FARADAY ROTATION MEASURE GRADIENTS FROM A HELICAL MAGNETIC FIELD IN 3C 273

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ABSTRACT

Using high-frequency (12–22 GHz) VLBA observations, we confirm the existence of a Faraday rotation measure gradient of $\sim 500 \text{ rad m}^{-2} \text{ mas}^{-1}$ transverse to the jet axis in the quasar 3C 273. The gradient is seen in two epochs spaced roughly 6 months apart. This stable transverse rotation-measure gradient is expected if a helical magnetic field wraps around the jet. The overall order to the magnetic field in the inner projected 40 pc is consistent with a helical field. However, we find an unexpected increase in fractional polarization along the edges of the source, contrary to expectations. This high fractional polarization rules out internal Faraday rotation but is not readily explained by a helical field. After correcting for the rotation measure, the intrinsic magnetic field direction in the jet of 3C 273 changes from parallel to nearly perpendicular to the projected jet motion at two locations. If a helical magnetic field causes the observed rotation-measure gradient, then the synchrotron-emitting electrons must be separate from the helical field region. The presence or absence of transverse rotation-measure gradients in other sources is also discussed.

Subject headings: galaxies: active — galaxies: jets — polarization — quasars: individual (3C 273) — radio continuum: galaxies

1. INTRODUCTION

How jets are launched by massive black holes remains one of the fundamental unsolved issues in astrophysics. Many researchers have suggested that magnetic fields are intimately involved in the collimation of the jet and, among other effects, create a Faraday screen. For a source with a jet axis in the plane of the sky, a helical field wrapping around a jet produces a maximum line-of-sight component along the jet boundary, and no net line-of-sight magnetic field component at the center. Blandford realized that this would produce a gradient in the magnetic field, consistent with a helical field. However, we find an unexpected increase in fractional polarization along the edges of the source, contrary to expectations. This high fractional polarization rules out internal Faraday rotation but is not readily explained by a helical field. After correcting for the rotation measure, the intrinsic magnetic field direction in the jet of 3C 273 changes from parallel to nearly perpendicular to the projected jet motion at two locations. If a helical magnetic field causes the observed rotation-measure gradient, then the synchrotron-emitting electrons must be separate from the helical field region. The presence or absence of transverse rotation-measure gradients in other sources is also discussed.

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Faraday rotation measure gradients in 3C 273 (Asada et al. 2002) based on 5–8 GHz Very Long Baseline Array (VLBA) observations present intriguing evidence for one source in which we may be able to see the effects of helically wound fields and measure the sense of rotation of an accreting black hole. With the search for these RM gradients in mind, we have reanalyzed 12–22 GHz VLBA polarimetry observations for two epochs on 3C 273 to obtain higher angular resolution transverse to the jet axis while maintaining good sensitivity to the faint polarized emission.

Throughout this discussion, we assume $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Spergel et al. 2003). $\Omega_\Lambda = 0.27$, and $\Omega_m = 0.73$. This gives a scale for 3C 273 of 1 mas $= 2.52$ pc.

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2 OBSERVATIONS AND RESULTS

The observations were made on 2000 January 27 (2000.07) and 2000 August 11 (2000.61) with the 10-element VLBA. Data reduction and calibration for the 2000.07 epoch were discussed in Zavala & Taylor (2001). We reexamined the data for 2000.07 and made polarization-angle maps using five frequencies: 12.1, 12.6, 14.9, 15.4, and 22.2 GHz. The 22.2 GHz maps were tapered to approximate the 12.1 GHz resolution, and all maps were convolved with a restoring beam matched to the 12.1 GHz beam. The observational setup for the 2000.07 observation was repeated for the 2000.61 epoch. The same data reduction and calibration procedures as for 2000.07 (Zavala & Taylor 2001) were applied to the previously unpublished 2000.61 data. A data cube of polarization position angle maps ordered in $\lambda^2$ was used to create the rotation measure maps. Pixels in the RM maps were blanked if the polarization position angle error was more than $\pm 10^\circ$ at any frequency.

Rotation measure images for the two epochs are presented in Figure 1a (2000.07) and Figure 1b (2000.61). Between the two epochs, the region immediately southwest of the Stokes $I$ peak (i.e., in the projected direction of the jet) shows a change in RM. At 2000.07, the RM is $\approx 1800 \text{ rad m}^{-2}$, and 6 months later it shows a south-to-north gradient with an RM from $-1000$ to $+1000 \text{ rad m}^{-2}$.

