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THE SUBLUMINAL PARSEC-SCALE JET OF MARKARIAN 501

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ABSTRACT

We have combined very long baseline interferometry (VLBI) data from several programs in order to resolve differences in reported parsec-scale jet speeds for the TeV gamma-ray source Markarian 501. Data from the Very Long Baseline Array (VLBA) 2 cm survey, and 8 and 15 GHz data from the Radio Reference Frame Image Database, have been combined with data from a 5 GHz VLBI Space Observatory Programme observation to determine the apparent motions of jet components in this source. The combined data set consists of 12 observations between 1995 April and 1999 July. Four jet components are detected at most epochs, all of which are clearly subluminal (i.e., with apparent speeds less than the speed of light) and two of which appear stationary. The established TeV gamma-ray sources Mrk 501 and Mrk 421 thus both have subluminal parsec-scale jets, in contrast to the apparently superluminal jets of the majority of GeV sources detected by EGRET. No new VLBI component has emerged from the core following the extended TeV high state in 1997, again in contrast to the general behavior of GeV gamma-ray sources.

Subject headings: BL Lacertae objects: individual (Markarian 501) — techniques: interferometric

On-line material: machine-readable table

1. INTRODUCTION

The BL Lacertae object Markarian 501 (1652+398, J1653+3945, DA 426) has been well studied at radio wavelengths (e.g., Mufson et al. 1984; Gabuzda et al. 1992), but interest in the source was rejuvenated by the discovery of TeV gamma-ray emission (Quinn et al. 1996). A prolonged high state at TeV energies in 1997 included activity on timescales of several hours, implying that the TeV gamma rays originate in a relatively compact area (see, e.g., the review of Catanese & Weekes 1999). The detection of correlated X-ray and TeV gamma-ray variability in the other well-studied TeV source, Markarian 421, is strong evidence in favor of the X-ray emission being the high end of the synchrotron component of the spectral energy distribution (SED), with the TeV emission arising from inverse Compton scattering of photons by the synchrotron-emitting electrons, and such a model is also widely accepted for Mrk 501.

On the parsec scale, VLBI observations have revealed that a jet emerges from the core at a position angle of ~180° and bends by ~90° within the first ~2 mas. The jet extends to the east until ~20 mas from the core, when it bends further, finally reaching the position angle of ~45° seen on the kiloparsec scale (Conway & Wrobel 1995; Giovannini et al. 1999). The parsec-scale jet of Mrk 501 is one-sided, and it is assumed that this jet is relativistically Doppler-boosted, while the counterjet is Doppler-deboosted to such an extent that it is invisible at the current sensitivity of VLBI observations. The jets are believed to originate in the accretion disk surrounding a central supermassive black hole, which for Mrk 501 has been suggested to have a mass of $10^{8.93\pm0.21}\ M_\odot$ (Falomo, Kotilainen, & Treves 2002).

A number of different motions have been reported for components in the Mrk 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). These studies have relied on only a small number of epochs, typically less than four, and, in hindsight, have probably underestimated the errors in locating jet components. As illustrated by Piner et al. (1999) for Mrk 421, a reliable determination of component motions generally requires larger, multiepoch data sets.

Here we study the parsec-scale jet of Mrk 501 from 12 VLBI observations spanning 4.28 yr, at frequencies of 5, 8, and 15 GHz. Mrk 501 lies at a redshift of 0.034 (Wills & Wills 1974) that, for the value of $H_0 = 65$ km s^{-1} Mpc^{-1} adopted throughout his paper, corresponds to a distance of 155 Mpc. At this distance, an angular separation of 1 mas corresponds to a projected linear distance of 0.72 pc.

2. VLBI OBSERVATIONS

We have compiled data from three programs for this study: the Very Long Baseline Array (VLBA) 2 cm survey (Kellermann et al. 1998),[1] the Radio Reference Frame Image Database (RRFID; Fey & Charlot 1997),[2] and a single VLBI Space Observatory Programme (VSOP; Hirabayashi et al. 1998, 2000) observation. The data used in this study are summarized in Table 1.

The VLBA 2 cm survey is being undertaken at multiple epochs to study the properties and evolution of over 100 active galactic nuclei. The Mrk 501 observations consisted of eight scans at 1 hr intervals of typically 5 minutes duration. Data were recorded with a bandwidth of 64 MHz using 1 bit samples and left-circular polarization. An image derived from the 1997 March data used in this Letter was published by Kellermann et al. (1998). The full 10 station array was used at all epochs except the last, for which the St. Croix telescope was unavailable.

The RRFID of the US Naval Observatory is a program to regularly image the radio sources used for precise astrometry. The VLBA was used at all epochs, although the 1995 October observation was made without the Mauna Kea and North Liberty telescopes. The 1998 June observation was made with the

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[1] See also http://www.cv.nrao.edu/2cmsurvey.

[2] See also http://rorf.usno.navy.mil/rrfid.shtml.

TABLE 1
Observations of Mrk 501

Date	Frequency (GHz)	Synthesized Beam FWHM of Major Axis (mas)	 FWHM of Minor Axis (mas)	 P.A. of Major Axis (deg)	Image rms Noise (μJy beam^{-1})	Program
1995 Apr 8	15	0.96	0.52	−5.2	390	2 cm survey
1995 Apr 12	8	1.33	1.26	18.4	675	RRFID
1995 Oct 17	15	1.24	0.59	−1.6	1195	RRFID
1995 Dec 15	15	0.96	0.54	−7.1	320	2 cm survey
1996 Apr 23	15	0.85	0.66	2.2	565	RRFID
1996 Apr 24	8	1.89	1.22	19.9	445	RRFID
1996 Jul 10	15	0.96	0.53	−1.4	275	2 cm survey
1997 Mar 13	15	0.95	0.54	−8.8	205	2 cm survey
1998 Apr 7	5	0.58	0.23	21.9	570	VSOP
1998 Jun 24	8	0.94	0.76	−19.7	515	RRFID
1998 Oct 30	15	0.90	0.53	2.9	300	2 cm survey
1999 Jul 19	15	1.26	0.61	−8.7	290	2 cm survey

addition of the Fairbanks 26 m (Alaska), Green Bank 20 m (West Virginia), Kokee Park 20 m (Hawaii), Medicina 32 m (Italy), