Astrophysical Phenomena Revealed by Space VLBI
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VSOP Observations of TeV Gamma-Ray Sources

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Abstract

VLBI Space Observatory Programme (VSOP) and ground VLBI observations of Mrk 421 and Mrk 501 are presented and the motions of milli-arcsecond scale jet components examined to compare the inferred doppler factors from the TeV-emission region with those from the parsec-scale VLBI observations.

1 Introduction

Mrk 421 and Mrk 501 are to date the only independently confirmed extragalactic sources at TeV energies. Short-timescale variability and correlated TeV and X-ray emission have been used to infer doppler factors of 15–40 for Mrk 421 and 1.5–20 for Mrk 501 (see e.g. the review of Catanese and Weekes 1999).

We have undertaken VSOP observations of these sources at 5 GHz to probe the milliarcsecond scale structure of these source for evidence of activity associated with this TeV activity, and have compared the VSOP images with ground-based VLBI images to study the motion of jet components in order to infer the properties of the parsec-scale jets.

2 Observations

The VSOP observation of Mrk 421 was made in November 1997 with the EVN and HALCA, and the Mrk 501 observation was made with HALCA and the VLBA in April 1998.

The Mrk 421 data are described in detail in Piner et al. (1999). The VSOP image, shown in Figure 1, reveals a core and jet components C6 (0.83 mas from the core) and C5 (1.63 mas). Model-fitting an elliptical gaussian component to the core yields a flux density of 370 mJy and a corresponding source frame brightness temperature of 4×10^{11} K.

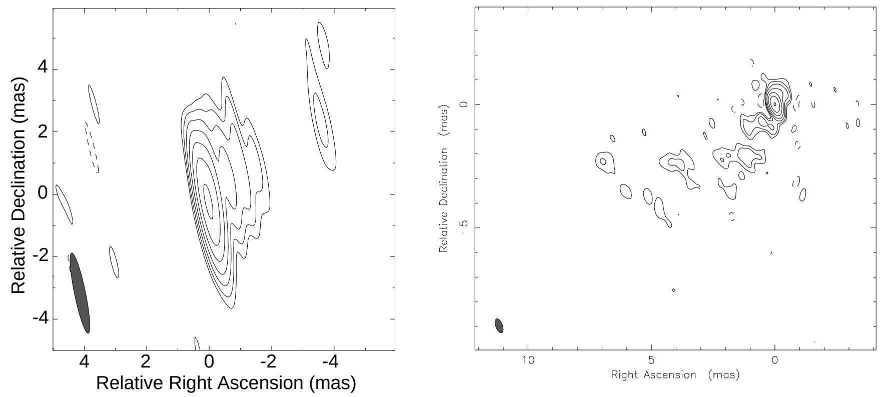

Figure 1: Left: VSOP image of Mrk 421, adapted from Piner et al. (1999). The beam (FWHM) is 2.6 x 0.4 mas at 12°. The lowest contour level is 3.6 mJy per beam, with each subsequent contour a factor of two higher. Right: VSOP image of Mrk 501. The beam (FWHM) is 0.6 x 0.3 mas at 20°. The lowest contour level is 4.7 mJy per beam, with successive contours a factor of two higher.

A preliminary VSOP image of Mrk 501 is also shown in Figure 1. Jet components ~2.5, 4.5 and 7.5 mas from the core are evident in the VSOP image. Closer to the core the situation is more complex: the brightest feature is presumably the core, however other features near the core should be interpreted with caution as they may be artefacts of the large holes in the (u, v) coverage between the ground-ground–baselines and the ground-space–baselines that are located at similar position angles to these components. Modelfitting a gaussian to the brightest feature in the core region results in a ~470 mJy component with a brightness temperature of $4{\times}10^{11}$ K.

3 Mrk 421 Component Motions

As discussed in Piner et al. (1999), the jet components in Mrk 421 display sub-luminal speeds of $\lesssim 0.3c$ (we adopt $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ throughout this paper). A re-interpretation of the observations of Zhang and Bååth (1990), assigning their model-fit components larger uncertainties in position, is quite consistent with this result. Figure 2 plots the model-fit components for Mrk 421 within 15 mas of the core from Table 3 of Piner et al. (1999), excluding 2 GHz components within 8 mas of the

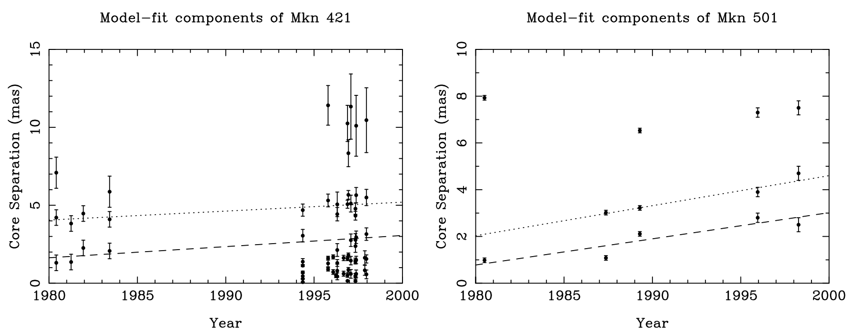

Figure 2: Component motions in Mrk 421 (left) and Mrk 501 (right). See text for details.

core and 5 GHz ground-VLBI components within 4 mas of the core as the large uncertainties on these components add unnecessary confusion.

It is tempting to try and identify the two brighter jet components of Zhang and Bååth (1990) with the more recent data. The lack of data between 1984 and 1994 renders this task open to large uncertainties, but Piner et al. found a possible match between the 2 mas and 4 mas components of Zhang and Bååth (1990) and the 5 mas (C4) and 10 mas (C3) components from the 1990s. Assuming the speeds of the components are similar, we can alternatively identify the 2 mas and 4 mas components of Zhang and Bååth (1990) with the weak 3 mas component and the 5 mas component from the 1990s, as indicated in Figure 2, which yields motions of $\sim$0.15 c. Regardless, the fact that the jet components display sub-luminal motions at both epochs appears beyond reproach.

4 Mrk 501 Component Motions

A number of different speeds have been reported for components in the Mkn 501 jet ranging from 0.27 ± 0.02 mas yr^{-1} (Gabuzda et al. 1994) to 2.4 mas yr^{-1} (Giovannini et al. 1999).

The epochs and references for the data in Figure 2 are 1980.5 (Pearson and Readhead 1998), 1987.4 (Gabuzda et al. 1992), 1989.3 (Gabuzda et al. 1994), 1995.9 (the VLBA 2 cm survey, see Kellermann et al. 1998 and http://www.cv.nrao.edu/2cmsurvey) and 1998.4 (our VSOP observation). This compilation of data suggests that there are two components moving at similar apparent speeds of $\sim$0.12 mas yr^{-1}, or $\sim$0.3 c.

5 Discussion

As outlined by Piner et al. (1999), there are several possible explanations for reconciling the large inferred doppler factors from TeV observations with the sub-luminal speeds determined from VLBI observations. Marscher (1999), citing the lack of emerging VLBI jet components associated the spectacular TeV flares seen from Mrk 421 in 1996 and the prolonged TeV activity of Mrk 501 in 1997, favors a change in doppler factor between the 10^{-4} pc–scale TeV emission region and the parsec-scale VLBI region, with most of the energy and momentum of an electron-positron dominated jet lost close to the base of the jet, and the resulting subsonic jets being decelerated and eventually dissipated on the parsec-scale. If, however, the seemingly constant sub-luminal jet speeds we have inferred for these objects are indeed correct, the components associated with the TeV activity may not yet have emerged – only further monitoring will answer this question.

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