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Testing adiabatic expansion of shocks in parsec-scale jets by dual-frequency VLBI experiments

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Abstract. We present results of simultaneous dual-frequency (2 GHz and 8 GHz) very long baseline interferometry (VLBI) observations of 12 active galactic nuclei with prominent jets. Spectral properties of the jets and evolution of their brightness temperature are discussed. Measured sizes and brightness temperatures of VLBI features are found to be consistent with emission from relativistic shocks dominated by adiabatic losses. Physical scenarios with different magnetic field orientation in the jets are discussed.

Key words. galaxies: active – galaxies: jets – radio continuum: galaxies

1. Introduction

Observations used for this work were made simultaneously at 2.3 and 8.6 GHz, with participation of all ten VLBA[1] antennas and up to nine geodetic and EVN[2] stations, in the framework of seven sessions of RDV (Research & Development – VLBA) observations started in 1994 under coordination of the NASA and the NRAO and aimed at observations of compact extragalactic radio sources. Four intermediate frequencies of 8 MHz wide each were recorded making up a total 32 MHz bandwidth. The data were correlated at the VLBA correlator in Socorro, with a 4 sec integration time, and were obtained by us from the open the NRAO archive and then calibrated using the NRAO Astronomical Image Processing System (AIPS). Phase corrections for residual delays and delay rates were done using the task FRING. Self-calibration, hybrid mapping, and model fitting were performed in DIFMAP (Shepherd et al. 1994). In the model fitting, we used a minimum number of circular Gaussian components that was reproducing adequately the observed interferometric visibilities.

2. Results

We selected 12 active galactic nuclei (out of 222 observed in the RDV31-37 sessions) with

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[1] Very Long Baseline Array of the National Radio Astronomy Observatory (NRAO), Socorro NM, USA

[2] European VLBI Network

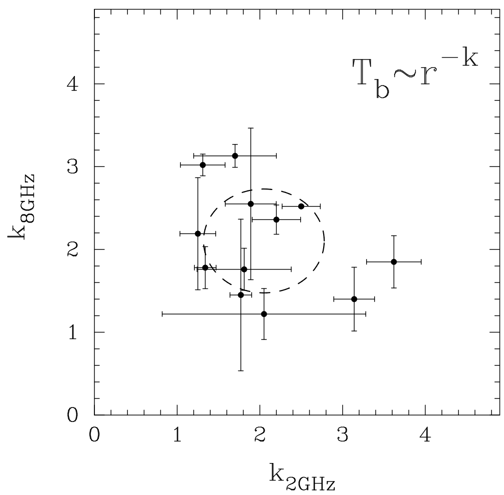

Fig. 1. Distribution of power-law indices of brightness temperature gradients with distance to the core at 2.3 and 8.6 GHz. The dashed ellipse represents a one-sigma error are of k-index distributions.

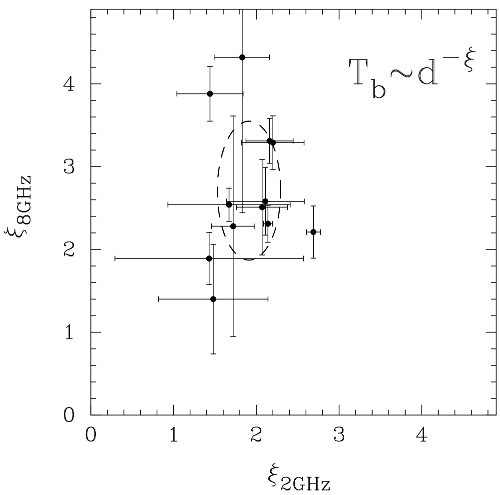

Fig. 2. Distribution of power-law indices of brightness temperature gradients with jet component size at 2.3 and 8.6 GHz. The dashed ellipse represents a one-sigma error area of ξ-index distributions.

prominent jets having at least 3 jet components detected at both frequencies. For these objects, we analyzed brightness temperature evolution as a function of (i) distance to VLBI core, r, (ii) size of jet component, d. For all components, flux densities, sizes, and relative positions to the core have been obtained from model fitting of the self-calibrated data. Evolution of $T_{\rm b}$ can be described with power law functions $T_{\rm b} \propto r^{-k}$ and $T_{\rm b} \propto d^{-\xi}$. The power law index k varies between 1.2 and 3.6, with the average value of $\overline{k}_{\rm 8\,GHz} \approx \overline{k}_{\rm 2\,GHz} \approx 2$. The power law index ξ varies between 1.4 and 4.3, with the average values of $\overline{\xi}_{\rm 8\,GHz} = 2.7$ and $\overline{\xi}_{\rm 2\,GHz} = 1.9$. Distributions of the fitted power indices k and ξ are shown in Figs. 1, 2.

