Proceedings of the 6th European VLBI Network Symposium
Ros, E., Porcas, R.W., Lobanov, A.P., & Zensus, J.A. (eds.)
June 25th-28th 2002, Bonn, Germany

Multi-frequency VLBI observations of the BL Lac 0735+178

I. Agudo[1], J. L. Gómez[1,2], D. C. Gabuzda[3], A. Alberdi[1], A. P. Marscher[4], and S. G. Jorstad[4,5]

[1] Instituto de Astrofísica de Andalucía (CSIC), Apdo. 3004, 18080 Granada, Spain
[2] Institut d'Estudis Espacials de Catalunya/CSIC, Edifici Nexus, C/Gran Capità, 2-4, E-08034 Barcelona, Spain
[3] University College of Cork, Department of Physics, Cork, Ireland
[4] Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA
[5] Sobolev Astronomical Institute, St Petersburg State University, Universitetskii Prospekt 28, Petrodvorets, St Petersburg, 198504, Russia

Abstract. We present a new set of VLBI observations of the BL Lac object 0735+178 at frequencies ranging from 5 to 43 GHz, covering a total of seven epochs from 26 March 1996 to 20 May 2000. This source presents one of the most pronounced curvatures observed in jets of AGN, with two sharp apparent bends of about 90° within the inner 2 milliarcseconds from the core. With the new information we study the structural evolution of the jet in this source since our first VLBI observations in 1996. We discuss a scenario in which the plasma of the jet is traveling inside a slowly moving curved funnel. Compilation of all available VLBI data allows us to argue about the reason for a large outburst in this source in 1989 (Aller et al. 1999).

1. Introduction

0735+178 was first identified as a BL Lacertae object by Carswell et al. (1974). It is point-like in appearance both at optical wavelengths (Blake 1970) and at radio wavelengths at arcsecond resolution (Ulvestad, Johnston & Weiler 1983; Kollgaard et al. 1992). Although Carswell et al. 1974 reported an absorption redshift $z_{\mathrm{abs}} = 0.424$ in the direction of the source and this was confirmed by Rector & Stoke (2001); its redshift still remains uncertain being z_{abs} only a lower limit for the redshift of 0735+178.

Centimeter VLBI images of this source have typically shown a compact core and a jet of emission extending to the north-east. But as higher frequencies observations became available, they provided evidence for curved structure in the inner jet of 0735+178 (Kellermann et al. 1998 and Gómez et al. 1999), which had not been apparent in the earlier images. The 22 and 43 GHz images of Gómez et al. (1999) revealed a twisted jet with two sharp apparent bends of about 90° within the inner two milliarcseconds of the jet. Polarimetric VLBI images of this source (Gabuzda, Wardle & Roberts 1989; Gabuzda et al. 1994; Gómez et al. 1999 and Gabuzda, Gómez & Agudo 2001) revealed a magnetic field predominantly perpendicular to the jet axis. Multi-epoch VLBI observations of 0735+178 (Cotton et al. 1980; Bååth & Zhang 1991; Bååth, Zhang & Chu 1991; Zhang & Bååth 1991; Gabuzda et al. 1994; Gómez et al. 1999; Homan et al. 2001) have indicated the existence of superluminal motions with apparent speeds in the range $\simeq$ 3.3–12.2 $h_{65}^{-1}c$ ($H_0 = 65h_{65}$ km s^{-1} Mpc^{-1}, q_0= 0.5). But Gómez et al. (2001) also proposed an alternative components identification in which almost all the features remained almost stationary (at least within the errors) during the period covered by their observations (since mid-1996 to the beginning of 1998).

Gómez et al. (2001) compare their data with previous observations of 0735+178, and discuss the nature of the bent structure, suggesting that it could be produced either by a change in the direction of ejection (e.g., jet precession or other more erratic variations) or by gradients in the external pressure that are not aligned with the initial direction of the jet flow. Gómez et al. (2001) also report very different jet geometries before and after the middle of 1992, suggesting that the jet geometry could have had a dramatic change at that time. About three years before, a large outburst occured in 0735+178 (Aller et al. 1999). According to Homan et al. (2001), the emission component located presently in the first bend was ejected in beginning of 1992. These authors also report a decelerating, essentially radial motion for this component.

Comparison of 15 GHz VLBA observations on 27 February 1999 and 5 GHz VSOP observations on 30 January 1999 (Gabuzda, Gómez & Agudo 2001) showed different paths for the jet at the two frequencies due to the faint emission at the region of the first bent of the jet at 5 GHz, producing a highly inverted spectrum in this area. The authors interpreted this as evidence for free-free absorption.

