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VLBA polarimetric observations of 3C 286 at 5 GHz

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Abstract. Polarimetric observations at 5 GHz using the VLBA are reported of the compact steep spectrum source 3C 286. There are two flat spectrum knots but both are too highly polarized to be a typical core component and both appear to be resolved in VLBA measurements. The morphology and polarization structure of this source is also quite distinct from typical core–jet sources. It is suggested that the core in this source is beamed away from us by relativistic effects and we see the portion of the jet that is beamed in our direction.

Key words: polarization – quasars: individual: 3C 286 – galaxies: jets – galaxies: nuclei – radio continuum: galaxies

1. Introduction

Compact radio sources associated with galactic nuclei and quasars are generally dominated by a very compact, flat spectrum, low polarization core emitting a steeper spectrum, frequently polarized jet. Recent workers have had difficulty interpreting the radio source 3C 286 (1328+307) in this context (Zhang et al., 1994; Jiang et al., 1996). This paper presents new polarimetric and spectral information which is very difficult to interpret as being from a core–jet source.

The radio source 3C 286 is identified with a 17th magnitude QSO at redshift z=0.846 (Burbidge and Burbidge, 1969). The quasar is nearly coincident on the sky with a foreground galaxy which gives rise to 21 cm HI absorption features at a redshift of z=0.692 (Brown and Roberts, 1973; Steidel et al., 1994). 3C 286 is an unusually strongly polarized source and is used as a polarization calibration standard for the VLA. The structure of this radio source has been extensively observed by Clarke et al. (1969); Wilkinson et al. (1979); Simon et al. (1980); Pearson, Readhead and Wilkinson (1980); Perley (1982); Phillips and Shaffer (1983), van Breugel, Miley and Heckman (1984); Pearson, Perley and Readhead (1985); Kus et al. (1988); Spencer et al. (1989); Hines, Owen, and Eilek (1989); Kollgaard, Wardle and Roberts (1990); Zhang et al. (1990); Spencer et al. (1991); Kus et al. (1993); Zhang et al. (1994); Akujor and Garrington (1995); and Jiang et al. (1996). 3C 286 has a straight spectrum, $\alpha = -0.55$, from 1.6 to 15.0 GHz, (Spencer et al., 1989) and is classified as a compact steep spectrum (CSS) source by Peacock and Wall (1982) and Fanti et al. (1985).

On the arcsecond scale the source is dominated by a subarcsecond component with a second component about 2.”6 away in position angle -115° (van Breugel, Miley and Heckman 1984, Pearson, Perley and Readhead 1985; Spencer at al. 1989, Kollgaard, Wardle and Roberts 1990). In addition, the high dynamic range images given by Hines, Owen and Eilek (1989) and Akujor and Garrington (1995) show a bridge of emission from the secondary component nearly back to the principal component. There is also a component 0.”8 to the east of the strongest component. A sketch of the major features of the arcsecond structure is given in Fig. 1.

3C 286 has long been observed by VLBI techniques but its large and complex structure rendered much of the early work of limited value in understanding the source. Global VLBI observations at 1.6 and 5 GHz by Zhang et al. (1994) show two bright, flat spectrum knots on the north–eastern end of the source with a lower brightness, wavy “tail” tending to the southwest and then curving towards the south western component seen in the VLA images. Zhang et al. (1994) suggested the possibility of a double nucleus in the core and give the frequency dependence of the separation of the knots as evidence against gravitational lensing by the foreground galaxy. EVN polarimetric observations at 5 GHz by Jiang et al. (1996) could not resolve the two knots but

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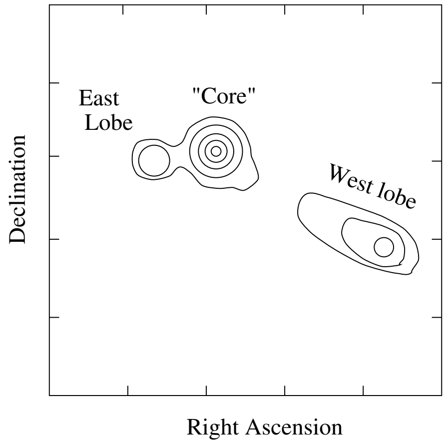

Fig. 1. A sketch of the arcsecond structure of 3C 286 interpreted from Hines et al. (1989) and Akujor and Garrington (1995). Tick marks are every arcsecond.

