CONCURRENT 43 AND 86 GHz VERY LONG BASELINE POLARIMETRY OF 3C 273

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ABSTRACT

We present submilliarcsecond resolution total intensity and linear polarization VLBI images of 3C 273, using concurrent 43 and 86 GHz data taken with the Very Long Baseline Array in 2002 May. The structure seen in the innermost jet suggest that we have fortuitously caught the jet in the act of changing direction. The polarization images confirm that the core is unpolarized (fractional polarization ≤1%) at 86 GHz, but also show well ordered magnetic fields (m ∼ 15%) in the inner jet, at a projected distance of 2.3 pc from the core. In this strongly polarized region, the rotation measure changes across the jet by ∼4.2 × 10^4 rad m^2 over an angular width of about 0.3 mas. If the lack of polarization in the core is also attributed to a Faraday screen, then a rotation measure dispersion ≥5.2 × 10^4 rad m^2 must be present in or in front of that region. These are among the highest rotation measures reported so far in the nucleus of any active galaxy or quasar, and must occur outside (but probably close to) the radio emitting region. The transverse rotation measure gradient is in the same sense as that observed by Asada and coworkers and by Zavala and Taylor at greater core distances. The magnitude of the transverse gradient decreases rapidly with distance down the jet, and appears to be variable.

Subject headings: galaxies: active — galaxies: jets — galaxies: magnetic fields — polarization — quasars: individual (3C 273)

Online material: color figure

1. INTRODUCTION

Multifrequency Very Long Baseline Polarimetry (VLBP) observations are crucial for determining the magnetic field structure and the distribution of Faraday rotating material in the innermost few parsecs of the cores of active galaxies and quasars.

The first successful VLBP observations at 86 GHz were reported by Attridge (2001), who presented polarized images of the well-known quasars 3C 273 and 3C 279. Here we report concurrent 43 GHz (λ = 6.9 mm) and 86 GHz (λ = 3.5 mm) VLBP of 3C 273 that allow us to investigate the distribution of Faraday rotating material near the core of this object.

3C 273 (J1229+0203) is a good source on which to attempt 86 GHz VLBP, as it is one of the brightest quasars in the sky at that frequency. Also, its low redshift of z = 0.158 gives very high linear resolution (2.73 pc mas^-1) at the source. It is also a well studied superluminal source. For instance, Homan et al. (2001) measured the proper motions of five jet components over six epochs in 1996 at both 15 and 22 GHz. Results ranged from 0.77 to 1.15 mas yr^-1, corresponding to superluminal motions of β_{app} = 7.9–11.9.

2. OBSERVATIONS AND CALIBRATION

Concurrent 43 and 86 GHz observations of 3C 273 were performed on 2002 May 9 (epoch 2002.35) using the Very Long Baseline Array (VLBA) over 10.5 hr. The VLBA was equipped with all ten 43 GHz receivers and seven 86 GHz receivers (Fort Davis, Kitt Peak, Los Alamos, Mauna Kea, North Liberty, Owens Valley, Pie Town), effectively yielding the same resolution at each frequency. With a CLEAN beam of about 0.5 × 0.25 mas, the linear resolution at the source is about 6 × 3 lt-yr.

The data were recorded with a total bandwidth of 64 MHz, and were correlated at the National Radio Astronomy Observatory (NRAO) in Socorro, New Mexico. Approximately 1.5 hr total integration was spent on 3C 273 at 43 GHz, and 3.0 hr at 86 GHz. These integration times lead to theoretical rms noise values of ~0.5 mJy beam^-1 at 43 GHz, and ~2 mJy beam^-1 at 86 GHz. The observations of 3C 273 were interleaved with those of the quasar 3C 279, which was a second target source and served to confirm our calibration. Results for 3C 279 will be presented in a separate paper.

The NRAO AIPS and Caltech DIFMAP packages were used for calibration and hybrid imaging. Details about VLBP calibration and imaging may be found in Cotton (1993) and Roberts et al.(1994). Methods to account for the complexities of 86 GHz calibration not present in lower frequency data, and to check the validity of the 86 GHz solutions are described in Attridge (2001) and Attridge et al. (1999).