2. Observations

The new VLBA observations were performed on 26 March 1996, 2 October 1996, 25 April 1997, 18 October 1997, 27 February 1999, 1 September 1999 and 20 May 2000 at the frequencies indicated in Table 1. Left circular polarization data were recorded at each telescope, using 8 channels of 8 MHz bandwidth and 1 bit sampling. The reduction of the data was performed within the NRAO Astronomical Image Processing System (AIPS) software, using the standard set of procedures (e.g., Leppänen et al.

Table 1. Epochs and their observing frequencies.

Epoch	*Day*	*Freq.(GHz)*
1996.23	26*Mar*	8.4, 22
1996.75	2*Oct*	8.4, 22
1997.26	25*Apr*	5, 8.4, 15, 22
1997.80	18*Oct*	8.4, 22
1999.16	27*Feb*	15, 22, 43
1999.67	1*Sep*	15, 22, 43
2000.39	20*May*	15, 22, 43

1995). Opacity corrections for the 43 GHz observations were introduced by solving for the receiver temperature and zenith opacity at each antenna.

3. Results

3.1. The global structure of the jet

Figure 1 shows the total intensity images of 0735+178 at 5, 8.4, 15 and 22 GHz made from the observation on 25 April 1997. The images at the four observing frequencies display the inner 20 milliarcseconds of the jet structure at the resolution sufficient for revealing both the inner double curvature and the outer regions. At 5 GHz, the map does not show an evident curvature in the inner jet, although the model fitting of the data detects a small curvature. In the higher frequency images, the two 90° bends are clearly visible in the inner three milliarcseconds of the jet. Comparison between the data presented here and the maps obtained by Kellermann et al. (1998), Gómez et al. (1999), Gómez et al. (2001), Gabuzda et al. (2001) and Homan et al. (2001) show that the source global structure has not changes from 1996 to 2000. In Figure 2, we present the positions of the VLBI model fit components at all of the observing frequencies and all of the epochs presented by Gómez et al. (1999, 2001), together with the model fit results from the seven new epochs listed in Table 1. The figure clearly demonstrates that the projected VLBI jet in 0735+178 had no strong structural changes in a period of four years since 1996 to 2000, at least at lower frequencies than 43 GHz.

3.2. Components identification

Although it is extremely complicated to identify through epochs all the features in the outer part of the source, there are regions in which the low velocity of the model fit components suggest the most simple and logical identification, i. e., each component correspond to its nearby in epoch and position. Following this, most of the components have been identified with slowly moving features. These features correspond to the clumps of points viewed in Figure 2.

The inset in Figure 2, shows how the feature at about 0.8 milliarcseconds east to the core (K8) is moving to the north. The mean velocity of this component is 1.5 $h_{65}^{-1}c$ which is in agreement with the decelerating motion for this component reported by Homan et al. (2001) who measured a mean velocity from 1996.05 to 1996.93 of 3.3 $h_{65}^{-1}c$.