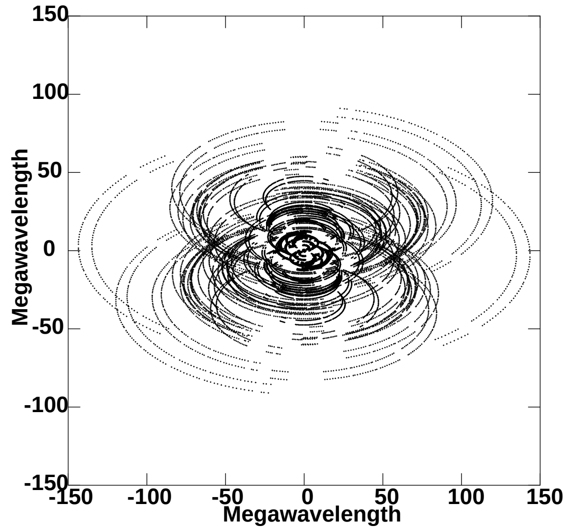

Fig. 2. The uv coverage obtained for 3C 286 at 5 GHz.

Table 1. VLBA polarization calibrators

Source	S_{VLA} Jy	$Poln_{VLA}$ mJy	$Poln_{VLBA}$ mJy	$Poln.Ang_{VLA}$ °
0235 + 164	2.19	54.8	46.6	78.6
0016 + 731	1.74	6.9	4.0	13.5

Notes: S_{VLA} is the total intensity measured using the VLA, $Poln_{VLA}$ is the polarized intensity measured using the VLA, $Poln_{VLBA}$ is the polarized intensity measured using the VLBA, $Poln.Ang_{VLA}$ is the polarization angle of the E-vectors measured by the VLA.

indicated a high overall polarization in that region and a constant overall orientation of the source polarization. This polarization structure is inconsistent with the general polarization structure seen in QSOs in which the core has very low polarization and strong variations in the orientation of the polarization are seen in the inner jet, although the field is generally parallel to the jet. Jiang et al. (1996) suggest the possibility that most of the emission from 3C 286 is from hot spots embedded in the lobe of the source rather than a nuclear core and jet.

2. Observations and data reduction

3C 286 was observed using the Very Long Baseline Array (VLBA) and a single antenna of the NRAO Very Large Array (VLA) on 19 December 1994. Two 8 MHz bands in each of right– and left– circular polarization were recorded, centered at 4.7 and 5.0 GHz. Observations of 3C84 were used to determine the relative phases of the different frequencies and polarizations. The calibration followed the general method of Cotton (1993) using global fringe fitting as described in Schwab and Cotton (1983). All processing was done using the NRAO AIPS data analysis software package.

The polarization calibrators 0235+164 and 0016+731 were measured using the VLA on 23 December 1994. The flux density scale was set using 3C48, and the polarization angle using 3C138. These sources together with the unpolarized source OQ208 were used to determine the instrumental polarization. Due to the low polarization of 0016+731, only 0235+164 was used to calibrate the polarization angle; the measured values of these calibrators are given in Table 1.

Initial amplitude calibration used the measured system temperatures and assumed antenna sensitivities. The calibration was then refined by constraining the models of 0235+164 and 0016+731 to the flux densities measured using the VLA.

The uv coverage obtained for 3C 286 is shown in Fig. 2. The use of two widely spaced bands significantly improves the coverage, especially on the longer baselines. The use of multiple frequencies and the variable spectral index across the source will reduce the dynamic range of the derived image. However, 3C 286 was heavily resolved on all baselines used and in order to achieve a reasonable starting model, the Merlin and EVN measurements of 3C 286 of Jiang et al. (1996) were initially included. Final imaging used only phase self calibration and only the VLBA data were included.

3. Results

The image derived from the VLBA observations of 3C 286 is shown in Fig. 3; the off source noise in this image is 167 μJy in total intensity and 82 μJy in the linearly polarized images. The fractional polarization, after correction for the amplitude bias, is shown in Fig. 4. The total flux density represented in Fig. 3 is 2.5 Jy or 33% of the total flux density of 7.5 Jy. The integrated linear polarization in this figure is 326 mJy with an orientation of the integrated E–vector of 30°.