The calibration of the instrumental polarization (D-terms) was performed for 3C 273 and 3C 279 separately, and results were compared. At 43 GHz, the typical D-term values were found to be ~0.03, and at 86 GHz they were ~0.11. The rms difference between the D-terms determined using 3C 273 and those determined using 3C 279 was 0.02 at 86 GHz. This is a measure of the errors in the determination of the D-terms. Following the prescription in Appendix 1 of Roberts et al. (1994), we estimate that the corresponding error in fractional polarization is less than 0.03.

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polarization in the images is $\sim0.003$ (0.3%). This is consistent with the observed fractional polarization of the core component of 3C 273, which is $\leq0.1\%$.

3. IMAGES

Naturally weighted images of 3C 273 in total intensity, polarized intensity, and fractional linear polarization at 43 and 86 GHz are shown in Figure 1. Tick marks represent the orientation of the electric vectors of the polarized radiation. The orientations of the electric vector position angle (EVPA) at 43 GHz were derived using data from the “VLA/VLBA Polarization Calibration Page” (Taylor & Myers 2000), in which 3C 273 was observed only one day prior to our own observations. Currently, there is no source to use as a calibrator to set the zero point of the EVPAs at 86 GHz. We therefore arbitrarily chose to rotate tick marks in the 86 GHz image so that the EVPA of component Q7/W7 is the same at 43 and 86 GHz. To see the EVPAs more easily, Figure 2 shows a zoom of the polarized emission from the core region at each frequency.

Model fits to the $u$-$v$ data are presented in Table 1 for components stronger than 0.1 Jy. Component labels for 86 GHz were matched to corresponding 43 GHz components for ease of comparison.

The 43 GHz total intensity image has a S/N (defined as peak flux divided by the rms flux in a source-free part of the image) of 2400, and a peak to lowest contour dynamic range of $\sim300:1$. The 86 GHz image presented in Figure 2a has a S/N of 590, and a peak to lowest contour dynamic range of $\sim75:1$. The corresponding numbers for the $P$ images are about 7 times smaller. These numbers indicate that we approached within a factor of 1.5 of theoretical noise at 86 GHz, but only within a factor of 4 at 43 GHz.

The 43 GHz images in Figure 1 show the well known core-jet structure of 3C 273. The core is component D and the jet stretches to the southwest (and continues for another 20,000 mas in all wavebands). At this resolution, the jet is quickly resolved. At 86 GHz, the resolution is similar (because of the smaller array) but the lower sensitivity means that essentially only the first milliarcsecond of the jet can be seen.

The bright inner jet components in Figure 1, components Q6/W6 and Q7/W7, are almost equidistant from the core at $\sim0.9$ mas, but at distinctly different structural position angles (SPAs). The northern component (Q6/W6) is somewhat better aligned with the downstream jet components, and has a SPA of $-123^\circ$. The southern component (Q7/W7) is stronger, has a flatter spectrum, and a SPA of $-144^\circ$. It is interesting that both are present simultaneously. We are not aware of earlier images that show such a morphology, and we conjecture that we have caught 3C 273 “in the act” of changing its jet direction. If this is so, component Q7/W7, because of its location and spectrum, is presumably the younger component, and is defining a new jet direction. Since it has already drawn level with
component Q6/W6, we expect component Q7/W7 to be moving faster. Proper motion measurements will easily support or refute these conjectures.

The polarized images shown in Figures 1 and 2 show that the inner jet is strongly polarized. Components Q6/W6 and Q7/W7 both exhibit fractional polarizations near 15% at both frequencies. Two years earlier, Attridge (2001) found a component at a similar location, whose fractional polarization was 11% at 86 GHz. By contrast, linear polarization is not detected in the core (component D) at either frequency. The limits are 0.2% at 43 GHz, and 1% at 86 GHz. This also agrees with the observations of Attridge (2001).

