Monitoring of the superluminal quasar 4C 34.47

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Abstract. 10.7 GHz VLBI observations of the giant double-lobed quasar 4C 34.47 (1721 + 343) are presented. Previous VLBI monitoring at 5 GHz indicated the presence of superluminal motion in the core of this large radio source, at velocities of \( \sim 2.5h^{-1}c \) (Barthel et al. 1989). In the present observations, the superluminal nature of the apparent motions is confirmed. The evolution of the individual core components is studied in more detail.

Key words: interferometry – quasars: general – radio sources: general – superluminal motion

1. The radio source 4C 34.47

The radio source 4C 34.47 (1721 + 343) is associated with a 16º5 QSO at a redshift \( z = 0.2055 \) (Hewitt & Burbidge 1987). With its total angular extent of 280º (Barthel 1987), this giant double-lobed quasar is one of the largest objects in the sky. Adopting the cosmological parameters \( H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( q_0 = 0.05 \) (used throughout this paper), the overall linear projected size of 4C 34.47 is \( 700h^{-1} \text{ kpc} \).

4C 34.47 is a radio source of intermediate luminosity, with \( L_{178} = 2.5 \times 10^{26} \text{ W Hz}^{-1} \). Maps of its overall radio morphology can be found in Jägers et al. (1982) and Barthel (1987). Apart from its huge size, the structure of 4C 34.47 is that of a typical Faranoff-Riley class II (FR II) radio source. Its lobe structure is double and nearly symmetric in both length and flux density. A knotty jet extends over \( \sim 200h^{-1} \text{ kpc} \) towards the southern lobe. No counterjet emission has been observed on arcsec-scale radio maps, yielding a minimum estimate for the jet-counterjet flux density ratio of 10:1 (Barthel 1987). In the optical regime, 4C 34.47 is a moderately strong broad line emitter, with unusually narrow Hβ emission (the full width at half maximum (FWHM) of this line is only 1800 \( \text{ km s}^{-1} \)); Miley & Miller 1979; de Waard priv. comm.). There is little or no line emission outside the nuclear regions (de Waard priv. comm.).

The radio core of 4C 34.47 is relatively bright, containing approximately half of the total source flux density at 5 GHz. It is easily observable with the presently available VLBI networks. Early VLBI maps (Barthel et al. 1985) showed the nuclear radio structure to be resolved and \( \sim 12 \text{ mas} \) in angular extent, containing a number of clearly defined, well-separated components.

2. Observations and data reduction

At 10.7 GHz 4C 34.47 was observed three times, in March 1986 (1986.17), June 1986 (1986.40) and September 1988 (1988.73). A description of the two 1986 observations was given in Barthel et al. (1989). An overview of the experiments and networks involved is given in Table 1.

All experiments were carried out using the Mk III recording system at 28 MHz bandwidth. Left circular polarization was recorded. The data were correlated at the 4-station Mk III correlator at the Max-Planck-Institut für Radioastronomie in Bonn. After correlation, the data were averaged coherently over a period of 2–3 min. To obtain an absolute flux scale, a few scans of a number of unresolved calibrator sources were included in each observing run. The uncertainties in the flux densities assumed for the calibrator sources (estimated to be a few percent) are the main source of error in the flux densities quoted below.

Both quantity and quality of the data varied between observations. The lowest signal-to-noise data were obtained from the first epoch, for which the fewest baselines were available. The highest quality dataset was the one from epoch 1988.73, covering a full twelve hours with seven stations and little data loss. At all epochs, the strong variations in the correlated amplitudes and phases yielded sufficient restrictions to allow an accurate determination of the positions of the major individual components.