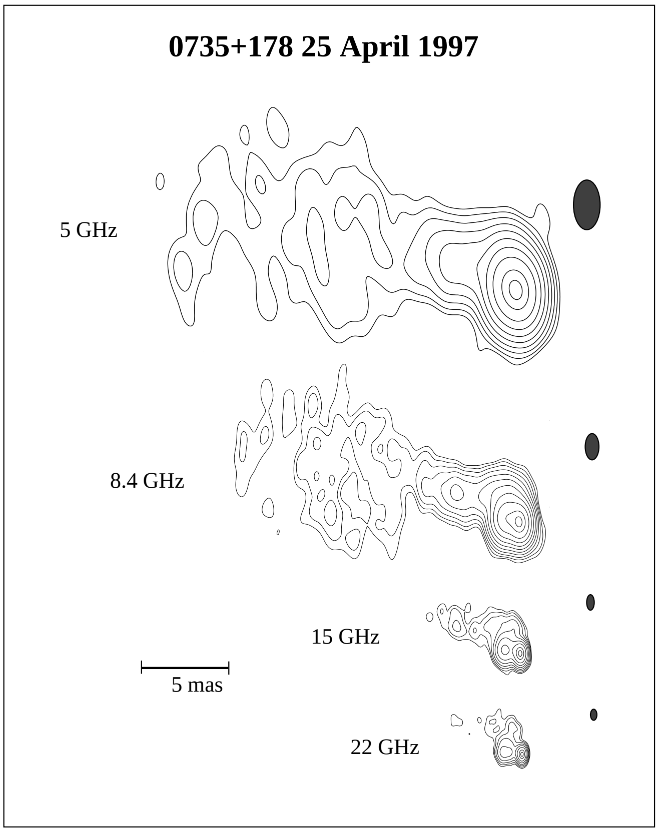

Fig. 1. 5, 8.4, 15 and 22 GHz (from top to bottom) VLBA images of 0735+178 in 25 April 1997. Contour levels increment by factor of 2 (plus 90 per cent contour). From top to bottom images, levels start at: 0.25%, 0.125%, 0.5% and 1% of the peak intensity of 0.684, 0.487, 0.445 and 0.321 Jy/beam. In the same order, convolving beams (shown as filled ellipses) are 2.55×1.38, 1.44×0.79, 0.85×0.46 and 0.58×0.32 mas, at position angles of 1.8°, 0.6°, -0.3° and -3.0°,respectively.

The innermost component in 0735+178 (K9) also seems to follow a path to the north-east, but the errors in model fit position for this component do not allow us to compute a mean velocity motion. Nevertheless, the difference between the position angles of model fit components K9 and K8 allows us to think about the presence of curvatures in the inner 0.3 milliarcseconds of the jet.

3.3. Flux evolution of the innermost jet

In Figure 3 we present the model fitted total flux densities of the innermost jet components (K8, K9 and the core) from all of the observations made from 1996 to 2000. These three components are responsible of more than the 95% of the total flux of the source at high frequencies (22 and 43 GHz) and more than the 80% at lower frequencies.

From 1996 to 1999, K9 is observed to be almost stationary, with a total flux of ∼100 mJy, and the core fluc-

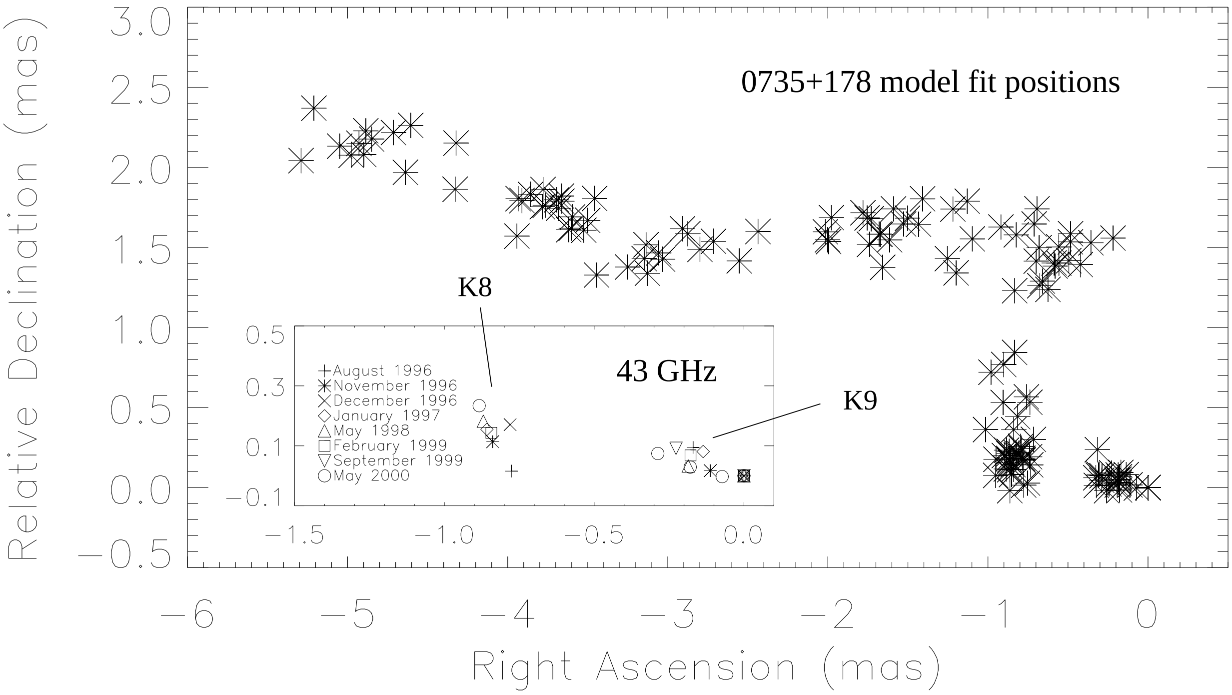

Fig. 2. Model components position, relative to the core, in the jet of 0735+178 from 26 March 1996 to 20 May 2000. The data points come from the observations listed in table 1 and from Gómez et al. (1999, 2001). All the epochs and available frequencies are represented by the same symbol in the large scale plot. Different symbols for each observing epoch are considered for the 43 GHz inset.