Beyond 3 mas from the Stokes $I$ peak (hereafter this region is referred to as the “jet”), the RM distribution becomes smoother and does not change dramatically between the two epochs. The mean RM for the jet is 642 rad m$^{-2}$ for the 2000.07 epoch and 652 rad m$^{-2}$ for 2000.61. An RM gradient transverse to the jet is apparent, and we discuss this in § 3.1.

In Figure 2, we show the RM-corrected intrinsic $B$-vectors for 3C 273 under the assumption that the source is optically thin from 12 to 22 GHz. We simply took the Faraday-corrected $\delta$-vectors and rotated them by 90$^\circ$. This was done for the entire jet, and for the core west of the Stokes $I$ peak. This does not take relativistic aberration into account (Lyutikov et al. 2003, 2005), which could change the orientation of the $B$-vectors by up to 20$^\circ$. The jet $B$-vectors are initially oriented roughly parallel to the projected jet direction and then rotate to almost a north-south orientation 6 mas southwest of the Stokes $I$ peak.
Fig. 1.—Rotation measure image for 3C 273 at two epochs. Total intensity contours at 12.1 GHz are overlaid with contour levels starting at 12 and 6.6 mJy beam$^{-1}$ for epochs 2000.07 and 2000.61, respectively, and increase by factors of 2. The synthesized beam is drawn in the lower left corner and has dimensions of 2.0 $\times$ 0.9 mas at 0$''$/H1034 for both epochs. The thick lines indicate the location of the slices shown in Fig. 3.

This changing $B$-vector orientation repeats itself as we move beyond 6 mas from the Stokes $I$ peak. For the 2000.61 epoch, we detected polarization as far as 15 mas down the jet, and the $B$-vectors there have returned to a direction parallel to the projected jet axis.

3. THE FARADAY SCREEN IN 3C 273

In Figure 1, we noted the change in the core RM at 3 mas southwest of the Stokes $I$ peak. What causes the change in the observed RM? One milliarcsecond corresponds to a projected distance of 2.5 pc at the redshift of 3C 273. A region of that size is unlikely to change over a 6 month time interval. We thus reject a change in the physical conditions of a foreground Faraday screen as the cause of the changing rotation measure. A more likely explanation for the RM changes in the core over the 6 month time interval is a relativistically moving polarized jet component seen through a foreground Faraday screen. Changes in the observed RM are caused by jet components sampling different sight lines as they move out from the core (Zavala & Taylor 2004). The structure in the core is consistent with the small-scale polarization structure reported by Attridge et al. (2003).

The Faraday screen in front of the jet appears to be relatively constant in time, as the RM does not significantly change over the 6 month interval presented here, or over 3 years (Zavala & Taylor 2001). The jet Faraday screen is also spatially uni-
form, as opposed to the substructure seen in the core (Fig. 1). The more uniform Faraday screen begins at a projected distance of approximately 10 pc from the core (Fig. 1). This may be the distance from the central engine beyond which the magnetic field in the Faraday screen has become more uniform and smooth.

3.1. Evidence for a Systematic RM Gradient

We now examine the case for a transverse RM gradient as suggested by Blandford (1993). We wish to take a slice across the broadest RM distribution in the jet transverse to the jet motion. We use Kellermann et al. (2004) to define a jet direction of $/H/11002/112/11034/11002/2$ at the location of the broadest RM distribution in Figure 1, which shows the locations of the slices across the jet, with the orientation of the slice perpendicular to the line connecting the Stokes $I$ peak of the component, at a relative R.A. $= −6.5$ mas and relative decl. $= −3$ mas, and the map center. Figure 3 shows the resulting RM of the slices at the two epochs: 2000.07 by the dashed line and 2000.61 by the solid line. A transverse gradient of approximately $500 \text{ rad m}^{-2}$ mas$^2$ is visible in Figure 3, with almost 4 beamwidths along the gradient. This is much larger than the gradient of $35 \text{ rad m}^{-2}$ mas$^2$ across almost 2 beamwidths obtained with the coarser resolution of Asada et al. (2002). This clearly demonstrates the advantage of working at the highest frequencies the VLBA is capable of, consistent with enough sensitivity to polarized emission. The gradient expected by Blandford (1993) is clearly present and is suggestive of a helical field wrapping around the jet.

The RM is predominantly low and mostly negative along the southern edge of the jet in 3C 273 (ignoring a few small and suspect patches of very high RM), even to a distance of 15 mas (38 pc) at epoch 2000.61. Along the northern edge of the source, the RMs are larger and predominantly positive. This overall RM structure is consistent with an ordered helical field and suggests that this field is the dominant source of the Faraday screen on projected linear scales out to at least $\sim 40$ pc.