The data have been reduced using the VLBI software package developed at Caltech. The usual procedures for flux density calibration (Cohen et al. 1975) and hybrid mapping (Cornwell & Wilkinson 1981) were applied. The noise level obtained in the maps is typically 1–2 mJy per beam. Model parameters of the major individual components in the maps are presented in Table 2. Positions and strengths of the various components were determined for all epochs in three ways: (a) by direct measurement

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Table 1. VLBI observing log

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Duration (h)</th>
<th>Telescope network</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/03/86 (1986.17)</td>
<td>2.5</td>
<td>BKGH</td>
</tr>
<tr>
<td>30/05/86 (1986.40)</td>
<td>12</td>
<td>BLKGO</td>
</tr>
<tr>
<td>25/09/88 (1988.73)</td>
<td>12</td>
<td>BLKGFO</td>
</tr>
</tbody>
</table>

Abbreviations of station names: B = Effelsberg (100 m), L = Medicina (32 m), K = Haystack (36 m), G = Green Bank (43 m), F = Ft. Davis (30 m), O = Owens Valley (40 m).

from the hybrid maps, (b) by model fitting the major nuclear components with Gaussians, using both the amplitude and closure phase information in the data, and (c) by model fitting, using the closure phase data only, to avoid systematic errors due to uncertainties in the amplitude calibration. The positions and flux densities of the individual components given in Table 2, represent a weighted average of these three methods. The listed error values represent 1σ errors, estimated from a χ²-fit of the Gaussian model to the observed visibility data.

3. The evolution of the nuclear radio structure

The cleaned maps of the nuclear radio emission of 4C 34.47 at epochs 1986.40 and 1988.73 are displayed in Fig. 1. (The 1986.17 map is not shown here, since the data of epoch 1986.17 yielded to within the errors the same structure as is present in the 1986.40 map.) On mas-scales, 4C 34.47 has a linear morphology approximately 15 mas in angular extent. The position angle of the nuclear structure was measured to be 169° ± 2°, as compared to 162° ± 1° for the mp-scale radio jet. Most of the flux in the VLBI maps is contained within four separate components, designated A, B, C, and D from north to south in Fig. 1. Low-amplitude structure in the correlated amplitudes on the shortest baselines points to the presence of additional weak (5–10 mJy) structure on a scale of 20–30 mas. The two dominant features in the map are A and C, which at 10.7 GHz are almost equal in flux density. The southernmost and weakest component D appears to be resolved, both in the 5 GHz and the 10.7 GHz maps. Since the visibility data offer relatively few constraints on the position of D, and because of its extended nature, the estimated errors in the position of D are larger than for the other three components.

The position of the flat-spectrum radio core of 4C 34.47 was determined from a 5 GHz map obtained at epoch 1986.44, i.e. almost simultaneous with the second 10.7 GHz observation (Barthel et al. 1989). The northernmost component, designated A in Fig. 1, was shown to have the flattest radio spectrum (α = 0.0, S ∝ ν⁰), and is therefore assumed to be the radio core, even though it is not the brightest feature in either the 5 or 10.7 GHz maps. The other three components B, C and D have radio spectral indices α = −0.6, −0.5 and −0.9, respectively. The mas-scale radio structure of 4C 34.47 is therefore presumably pointing towards the south, and thus asymmetric in the same sense as the large scale jet, similar to what is observed in the nuclei of other lobe-dominated quasars (e.g. Porcas 1987; Hough & Readhead 1987, 1989).

The time interval between the first two epochs at 10.7 GHz, 1986.17 and 1986.40, was too short to observe any component proper motion. Between the 1986.40 and 1988.73 epochs, however, an expansion of the mas-scale structure is evident from both the correlated visibility amplitudes and the cleaned maps. The earlier 5 GHz maps indicated components B and C, and possibly D as well, to move away from A at superluminal velocities. Measured apparent velocities for components B and C were 1.3±0.3 and 2.5±0.2 h⁻¹c, respectively (Barthel et al. 1989). The present 10.7 GHz data confirm the presence of superluminal expansion in the nuclear regions of 4C 34.47. In the period Fig. 1a and b. The nuclear radio structure of 4C 34.37 at 10.7 GHz at epochs 1986.40(a) and 1988.73 (b). Contour levels in the maps are 1, 2, 4, 8, 16, 32, 64 and 96% of the peak flux density, which is 108 mJy beam⁻¹ at epoch 1986.40 and 115 mJy beam⁻¹ at epoch 1988.73. The size of the restoring beam is indicated in the lower left corner.
Table 2. Parameters of model components