tuates around a level of ∼500 mJy. On the other hand, K8 shows a clear trend of the flux density decreasing from ∼650 mJy at the beginning of 1996 to ∼50 mJy at the beginning of 1999. The behavior of K8 is similar to the variability observed in the total flux density measurements made between 1996 and beginning 1998 at 4.8, 8 and 14.5 GHz (Margo F. Aller, private communication) and at 22 and 37 GHz (Harry Teräsranta, private communication). During that period, both monitoring programs recorded a ∼500 mJy decrease in total flux density at all of the frequencies monitored. This indicates that the integrated total flux evolution of 0735+178 was governed by the flux density evolution of K8.

4. Discussion

The slowly changing curved structure of the BL Lac 0735+178 at frequencies lower than 43 GHz on a time scale of about four years (1996–1999) and, most importantly, the indications of a non-radial superluminal motion of the emission component K8 in the region of the first sharp bent in the jet, suggest a model of non-ballistic motion of the fluid in the inner jet. Assuming this, the jet in the inner region could be related to a curved funnel in which the fluid patterns travel inside this tube following curved trajectories.

The funnel should not be necessarily stationary, but it can have smaller motion velocity than the fluid patterns, as shown in the three dimensional relativistic hydrodynamic and synchrotron emission (taking into account time delay effects) simulations of a twisted jet performed by Aloy et al. (2002). In these simulations, a superluminal emission component is observed to pass through different Doppler boosted regions of the jet, which are related to curvatures, following a non-ballistic curved trajectory. The main superluminal component has a much larger velocity than those moving features boosted in emission by orientation effects. The Aloy et al. (2002) simulations also show how the integrated total flux evolution of jet emission is governed by the passing of the strong component ejected from the core through the different curvatures of the hydrodynamical jet (the jet emission is able to increase in about a 50% for a viewing angle of 15°).

Likewise, the large outburst reported in 0735+178 by Aller et al. (1999) might be due to the ejection of a strong perturbation from the jet inlet that produced the first peak of the outburst at mid-1989. The following peaks at the beginning of 1991 and mid-1995 could be produced by the passing of the same perturbation through different curvatures in the inner jet where the fluid gets closer to the observer. This is in good agreement with i) the reported indications that the integrated total flux density evolution from beginning 1996 to beginning 1998 (and related to the mid-1995 peak) is governed by the component passing through the first 90° bend of the jet and ii) with the deceleration reported by Homan et al. 2001 for this component. This deceleration is confirmed by our analysis through the comparison of the mean velocity of K8

