small. Given this situation, we applied improved, new determinations of the RMs of neighboring background radio sources (Kronberg & Newton-McGee 2011). This allows the most accurate available estimate of the “RM zero level,” so that our observed RM gradients and RM = 0 crossings are minimally affected by foreground plasma (Section 5).

The above combination of radio and X-ray images plus background source’s RMs permits the jet’s physical parameters, including its current, to be analyzed in isolation. 3C303’s radiating knots are large, a few thousand times larger in volume than those in, for example, the well-studied nearby M87 radio galaxy. The laterally unresolved “spine” of its jet is surrounded by a “cocoon” of relativistic, radio- and X-ray-visible, gas mixed with thermal plasma which has both a low plasma β (ratio of plasma pressure to magnetic pressure) and a highly ordered magnetic field structure (Figure 1).

The plasma β, along with the other plasma parameter, and minimum energy estimates are derived and presented in LK05, which can be consulted for further details. We distinguish the jet spine, of cylindrical radius r_j normal to the propagation direction (z) and which is laterally unresolved and appears...
Figure 1. 1.4 GHz, 1″ resolution VLA image of the entire 3C303 system showing an apparent counterjet knot, the highly polarized western lobe, and a continuation of the jet to its final western stopping point. Linear polarization lines are scaled such that a 1″ equivalent length = 2.5 mJy beam^−1. I contours are shown at −0.5, 0.5, 1, 1.5, 2, 3, 6, 12, 24, 50, 100, and 150 mJy beam^−1.

to carry the jet power, from the “knots,” which are partially resolved “cocoons” around the unresolved “spine.” The cocoons contain a mix of magnetized thermal and relativistic plasma. We find no detectable growth in the knot widths away from the active galactic nucleus (AGN), which puts an upper limit of 0.7° on the opening angle of the jet.

The jet’s regular structure, combined with the appearance of a transverse, magnetically coherent, western lobe complex also suggests it has a clear laboratory of jet disruption. The disruption point is indicated in Figure 1. Model simulations by LK05 applied MHD soliton-like solutions of the Grad–Shafranov equation to the radio and X-ray radio images of the regular knot structure of the 3C303 jet. Their models successfully computed jet stability times and constrained its plasma parameters. The above analysis forms a basis for this Letter, independent of the MHD model details in LK05. It is the visible, synchrotron radiating cocoon surrounding the jet that enables us to probe the current, most of which is probably confined to the unresolved “spine.” It is also apparent that the jet continues beyond the disruption point in Figure 1 and terminates in a bow-shock-like extremity to the west. To the east, a large polarized loop is also seen, as well as a possibly related “counter hot spot” that aligns with the western jet. We do not attempt interpretation of these latter two features in this Letter and defer them to a following paper.

Below, we describe a rare opportunity to measure the Faraday rotation (RM) variation transverse to, and along, a segment of the jet in knot E3 (Figure 1). Combined with the full plasma diagnostics and a determination of the RM zero level from surrounding sources, this provides, for the first time, a direct estimate of both the magnitude and sign of a jet’s electric current on kiloparsec (kpc) scales in a low-density intergalactic environment.

The partial resolution of the knots in the VLA images at 1.4 and 4.9 GHz permits estimates of the relativistic gas density and approximate magnetic field energy within each kpc-scale synchrotron radiating knot (cocoon).

We estimate a field strength in 3C303’s jet knots, where B_{knot} \sim 0.5 mG (LK05), measured with a 0′.35 beam and allowing for some out-of-plane component due to the expected helical form of the jet’s magnetic field. At the 0′.35 resolution of the 4.9 GHz VLA image (Figure 2), the projected line-of-sight magnetic field orientation within