4. DIFFERENTIAL FARADAY ROTATION ACROSS THE JET

Although we are unable to determine the zero point for the EVPAs at 86 GHz, Figure 2 shows clearly that there is a large difference in Faraday rotation between jet components Q6/W6 and Q7/W7. At 43 GHz the difference in EVPAs is $\chi_7 - \chi_6 = +32^\circ7$. At 86 GHz the difference in EVPAs is $\chi_7 - \chi_6 = -33^\circ9$. The difference between these numbers is $66^\circ6 = 1.16$ radians, and this is independent of the zero point at 86 GHz. There is therefore an absolute difference in rotation measure between components Q6/W6 and Q7/W7 of $\sim3.2 \times 10^4$ rad m$^{-2}$. In the source frame we multiply by $(1 + z)^2$, which gives $\sim4.3 \times 10^4$ rad m$^{-2}$.

The smallest possible rotation measures consistent with these data are $-2.1 \times 10^3$ rad m$^{-2}$ for component Q7/W7 and $+2.1 \times 10^3$ rad m$^{-2}$ for component Q6/W6. These are among the largest rotation measures ever observed. One or both of them are actually lower limits, because we have only determined their difference. The distance between components Q6/W6 and Q7/W7 is 0.3 mas. If we express the rotation measure difference as an angular gradient, then it is $1.3 \times 10^4$ rad m$^{-2}$ mas$^{-1}$.

Both Asada et al. (2002) and Zavala & Taylor (2005) have measured differences in rotation measure across the jet of 3C 273 at about 7 mas from the core, but at different epochs (1995.9 and two epochs in 2000 respectively). Asada et al. found a gradient of about 80 rad m$^{-2}$ mas$^{-1}$. Zavala & Taylor find a gradient of 500 rad m$^{-2}$ mas$^{-1}$, and suggest that Asada et al. measured a smaller value because of lower resolution (their observations were made at 5 and 8 GHz). The transverse gradient at 7 mas from the core has the same sign as we find at 0.9 mas (more positive rotation measure on the north side of the jet), but it is smaller by 2–3 orders of magnitude.

It is interesting to compare the rotation measures found in the middle of each slice where the signal to noise ratio is highest. Asada et al. measure about 350 rad m$^{-2}$ at the center of their slice in 1995. This is consistent with the observations at 15 and 22 GHz throughout the following year reported by Ojha et al. (2004). Zavala and Taylor measure about 800 rad m$^{-2}$ at the same location some four years later. We suggest that all these measurements are in fact correct, and that the rotation measure distribution varies in time. This would also be consistent with the results of multiwavelength VLBP observations made by T. Chen (2005, in preparation).

The Faraday rotation we observe must be external to components Q6/W6 and Q7/W7. Internal Faraday rotation will inevitably depolarize the source (often called “front-back” depolarization) and there is no sign of this (see Table 1). It is a very general result for internal Faraday rotation that the fractional polarization drops by a factor of about two when the observed rotation reaches $\sim45^\circ$ (Burn 1966). Here, the least depolarization would be observed if the rotation measures of components Q6/W6 and Q7/W7 were $\pm2.1 \times 10^3$ rad m$^{-2}$. Even then, the predicted fractional polarizations at 43 GHz would be only $\sim10\%$, whereas the observed values are close to 15%. This rules out internal Faraday rotation by material that fills the jet, but Faraday rotation in a sheath or boundary layer is still a possibility. Inoue et al. (2003) reached the same conclusion for the gradient observed by Asada et al., and the same argument can be applied to Taylor & Zavala’s observations.

5. FARADAY DEPOLARIZATION IN THE CORE

No linear polarization is detected from the core component D in these observations. The limits are 0.2% at 43 GHz, and 1% at 86 GHz. The high rotation measures observed less than 1 milliarsecond downstream from component D suggest that it may be depolarized by differential Faraday rotation. This could be internal to the jet, but we favor an external screen because it is a natural extension of the screen that causes the Faraday rotation in front of components Q6/W6 and Q7/W7. If the intrinsic polarization of component D is $m_0$, and the variance in rotation measure along different lines of sight to
component D is \( \sigma_{\text{RM}} \), the observed polarization is given by 
\[
m(\lambda) = m_{\circ} \exp \left( -2\sigma_{\text{RM}} \frac{\lambda^2}{c} \right) \]
(Burn 1966). We do not know the value of \( m_{\circ} \), but the results are insensitive to the precise value. If \( m_{\circ} \) is in the range 2% to 10%, say, the corresponding minimum values for \( \sigma_{\text{RM}} \) are \( 5 \times 10^{-4} - 9 \times 10^{-4} \text{ rad m}^{-2} \).