These results are in general agreement with those of Zhang et al. (1994) and Jiang et al. (1996). The two knots are well re-

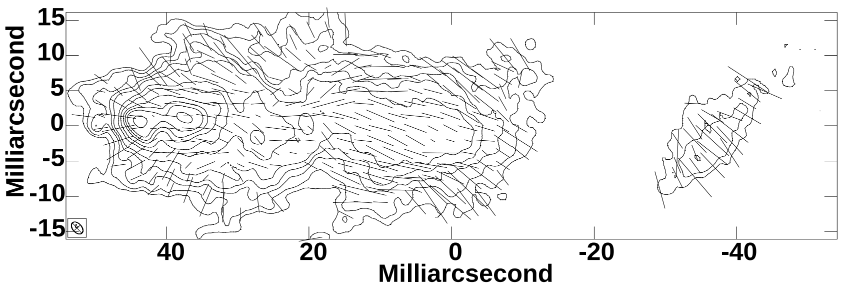

Fig. 3. The VLBA image of 3C 286 rotated by 45° counterclockwise. The peak brightness in the image is 103 mJy and contours are drawn at -0.8, 0.8, 1.2, 2.0, 2.8, 4.0, 8, 12, 20, 28, 40, and 80 mJy/beam. The polarization vectors have a length proportional to the fractional polarization after correction for the positive amplitude bias and show the orientation of the E-vectors of the radiation. The restoring beam is 2.0 × 1.3 mas with position angle -4° and is shown in the lower left corner.

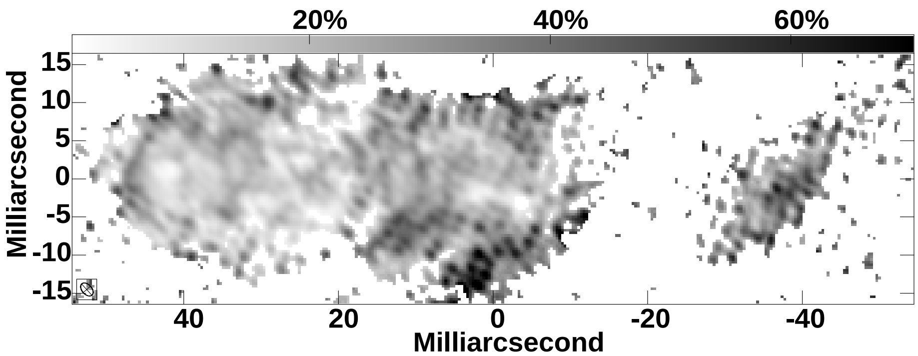

Fig. 4. The fractional polarization of 3C 286 as shown in Fig. 3. The wedge at the top gives the representation of the fractional polarization.

solved from each other and are strongly polarized with orientations roughly the same as the surrounding regions. The fractional polarizations are 8.9 and 11.0% respectively for the eastern and western knots. The two knots appear surrounded by a lower brightness cocoon with similar fractional polarization and orientation. Since 3C 286 has very low overall rotation measure, the E-vectors presented in Fig. 3 can be interpreted as being perpendicular to the magnetic field which appears to be normal to the ridge line of the source but wraps around the eastern margin of the source. The magnetic field appears to follow the ridge line of the isolated, western component. The inferred magnetic field orientation in this western component is approximately 45° from the rest of the source and points in the general direction of the western lobe seen at arcsecond scales.

4. Discussion

The images presented here are in significant disagreement with those typically observed in QSO nuclei in a number of important features. First, there are two high brightness regions, known from the work of Zhang et al. (1994) to be flat spectrum and therefore candidates for the "core". Both of these components are much more strongly polarized than the typical nuclear core and the orientation of the polarization is not significantly different from the surrounding regions. Finally, the knots are surrounded by a cocoon of emission not generally observed in core–jet sources.

In order to further investigate the spectral properties of this source, Dr. K. Kellermann provided us with unpublished VLBA observations at 15 GHz. These observations consisted of six 5 minute "snapshots". The image derived from these data is shown in Fig. 5; the RMS off source noise in this image is 1.4 mJy/beam. The 15 GHz image has insufficient surface brightness sensitivity to detect anything but the two knots, both of which are resolved in Fig. 5. Table 2 gives the parameters of Gaussians fitted to the images shown in Figs. 3 and 5. The results of fitting simple models to complex structures imaged with different uv coverages are somewhat uncertain but Table 2 gives similar sizes and inverted spectra ($\alpha \approx +0.3$) for both knots. Both knots are larger than the typical core component. The error estimates in Table 2 are standard least squares one sigma errors assuming uncorrelated pixel values; no correction is made for the extended emission which is very heavily resolved.