Figure 2. 4.9 GHz VLA image of the 3C303 jet at 0′.35 resolution showing the three prominent, elongated, and equally spaced knots E1, E2, and E3 to the right of the stronger, variable milliarcsec-size galaxy nucleus source.
the presence of some thermal plasma in the cocoon. The RM gradient, $\nabla$RM, and its sign in a $y-z$ patch of sky around knot E3, is $\sim$10 rad m$^{-2}$ kpc$^{-1}$. Within the conservatively clipped knot E3 boundary in Figure 3 the RM is resolved in two dimensions over $O(8)$ independent sampling points (defined as 2 per FWHM beamwidth in each dimension). If we were to expand the boundary by 15%, where there is still RM signal, it would include $O(11)$ sampling points. Even for the tighter cocoon boundary in Figure 3 there is sufficient signal and resolution to define the direction and magnitude of the vector, $\nabla$RM within the knot E3 cocoon.

Having measured a differential RM over the knot, its dimension, and the approximate magnetic field strength, we can estimate the non-relativistic plasma density within the knot via the following equation:

$$RM = 4.1 \times 10^5 \left( \frac{n_e}{\text{cm}^{-3}} \right) \left( \frac{B_i}{\text{mG}} \right) \left( \frac{x}{500 \text{ pc}} \right) \text{ rad m}^{-2} \approx 10 \text{ rad m}^{-2},$$

where $x$ is the line-of-sight distance through the knot. Inserting $B_i$ and $x$ gives $n_e \sim 1.4 \times 10^{-5}$ cm$^{-3}$, similar to the value obtained in LK05.

An independent estimate of $n_e$ can be made from the observed polarization degree in the knots. On the reasonable assumption that the very regular field geometry in knot E3 results from a helical geometry, knot-internal Faraday dispersion is limited by the high observed degree of polarization $\geq 25\%$ at 5 GHz. This test implies a back-to-front, knot-internal differential Faraday rotation at 5 GHz of $\leq 30^\circ$, consistent with the knot’s RM observed above (LK05). It is consistent with the above $n_e$ estimate and gives us confidence in the local $n_e$ scaling that is required to estimate the jet current—which we discuss next.

This low value of $n_e$ outside the jet spine points to a magnetically confined (or dominated) jet (LK05): confinement of the jet by hot gas at X-ray temperatures is not possible because $p_{\text{gas}} = n_e kT_x \ll B_i^2 / 8\pi$. A common feature of the magnetic jets is that the internal pressure of the magnetic field $B_{\text{mag}}^2 / 8\pi$ (and relativistic particles) is confined by the pinch force of the external toroidal magnetic field $B_i$. The models give $B_{\text{knot}} \sim B_i$ (LK05).

5. ESTIMATE OF THE ELECTRIC CURRENT IN THE 3C303 JET

An important final step in relating ($\nabla$RM) to an axial current is to calibrate the RM zero level. We averaged discrete source RMs along neighboring lines of sight to 3C303 from a recent accurate RM data set (Simard-Normandin et al. 1981; Kronberg & Newton-McGee 2011). The resulting RM zero-level correction, $-18 \pm 4$ rad m$^{-2}$, has been applied to the RM scale of Figure 3. With this zero-level correction, we find that the RM in knot E3 changes sign on the jet axis, within the limit of our uncertainties. Furthermore, its gradient ($\nabla$RM = $n_eB_\theta$) is found to be perpendicular to the (independently measured) axis of knot E3 and the jet axis. This corresponds to the expected RM behavior around an electric current flowing along a jet’s axis.

The reversal of the RM sign on the jet axis matches the signature of a current-carrying cylinder, where we are measuring the azimuthal component of a helical magnetic field at distances $\approx y$ on opposite sides of the synchrotron radiating cocoon surrounding the unresolved spine of the jet. The inferred current, $I_e \propto (y/n_e)\nabla$RM, is the total current within the cocoon’s radius
y, over which we have measured the transverse \( \nabla \)RM. Thus, within knot E3

\[
I_z \sim 7.7 \times 10^{18} \left( \frac{B_\phi}{\text{mG}} \right) \left( \frac{y}{0.5 \text{kpc}} \right) A, \tag{2}
\]

where \( B_\phi \) is the toroidal component of magnetic field at a distance \( y \) in the sky plane from the jet (\( z \) axis). The positive sign of the gradient \( \nabla \) RM indicates that a current of \( \approx 3.85 \times 10^{18} \) A, for \( B_{\text{eq}} = 0.5 \) mG, is directed away from the galaxy nucleus. That is, within 0.5 kpc of the jet axis there is a net flow of negative charge toward the AGN core within knot E3.