However, Jorstad et al. (2005) find that integrated polarizations measured at 86, 220, and 350 GHz are strongly correlated with the polarization of the innermost jet components observed with the VLBA at 43 GHz. This suggests that the “core” is still unpolarized, even at 350 GHz. If it is intrinsically unpolarized, due to a highly tangled magnetic field, then we have no constraint on the Faraday screen in front of it, and the above calculation is irrelevant. On the other hand, it is also possible that the core is intrinsically polarized, and that it is already depolarized by differential Faraday rotation at 350 GHz. This would require \( \sigma_{\text{RM}} > 5 \times 10^{-4} \text{ rad m}^{-2} \). To distinguish between these possibilities will probably require IR polarimetry and simultaneous millimeter VLBA monitoring.

### 6. CONCLUSIONS

At 86 GHz, 3C 273 reveals two strongly polarized (\(~16\%) components within a milliarcsecond of the core that have rotation measures that differ by \( \sim 4.3 \times 10^4 \text{ rad m}^{-2} \). This gradient is transverse to the jet direction and it has the same sign, but is 2–3 orders of magnitude larger than the gradients found by Asada et al. (2002) and by Zavala & Taylor (2005) at greater distances from the core. Extrapolating such a gradient to the core component readily accounts for its persistent lack of polarization at 86 GHz.

The lack of depolarization in the jet requires that the Faraday rotation occurs in a region external to the visible jet itself, but presumably close to it. The data suggest that this Faraday rotating region is variable in time as well as spatially, and may be a boundary layer that represents the interaction of the jet with its environment. Rotation measure observations at the highest frequencies therefore offer a new way of exploring this environment.

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### TABLE 1

| Component | \( r \) (mas) | \( \theta \) (deg) | \( I \) (Jy) | \( m \) (%) | \( \chi \) | Major axis (mas) | Minor axis (mas) | \( \phi \) (deg) |
|-----------|--------------|----------------|---------|----------|------|-----------------|----------------|-------------|
| 43 GHz    |              |                |         |          |      |                 |                 |             |
| D ....... | \ldots      | 3.03 \( \leq 0.2 \) | \ldots | 0.1      | 0.1 | 40              |                 |             |
| Q8 ....... | 0.35        | 148            | 1.32    | 6.7      | 28  | 0.3             | 0.3             | 0.1         |
| Q7 ....... | 0.85        | 145            | 4.60    | 14.8     | 63  | 0.1             | <0.1           | <0.1        |
| Q6 ....... | 0.87        | 124            | 2.95    | 15.6     | 31  | 0.3             | 0.1             | 0.1         |
| Q3 ....... | 3.62        | 133            | 0.91    | 9.5      | 28  | 1.5             | 0.4             | 0.4         |
| Q2 ....... | 4.56        | 132            | 0.39    | \ldots   | \ldots | 0.7             | 0.2             | 0.2         |
| Q1 ....... | 9.69        | 116            | 0.90    | 23.3     | 82  | 0.9             | 0.6             | 0.6         |
| 86 GHz    |              |                |         |          |      |                 |                 |             |
| D ....... | \ldots      | 1.37 \( \leq 1.0 \) | \ldots | 0.1      | <0.1| 55              |                 |             |
| W9 ....... | 0.16        | 151            | 0.16    | \ldots   | \ldots | <0.1           | <0.1           | <0.1        |
| W8 ....... | 0.39        | 137            | 0.12    | \ldots   | \ldots | <0.1           | <0.1           | <0.1        |
| W7 ....... | 0.86        | 143            | 2.09    | 16.7     | 63* | 0.2             | 0.1             | <35         |
| W6 ....... | 0.93        | 122            | 0.71    | 16.2     | 97  | 0.2             | <0.1           | 70          |

Notes.—Col. (1): Component name; col. (2): distance from easternmost feature D; col. (3): distance from D; col. (4): total intensity; col. (5): fractional linear polarization; col. (6): orientation of the linear polarization position angle; col. (7): major axis of the model component; col. (8): minor axis of the model component; and col. (9): orientation of the major axis.