Magnetic Field Geometry of the Broad Line Radio Galaxy 3C111

P. Kharb, D. Gabuzda, W. Alef, E. Preuss, P. Shastri

aIndian Institute of Astrophysics, Koramangala P.O., Bangalore - 560034
bPhysics Department, University College Cork, Cork, Ireland and Astro Space Center, Lebedev Physical Institute, Moscow, Russia
cMax-Planck-Institut-für-Radioastronomie, Bonn, Germany

Abstract

Very Long Baseline Polarimetric observations of the Broad Line Radio galaxy 3C111 performed in July and September of 1996 at 8 and 43 GHz reveal rapidly evolving parsec-scale radio structure after a large millimetre outburst. The B-field geometry is not simple. We present a first analysis of possible Faraday and optical depth effects based on a comparison of the polarization images for the two frequencies.

Key words: Galaxies: Individual (3C111), Interferometry, Polarimetry

1 Introduction

The broad-line radio galaxy 3C111 (0415+739) is the nearest (z = 0.0485) classical FR II radio galaxy with a strong compact core at cm/mm wavelengths [Wills 1975]. Radio observations on kiloparsec scales show a highly collimated jet leading from the core to the northeastern lobe [Linfield & Perley 1984]. On parsec scales, the jet is much more prominent and is one-sided towards the northeast, roughly aligned with the kpc-scale jet [Linfield 1981].

Following a large mm-outburst, we observed the source with the NRAO VLBA (10 × 25 m) and the Effelsberg antenna (100 m) in dual-polarization mode at 8.4 GHz and 43 GHz, on July 8 and September 19, 1996. A preliminary analysis of the total intensity images was presented by Alef et al. [1998]. We present here the first results of our polarization analysis.

2 Observations and Results

The data for both epochs were reduced using standard techniques in the NRAO AIPS package. The instrumental polarizations (‘D-terms’) were determined using the task LP-CAL, using the compact source...
0420–014 at 43 GHz and the unpolarized source 3C84 at 8 GHz. We calibrated the absolute values of the polarization position angles $\chi$ by applying the calibrations determined for other VLBA experiments at 43 and 8 GHz within a few months of our epochs, taking care to use the same reference antenna during the calibration (Los Alamos). This procedure is justified by the fact that the right–left phase differences of the VLBA antennas are stable on time scales of six months or more (e.g. Reynolds et al. 2001).

We show the two 43-GHz and the two 8-GHz images convolved with the same beams, corresponding roughly to the beam sizes obtained for uniform weighting: 0.20 $\times$ 0.15 mas in $PA = -20^\circ$ for the 43-GHz maps and 1.15 $\times$ 0.70 mas in $PA = -20^\circ$ for the 8-GHz maps. The maps show contours of total intensity ($I$) increasing in steps of two with polarization ($P$) vectors superimposed.

2.1 July 8, 1996

Figure 1a shows the 43 GHz image for July 8, 1996. The jet to the northeast is clearly visible. Polarization is reliably detected from the core and a bright knot at a distance of $r \sim 0.5$ mas from the core. The $P$ vectors in the core are aligned with the inner jet, but the relationship between $\chi$ for the bright knot and the local jet direction is unclear. The degree of polarization in the core region is approximately 1%, and rises to 3–4% in the bright knot.

Figure 1b shows the 8 GHz image for the same epoch. The polarization at the western edge of the core region has roughly the same $\chi$ as the 43-GHz core ($\chi \simeq 45 - 55^\circ$), suggesting that they may originate in the same region. The inner part of the 8-GHz jet has a region with transverse $P$; if Faraday effects are not significant and this region is optically thin, this implies a longitudinal $B$ field. However, this region roughly coincides with the bright knot at
$r \simeq 0.5 \text{ mas}$ in the 43-GHz image, and we would expect the 43-GHz and 8-GHz $\chi$'s to be more similar in the absence of significant Faraday or optical depth effects. We are in the process of a more detailed analysis of the origin of this large offset between the observed $P$ vectors at 8 GHz ($\chi \simeq -20^\circ$) and 43 GHz ($\chi \simeq 90^\circ$). If Faraday or optical depth effects are substantial, the 43-GHz $\chi$ more accurately reflects the underlying $B$-field geometry. Further from the core ($r \simeq 4 \text{ mas}$), the polarization appears to become somewhat oblique to the jet direction ($\chi \simeq 45^\circ$).

### 2.2 September 19, 1996

Figure 2a shows the 43 GHz image for September 19, 1996. The peak has decreased by a factor of about 1.7. It is now clear that the jet first emerges to the northeast, turns nearly directly east, then turns again to the northeast. In this light, the earlier orientation of the 43-GHz $\chi$ for the knot at $r \simeq 0.5 \text{ mas}$ now makes sense: $\chi$ was apparently well aligned with the direction of the jet flow, nearly directly eastward. This bright feature has moved to $r \sim 0.75 \text{ mas}$. Its $\chi$ again appears oblique to the jet direction; however, it is possible that it bears some relationship to the local flow direction (either parallel or perpendicular to it), but that the flow direction is again not known. The core polarization was not detected at this epoch.

Figure 2b shows the 8 GHz image for the same epoch. The polarization in the core region is aligned with the inner jet (see Fig. 2a). There is a region of transverse $\chi$ at $r \simeq 3 \text{ mas}$ from the core, implying a longitudinal $B$ field (if this region is optically thin and Faraday effects are not important). The $\chi$ in the knot $r \sim 4.5 \text{ mas}$ from the core is very similar to that at the earlier epoch ($\chi \simeq 45^\circ$), although in both cases this appears to be somewhat oblique to the local jet direction. The degree of polarization in the core region is 1–2%, and rises
to 8–10% in the 3-mas and 4.5-mas knots. It is interesting that, at both epochs, there is weak polarization at the northern edge of the inner 8-GHz jet with $\chi$ roughly along the jet direction, suggesting this polarization may be associated with a transverse $B$ field that is not well aligned with the jet ridgeline.

3 Conclusions

Our images of 3C111 for two epochs separated by only 2.5 months reveal dramatic changes in the VLBI structure after a millimetre outburst. The 43-GHz images show obvious expansion of a bright knot from the core. The $\chi$ of this knot rotated by about $60-70^\circ$ between the two epochs. At the earlier epoch, $\chi$ is well aligned with the local flow, implying a transverse $B$ field. The orientation of $\chi$ relative to the jet flow at the later epoch is not obvious, but may become clearer as we are able to better elucidate the local flow direction. The polarization of an 8-GHz knot roughly $r \simeq 4$ mas from the core has the same $\chi$ at both epochs, somewhat oblique to the jet direction.

In general, the degree of polarization in the core region is modest (1–2%), while it is somewhat higher in the jet and may increase with distance from the core. The degree of polarization reaches 3–4% at 43-GHz $\sim 0.5$–1 mas from the core and 8–10% at 8 GHz $\sim 3$–5 mas from the core.

Comparison of our 43 and 8-GHz images for July 1996 shows a large offset between the $P$ vectors at $r \simeq 0.5$ – 1 mas, indicating that Faraday and/or optical-depth effects may be playing a significant role. However, these images also suggest that the $P$ vectors in the core region have nearly the same orientations at the two frequencies, in which case Faraday and optical depths are less important there than in the inner jet.

We are in the process of a more detailed analysis of these data, including model fitting of the $I$ and $P$ data. In addition, we are reducing additional 8+43 GHz VLBA data for June 1997, as well as 43-GHz data for December 1997, May 1998, and December 1998.

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