Jiang et al. (1996) propose an alternate interpretation of 3C 286 in which the observed structure is a lobe and hot spots rather than the jet. The similarities between the typical lobe/hot spots source and 3C 286 pointed out by them are 1) knots embedded in a cocoon, and 2) high polarization and magnetic field perpendicular to the ridge line of the structure.

The image of Hines et al. (1989) shows a 25 mJy component 0.7" east and 0.1" south of the core. In order to search for a high brightness component, this region was imaged using a range of baseline lengths of 5 to 70 million wavelengths; nothing could be seen above the noise of 1.5 mJy/beam. Bandwidth smearing effects should not cause more than a 20% amplitude loss on the longest baselines.

The apparent brightness of quasar jets is usually assumed to be the result of Doppler beaming of a highly relativistic jet. If the jet is very relativistic, the cone angle of the beaming can be quite small and a misaligned, very relativistic, jet would have a low apparent brightness. The "core" of the source is likely the position in the jet that becomes optically thin, so the core in a misaligned jet could appear quite weak. A bend in the jet

Table 2. Gaussians fitted to 5 and 15 GHz images

	5GHz				15GHz			
Knot	FluxDensity Jy	Major mas	Minor mas	Pos.Ang ∘	FluxDensity Jy	Major mas	Minor mas	Pos.Ang ∘
East	0.41 ± 0.03	3.2 ± 0.1	2.5 ± 0.2	−11 ± 8	0.55 ± 0.01	2.6 ± 0.1	2.3 ± 0.1	−4 ± 15
West	0.73 ± 0.06	5.2 ± 0.2	3.9 ± 0.2	28 ± 8	1.03 ± 0.02	5.1 ± 0.1	2.9 ± 0.1	41 ± 2

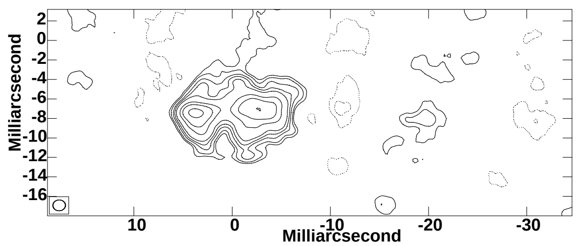

Fig. 5. Image of 3C 286 at 15 GHz from data of Kellermann et al. rotated by 45° counterclockwise. The peak brightness in the image is 119 mJy/Beam and contours are drawn at -6, -4, 4, 6, 10, 14, 20, 40, 60 and 100 mJy. The restoring beam is 1.3 × 1.1 mas with position angle 47° and is shown in the lower left corner.

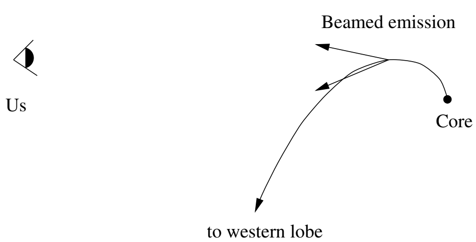

Fig. 6. A cartoon of the suggested scenario for 3C 286. Relativistic beaming causes only the portion of the jet pointed in our direction to be easily visible.

could then point the cone of beamed emission in our direction in which case that portion of the jet could become quite bright. This interpretation of 3C 286 is that the jet is initially sufficiently misaligned that the core is very weak but then curves into our line of sight before bending off to the southwest. The curvature need not be large if the jet is sufficiently relativistic. This scenario is illustrated in Fig. 6. In this scenario, the core and inner jet could be quite weak and difficult to locate while the emission we see is from that portion of the jet pointed nearly along our line of sight. Cores in other sources have been reported as weak as a few percent of the jet flux densities; see Lonsdale and Barthel (1987) and Saikia et al. (1989). A one percent core in 3C 286 would be easily visible and any core present must be substantially weaker.

5. Conclusions

We present 5 GHz VLBA polarization observations of 3C 286 in which no identified component has the properties generally associated with the core of a core–jet source. A suggested interpretation of this source is that its jet is highly relativistic and initially beamed away from us but then curves through our line of sight. The Doppler boosting of the jet would make only the portion of the jet pointed directly at us highly visible and the core very faint.

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