The dependence of $T_{\rm b} \propto d^{-\xi}$ that also includes VLBI core components may be used for testing the shock-in-jet model (Marscher 1990), with the component emission dominated by adiabatic energy losses in relativistic shocks developing in a flow with a power law particle energy distribution $N(E)\,{\rm d}E \propto E^{-s}\,{\rm d}E$ and the magnetic field $B \propto d^{-a}$. Here, d is the transverse jet size and a describes the orientation of the magnetic field ($a = 1$ for a transverse field and $a = 2$ for a longitudinal field). Assuming the Doppler factor changing weakly along the jet, the brightness temperature of each jet component, $T_{\rm b,jet}$, can be related to the measured brightness temperature of the core, $T_{\rm b,core}$, as $T_{\rm b,jet} = T_{\rm b,core}(d_{\rm jet}/d_{\rm core})^{-\xi}$, where d represents the measured sizes of the core and jet components, and $\xi = [2(2s+1) + 3a(s+1)]/6$ (Lobanov 2000). For the spectral index $\alpha = (1-s)/2$ ($S \propto \nu^{\alpha}$), we obtain $\xi = a + 1 - \alpha(a + 4/3)$. With ξ determined from the data, we can test the shock-in-jet model by (i) comparing the jet brightness temperatures predicted by the model with those from the data; (ii) choosing the appropriate pair ($\alpha_{\rm mod}$, $a = 1$) or ($\alpha_{\rm mod}$, $a = 2$) by comparing with observed jet spectral indices obtained after applying core shift correction (Kovalev et al. 2008); (iii) using VLBA polarization observations from which the magnetic field orientation is determined directly.

Results of such an analysis are presented in Figs. 3-6 for the BL Lac object 1823 + 568 and in Figs. 7-10 for the quasar CTA 102. In both cases, the model brightness temperatures agree with the measured values. Our conclusion about the transverse B-field in 1823 + 568 (Fig. 3) is supported by the polarization map at 8.4 GHz in Fig. 6 (Pushkarev et al. 2008). In

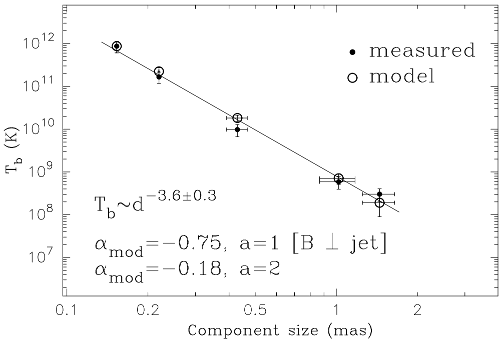

Fig. 3. Brightness temperature as a function of jet components for BL Lacertae object 1823 + 568.

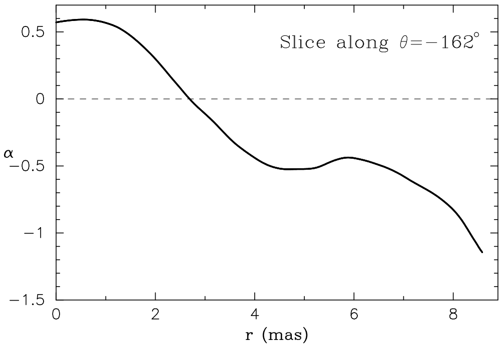

Fig. 5. Profile of spectral index $\alpha_{2-8\,\mathrm{GHz}}$ along the jet direction in 1823 + 568.

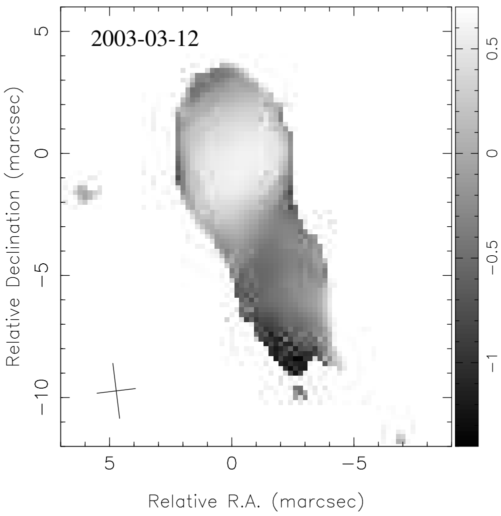

Fig. 4. Distribution of spectral index $\alpha_{2-8\,\mathrm{GHz}}$ in 1823 + 568.

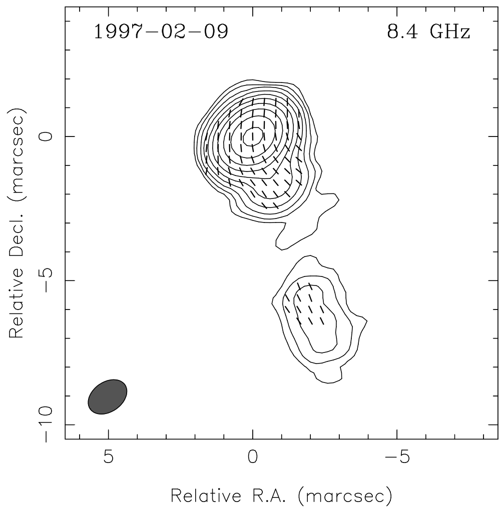

Fig. 6. Total intensity image of 1823 + 568 at 8.4 GHz with the polarization vectors superimposed.

the quasar CTA 102, both transverse and longitudinal magnetic field orientations are consistent with the model (Fig. 7). This is confirmed by MOJAVE (Lister & Homan 2005) observations of this source (Fig. 10). In the innermost part of the jet, the magnetic field is predominantly transverse, and it becomes longitudinal at larger distances, implying dissipation of shocks and creation of polarization sheath around the jet. It should also be noted that the observed brightness temperature of the largest (d = 3.1 mas) jet component located at ≈ 12 mas from the core is higher than the model brightness temperature ($T_b^{obs}/T_b^{model} \approx 6$). This can be explained by an interaction with the ambient medium, also seen in the spectral index map (Fig. 8).