Our result for the jet current is subject to different corrections and adjustments: for example, (1) if the jet axis is significantly out of the plane of the sky then the observed RM gradient can arise from a purely toroidal field, but a helical field would, contrary to the present observations. (2) In another example, if the magnetic field of the jet is not symmetric about its axis the field estimates will be modified. Such possibilities, especially (1), underline the importance of establishing from observations, an optimally foreground-free RM (\( \gamma, z \)) over the source image, as we have done here. Considering these uncertainties and the limited angular resolution, our best estimate of the axial jet current at knot E3 is \( 10^{18.5 \pm 0.5} \) A. This is the first direct estimate of a current in a kpc-scale extragalactic jet.

6. DISCUSSION AND IMPLICATIONS

A magnetically dominated jet can be modeled as a transmission line running in the \( z \)-direction with the electric potential drop across it \( \Delta V \). This is equal to the potential drop across the black hole accretion disk from its inner-to-outward radius (Lovelace 1976; Lovelace & Ruchti 1983). A typical value is \( \Delta V \sim 10^{20} V(B_{\text{bb}}/10^4 \text{G})(M_{\text{bh}}/10^8 M_\odot) \), where \( B_{\text{bb}} \) is the poloidal magnetic field strength near the black hole and \( M_{\text{bh}} \) is its mass (Lovelace 1976). The current flow in this “transmission line” is \( I_z = \Delta V / Z \), where the impedance of a relativistic jet is \( Z \sim c^{-1}(\text{cgs}) = (4\pi)^{-1}(\mu_0/\varepsilon_0)^{3/2} (\text{MKS}) = 30Q \) (Lovelace 1976). More generally, for a jet with bulk axial velocity \( u_z \), \( Z = (1/c)(u_z/c) \) (Lovelace & Romanova 2003). The electromagnetic power transported by the jet is \( L_{\text{jet}} = I_z^2 Z \).

We can now apply these ideas to the 3C303 system. The total photon luminosity \( L_{\text{rad}} \) integrated from \( 10^9 \) Hz to \( 10^{17} \) Hz is about \( 3.7 \times 10^{34} \text{ erg s}^{-1} \) or \( 3.7 \times 10^{34} \text{ W} \) (LK05). The radiated power is expected to be significantly less than the jet power because the jet power goes into a combination of \( pdV \) work on the ambient medium, and to energizing electrons and ions around the jet and in the outer radiating lobes. Thus, we let \( L_{\text{rad}} \approx \varepsilon L_{\text{jet}} \), where \( \varepsilon < 1 \) is an efficiency factor. Substituting the observed values of \( L_{\text{rad}} \) and \( I_z \) we find

\[
\varepsilon = \frac{L_{\text{rad}}}{L_{\text{rad}}^2 / I_z^2 Z} \approx 10^{-3} \left( \frac{L_{\text{rad}}}{3.7 \times 10^{34} \text{ W}} \right) \times \left( \frac{3.85 \times 10^{18} \text{ A}}{I_z} \right)^2 \left( \frac{0.1c}{u_z} \right), \tag{3}
\]

where we have normalized the jet bulk velocity to \( 0.1c \). Note that \( \varepsilon \) is safely less than unity, and the model of Poynting flux transport of jet energy in 3C 303’s black hole/accretion disk system appears to be self-consistent.

The system evidently needs to incorporate a “transducer” that converts the Poynting energy flux into high energy particles which then produce synchrotron radiation. These issues and the complex lobe structure will be discussed in a subsequent paper.

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