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Component</th>
<th>Flux density (mJy)</th>
<th>Separation (mas)</th>
<th>P.A. (°)</th>
<th>Size (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986.17</td>
<td>A</td>
<td>115 ± 6</td>
<td>0.00</td>
<td>0</td>
<td>0.29 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>27 ± 10</td>
<td>3.45 ± 0.15</td>
<td>169 ± 1</td>
<td>0.32 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>102 ± 8</td>
<td>6.27 ± 0.10</td>
<td>169 ± 1</td>
<td>0.42 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>~7</td>
<td>~11.8</td>
<td>~166</td>
<td>~0.7</td>
</tr>
<tr>
<td>1986.40</td>
<td>A</td>
<td>109 ± 5</td>
<td>0.00</td>
<td>0</td>
<td>0.24 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>23 ± 5</td>
<td>3.50 ± 0.09</td>
<td>168 ± 1</td>
<td>0.32 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>110 ± 5</td>
<td>6.25 ± 0.05</td>
<td>169 ± 1</td>
<td>0.30 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>~9</td>
<td>~12.6</td>
<td>~167</td>
<td>~0.6</td>
</tr>
<tr>
<td>1988.73</td>
<td>A</td>
<td>141 ± 3</td>
<td>0.00</td>
<td>0</td>
<td>0.28 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>17 ± 2</td>
<td>3.85 ± 0.07</td>
<td>169 ± 1</td>
<td>0.29 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>92 ± 5</td>
<td>6.91 ± 0.07</td>
<td>168 ± 1</td>
<td>0.36 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>~10</td>
<td>~13.1</td>
<td>~167</td>
<td>~0.6</td>
</tr>
</tbody>
</table>

1986.17–1988.73 the distance of components B and C to the core is seen to increase (Table 2). In the same time interval, the mas-scale jet structure appears to have faded, due to a decrease in flux density of both B and C.

Figure 2 shows a weighted least-squares fit of the proper motions \( \mu_B \) and \( \mu_C \) to the three epochs. The best fit yields \( \mu_B = (0.16 \pm 0.05) \text{ mas yr}^{-1} \) and \( \mu_C = (0.28 \pm 0.03) \text{ mas yr}^{-1} \). Under the adopted cosmology, these values convert to apparent velocities \( v_{\text{app},B} = (1.4 \pm 0.5) h^{-1} c \) and \( v_{\text{app},C} = (2.5 \pm 0.3) h^{-1} c \). Both velocities are within the errors equal to those found in the earlier 5 GHz data (Barthel et al. 1989); there is no evidence for acceleration or deceleration of the moving components. Inclusion of the 5 GHz data in the least squares fits results in optimum fits for the proper motions of \( \mu_B = (0.15 \pm 0.04) \text{ mas yr}^{-1} \) and \( \mu_C = (0.27 \pm 0.02) \text{ mas yr}^{-1} \). These motions correspond to expansion velocities \( v_{\text{exp},B} = (1.3 \pm 0.4) h^{-1} c \) and \( v_{\text{exp},C} = (2.5 \pm 0.2) h^{-1} c \). At these superluminal velocities the radio structure of 4C 34.47 should be inclined to within 44° of the line of sight. Minimizing the bulk flow velocity would imply a Lorentz factor \( \gamma_{\text{min}} = 2.7 \) and a deprojected linear size of \( \sim 850 h^{-1} \text{kpc} \) for 4C 34.47.

The fact that the ratio of the velocities \( v_{\text{exp},B} \) and \( v_{\text{exp},C} \) is closely equal to 2 is suggestive. One possibility that would be consistent with this velocity difference would be that we are in fact observing a two-sided jet system, the core of which is located at
component B, and A and C being features expanding at equal but oppositely directed velocities of $\sim 1.3h^{-1}c$. The relatively weak radio flux density and the comparatively steep spectrum of component B with respect to A and C argue against this interpretation, however.

4. Conclusions

Monitoring of the mas-scale nuclear structure of the giant radio source 4C 34.47, initially carried out at 5 GHz, has been continued at 10.7 GHz. At this higher frequency and resolution, the occurrence of superluminal expansion, ascertained earlier by Barthel et al. (1989) has been confirmed. Individual features on mas-scales are observed to move away from the core at superluminal velocities of 2–3c. The speed of the expanding components appears to have remained unchanged in the period 1982–1988.

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