3. Conclusions

Measured sizes and brightness temperatures of VLBI components in BL Lac object 1823+568 and quasar CTA 102 are consistent with emission from relativistic shocks dominated by adiabatic losses.

Acknowledgements. This work is based on the analysis of global VLBI observations including

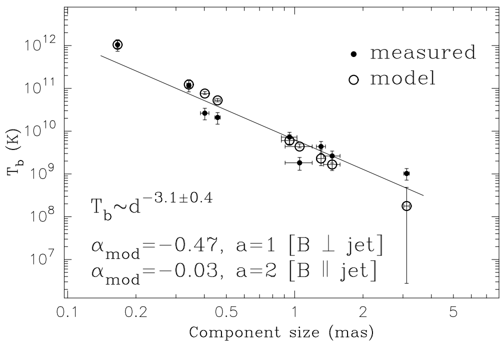

Fig. 7. Brightness temperature as a function of jet components for quasar CTA 102.

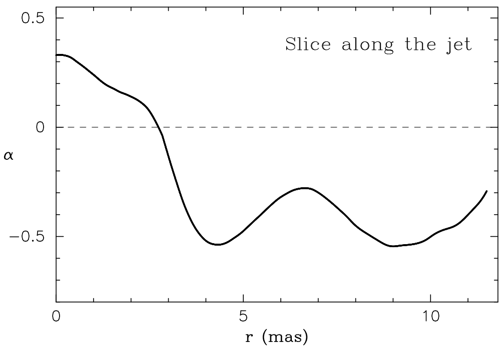

Fig. 9. Slice of spectral index $\alpha_{2-8\,\mathrm{GHz}}$ distribution map along the jet direction in CTA 102.

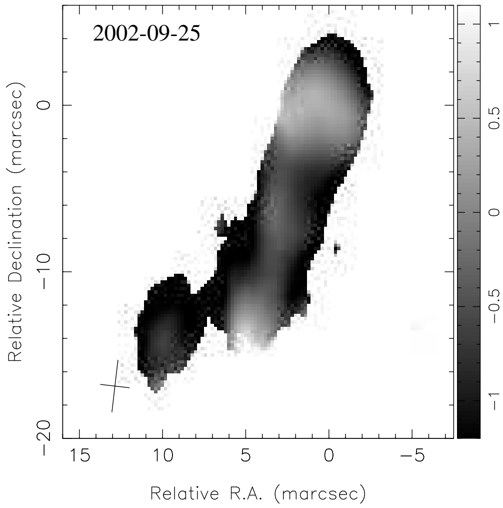

Fig. 8. Spectral index $\alpha_{2-8\,\mathrm{GHz}}$ distribution map of CTA 102.

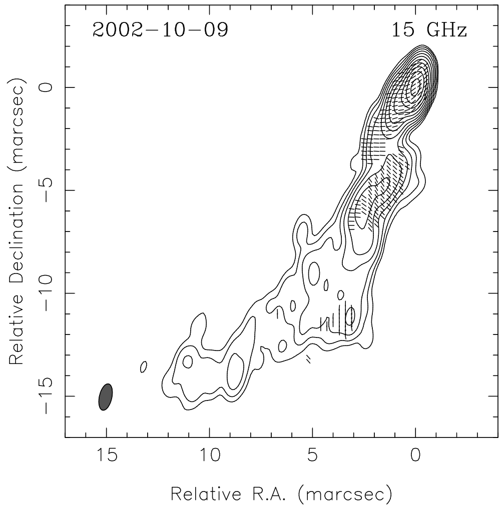

Fig. 10. Total intensity image of CTA 102 at 15 GHz with the polarization vectors superimposed.

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References

Kellermann, K. I., Lister, M. L., Homan, D. C. et al. 2004, ApJ, 609, 539

Kovalev, Y. Y., Lobanov, A. P., Pushkarev, A. B., and Zensus, J. A. 2008, A&A, 483, 759

Lister, M. L. & Homan, D. C. 2005, AJ, 130, 1389

Lobanov, A. P. 2000, A&A, 364, 391

Marscher, A. P. 1990, Parsec-Scale Radio Jets, ed. J. A. Zensus & T. J. Pearson (Cambridge: Cambridge Univ. Press), 236

Pushkarev, A. B., Gabuzda, D. C., Bezrukovs, V. 2008, MNRAS (in prep.)

Shepherd, M. C., Pearson, T. J., Taylor, G. B. 1994, BAAS, 26, 987