3.2. An Alternative View: Evidence for Localized RM Enhancements

In Figure 4, we present the 12 GHz fractional polarization along the slices shown in Figure 1. Along with a gradient in the RM, we also see a gradient in the fractional polarization. This indicates that the polarization is more ordered as one proceeds from south to north along the transverse RM gradient. Consider the simplest case of a jet in the plane of the sky with a helical magnetic field wrapped around the jet. The fractional polarization should be highest at the jet center, where the RM is zero. The fractional polarization then falls off as one approaches either edge of the jet, as the RM depolarizes the underlying emission (Gardner & Whiteoak 1966). Severe projection effects are surely present in 3C 273, yet it is still surprising to see that the highest RM in the jet corresponds to high fractional polarization. Could the localized RM and fractional polarization enhancements be the site of an interaction of the jet with the ambient thermal gas that forms the Faraday screen (Bicknell et al. 2003)? In this case the rotation of the $B$-vectors in Figure 2 to approximately perpendicular to the jet motions seen by Kellermann et al. (2004) could be a compression and enhancement of the local magnetic field due to a collision with the Faraday rotating thermal gas. If such an interaction is responsible for the observed RM and fractional polarization gradients, then the lack of free-free absorption of the jet of 3C 273 may set interesting limits on the electron density of the thermal gas (Zavala & Taylor 2004).

3.3. RM Distributions in Other Sources

Sources with jets broad enough to be well resolved are rare (Pollack et al. 2003), but a few examples do exist. The jet of M87 is resolved, but the RM data cover a relatively small area (Zavala & Taylor 2002). There is no obvious RM gradient, but the sign change of M87’s rotation measure is consistent with a helical magnetic field. Gabuzda et al. (2004) report RM gra-
Gradients in four BL Lacertae sources with an angular resolution comparable to that of Asada et al. (2002). The compact steep-spectrum quasar 3C 147 has a relatively broad jet with an RM gradient observed at 8 GHz (Zhang et al. 2004). The quasars B1611+343 and B2251+158 are well resolved, but there is no evidence of a transverse RM gradient (Zavala & Taylor 2003). BL Lac is marginally resolved, and no gradient is apparent (Zavala & Taylor 2003). Another quasar with a resolved jet, B0736+017, fails to display an obvious transverse RM gradient. At present we can say that transverse RM gradients do exist, but these gradients are not a universal feature.

The very high fractional polarization we observe rules out internal Faraday rotation as a cause for the observed RM. Internal Faraday rotation is expected to cause severe depolarization and discontinuities in the observed position angle versus \( \lambda^2 \) plots (Burn 1966; Tribble 1991). If a helical field is responsible for the observed RM gradient, this implies a segregation of the synchrotron-emitting electrons from the helical field region.

4. SUMMARY

We confirm the presence of a transverse rotation-measure gradient of 500 rad m\(^{-2}\) mas\(^{-1}\), significantly larger than the gradient observed by Asada et al. (2002). This rotation measure gradient, as first suggested by Blandford (1993), is expected if a helical magnetic field wraps around the relativistic jet of 3C 273. This field imposes an order on the Faraday screen, which we see as predominantly negative RMs along the south edge and positive RMs along the north edge in the inner projected 40 pc of the jet. The increase in fractional polarization along the RM gradient, and the turning of the \( B \)-field vectors from parallel to perpendicular to the projected jet motion, suggest that an interaction may also explain the gradient, although in this case the overall order of the RM distribution has to be explained as a coincidence, or some other mechanism that imposes an overall order to the surrounding magnetic fields. The magnetic field responsible for the Faraday rotation appears to have structure on subparsec scales within 3 mas (8 pc) from the core of 3C 273. The relatively smooth RM structure of the jet implies a well ordered (on parsec scales) magnetic field in the Faraday screen.

The larger RM gradient and the gradient in fractional polarization structure in 3C 273 revealed by these observations illustrate the advantages of observing broad jets at the highest frequencies at which the VLBA operates. The superb resolution and polarization sensitivity of the VLBA from 12 to 22 GHz enable high spatial resolution tests of theoretical predictions that are key to understanding the physics of relativistic jets. A convincing test of the helical magnetic field model awaits a clear predominance of RM gradients with the expected helicity in many sources, or the detection of a polarized counterjet with gradients in opposed directions (Asada et al. 2002). If a helical magnetic field is responsible for the observed RM gradients, then because the high fractional polarization observed rules out internal Faraday rotation, the synchrotron-emitting electrons must somehow be segregated from the helical \( B \)-field region.

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