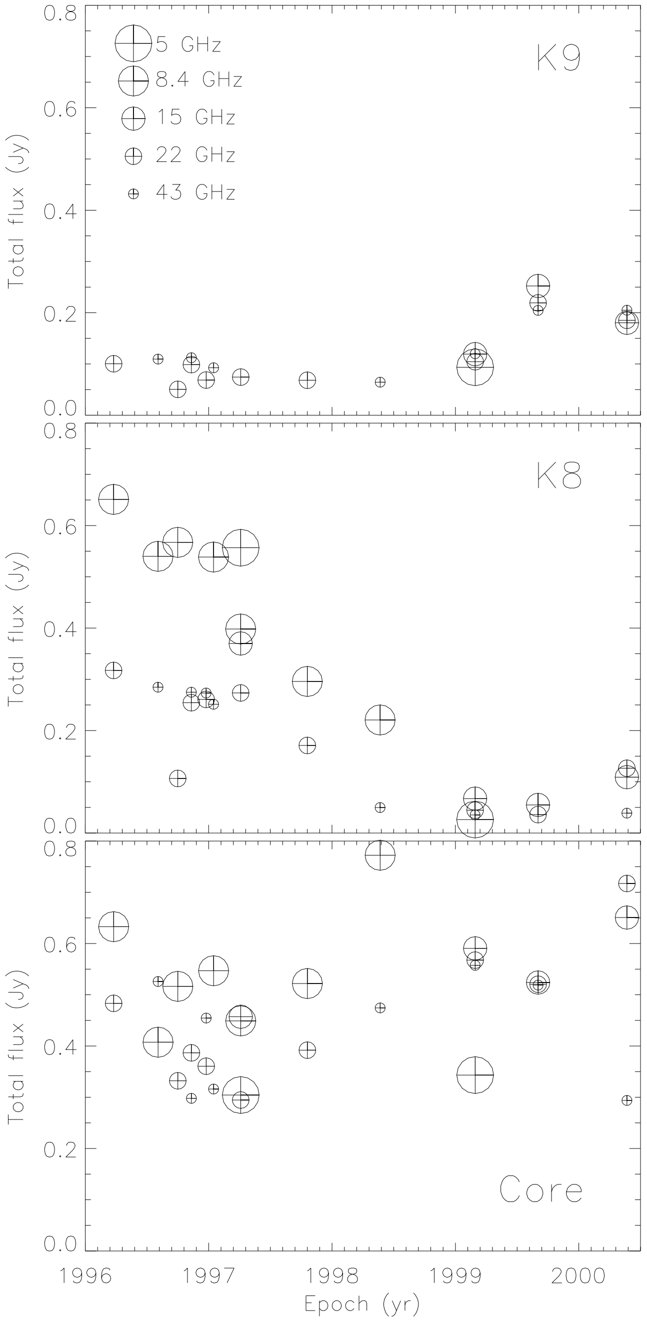

Fig. 3. 5, 8.4, 15, 22 and 43 GHz total intensity flux evolution with time for components (from top to bottom) K9, K8 and Core from 26 March 1996 to 20 May 2000. Epochs represented are those listed in table 1, Gómez et al. (1999, 2001) and Gabuzda et al. (2001). Each frequency is represented by its corresponding symbol size expressed in the first sub-plot for K9.

(1.5 $h_{65}^{-1}c$ between 1996 and 2000) with respect to the 3.3 $h_{65}^{-1}c$ value given by Homan et al. (2001). For analogy, and in view of the indications of curvatures in the inner 0.3 mas of the jet, the second peak of the outburst at the beginning of 1991 could be produced by the passing of the same perturbation through this innermost curvature of the same perturbation.

Acknowledgements. We gratefully acknowledge Margo F. Aller and Hugh D. Aller for their data from the University of Michigan Radio Astronomy Observatory which is supported by funds of the University of Michigan. We gratefully acknowledge Harry Teräsranta for the Metsähovi AGN monitoring data. I.A. and J.L.G. acknowledge partial support from the EC ICN RadioNET (Contract No. HPRI-CT-1999-40003).

References

Aloy, M. A., Martí, J. M., Gómez, J. L., Agudo, I., Müller, E. & Ibáñez, J. M. 2002, in preparation

Aller, M. F., Aller, H. D., Hughes, P. A. & Latimer, G. E. 1999, ApJ, 512, 6001

Bååth, L. B. & Zhang, F. J. 1991, A&A, 243, 328

Bååth, L. B., Zhang, F. J. & Chu, H. S. 1991, A&A, 250, 50

Blake, G. M. 1970, Ap Letters, 6, 201

Carswell, R. F., Strittmatter, P. A., Williams, R. D., Kinman, T. D. & Serkowski, K. 1974, ApJ, 190, L101

Cotton, W. D., Wittels, J. J., Shapiro, I. I., Marcaide, J., Owen, F. N., Spangler, S. R., Rius, A., Angulo, C., Clark, T. A. & Knight, C. A. 1980, ApJ, 238, L123.

Gabuzda, D. C., Wardle, J. F. C. & Roberts, D. H. 1989, ApJ, 338, 743

Gabuzda, D. C., Wardle, J. F. C., Roberts, D. H. et al 1994, ApJ, 435, 128

Gabuzda, D. C., Gómez, J. L. & Agudo, I. 2001, MNRAS, 328, 719

Gómez, J. L., Marscher, A. P., Alberdi, A. & Gabuzda, D. C. 1999, ApJ, 519, 642

Gómez, J. L., Guirado, J. C., Agudo, I., Marscher, A. P., Alberdi, A., Marcaide, J. M. & Gabuzda, D. C. 2001, MNRAS, 328, 873

Homan, D. C., Ojha, R., Wardle, J. F. C., Roberts, D. H., Aller, M. F., Aller, H. D. & Hughes, P. A. 2001, ApJ, 549, 840

Kellermann, K. I., Vermeulen, R. C., Zensus, J. A. & Cohen, M. H. 1998, AJ, 115, 1295

Kollgaard R. I., Roberts D. H., Wardle J. F. C., & Gabuzda D. C. 1992, AJ, 104, 687

Leppänen, K. J., Zensus, J. A. & Diamond, P. J. 1995, AJ, 110, 2479

Rector, T. A. & Stocke, J. D. 2001, ApJ, 122, 565

Ulvestad, J. S., Johnston, K. J., & Weiler, K. W. 1983, ApJ, 266, 18

Zhang, F. J. & Bååth, L. B. 1991, MNRAS, 248, 566