VLBI and space VLBI observations of TeV gamma-ray sources

By P. G. EDWARDS[1], B. G. PINER[2] AND S. FODOR[2]

[1] ISAS, Yoshinodai 3-1-1, Sagamihara, Kanagawa 229-8510, Japan

[2] Dept. of Physics and Astronomy, Whittier College, Whittier CA 90608, USA

We have commenced a program of VLBI observations of extra-galactic TeV sources and candidates. Our main result to date is that, despite the high inferred Doppler factors from higher energy observations, the jet components in Mrk 421 and Mrk 501 display sub-luminal motions.

1. Introduction

Detectable fluxes of TeV (10^{12} ev) gamma-rays have been reported for several extragalactic sources, however at present only Mrk 421 and Mrk 501 have been independently confirmed as extragalactic sources at these 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 are undertaking VLBI and VSOP observations of these sources to determine whether these inferred doppler factors are evident in the motions of jet components.

2. Observations

A VSOP observation was made of Mrk 421 (1101+384) in November 1997 at 5 GHz. The image derived from this observation is shown in Figure 1. A study of the component motions from this data and a number of other ground-based VLBI observations was presented by Piner et al. (1999a) and in more detail by Piner et al. (1999b). The jet components in Mrk 421 display sub-luminal speeds of $\lesssim 0.3c$ ($H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$), in contrast to the report of superluminal motions in Mkn 421 by Zhang and Bååth (1990). With the benefit of hind-sight, it is apparent that the uncertainties in component positions assigned by Zhang and Bååth were too small and, by assuming larger errors, these earlier observations are quite consistent with the results of Piner et al. (1999b).

VSOP observations were made of Mrk 501 (1652+398) with HALCA and the VLBA in April 1998 at 1.6 GHz Giovannini et al. (1999) and 4.8 GHz Edwards et al. (2000a). These two observations have been combined to create a spectral index map of Mkn 501 Edwards et al. (2000b). Edwards et al. (2000a) used the 4.8 GHz VSOP observation and published images to infer that two jet components were moving at apparent speeds of $\sim 0.12\,\mathrm{mas\,yr^{-1}}$, or $\sim 0.3\,c$. As the large gaps between the epochs of published images introduce uncertainties in the identifications of components at each epoch, we are now combining more recent data from the VLBA 2cm survey (Kellermann et al. 1998; see also http://www.cv.nrao.edu/2cmsurvey) and USNO Radio Reference Frame Images (Fey et al. 1996; see also http://maia.usno.navy.mil/rorf/rrfid.html) to measure the apparent motions more precisely.

Other sources for which the detection of TeV emission has been claimed include 1ES 2344+514, 1ES 1959+650 and PKS 2155−304 (see Catanese & Weekes and references therein), and we have commenced multi-epoch VLBA observations of these sources while awaiting clarification of their status as TeV sources.

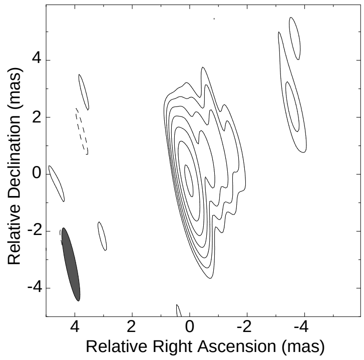

FIGURE 1. VSOP 5 GHz image of Mrk 421 from an observation with HALCA, Eb, Gb, Jb, Mc, Nt, On, Tr and Wb (adapted from Piner et al. 1999b). The beam (FWHM) is 2.6 x 0.4 mas at 12°. The lowest contour level is 3.6 mJy per beam, with each subsequent contour 2× higher. The jet components C6 (0.8 mas from the core) and C5 (1.6 mas) can be clearly seen.

3. Discussion

Despite Doppler factors of $\gtrsim$10 inferred from TeV and X-ray observations (Catanese and Weekes 1999), on the parsec-scale Mrk 421 and Mrk 501 show sub-luminal apparent motions. These speeds are much slower than those of EGRET-detected sources Piner et al. (2000). One possibility may be that the angle to the line-of-sight of these jets is very small, however the VSOP observations reveal Mkn 421 and Mkn 501 have source frame brightness temperatures of $\sim 4 \times 10^{11}$ K, and ground monitoring shows neither are remarkably variable, casting doubt on this hypothesis.

An alternative explanation is that, if most of kinetic energy at the base of an e^+e^- dominated jet is in high energy electrons, these will lose energy very efficiently to synchrotron radiation and inverse Compton scattering. As a result, most of the energy and momentum will be lost close to the base of the jet, where the X-ray and TeV emission occurs, and slow component speeds would be a natural consequence Marscher (1999).

We gratefully acknowledge the VSOP Project, which is led by ISAS in cooperation with many organizations and radio telescopes around the world. The VLBA is operated by NRAO, a facility of the NSF operated under cooperative agreement by AUI.

REFERENCES

CATANESE, M & WEEKES, T.C. 1999 *PASP* **111**, 1193.

EDWARDS, P.G., PINER, B.G., UNWIN, S.C. ET AL. 2000a in *Astrophysical Phenomena Revealed by Space VLBI* p. 235.

EDWARDS, P.G., GIOVANNINI, G. ET AL. 2000b *PASJ* in press.

FEY, A.L., CLEGG, A.W. & FOMALONT, E.B. ET AL. 1996 *ApJSupp*, **105**, 299.

GIOVANNINI, G., FERETTI, L. ET AL. 1999 in *BL Lac Phenomena: ASP Conf. Ser.* **159**, 439.

KELLERMANN, K.I., VERMEULEN, R.C., ZENSUS, J.A. AND COHEN, M.H. 1998 *AJ*, **115**, 1295.

MARSCHER, A.P. 1999 *Astropart. Phys.*, **11**, 19.

PINER, B.G., UNWIN, S.C., WEHRLE, A.E. ET AL. 1999a *NewAR* **43**, 711.

PINER, B.G., UNWIN, S.C., WEHRLE, A.E. ET AL. 1999b *ApJ* **525**, 176.

PINER, B.G. ET AL. 2000 *Blazar Demographics and Physics: ASP Conf. Series* in press.

ZHANG, F.J. & BÅÅTH, L.B. 1990 *A&A*, **236**, 47.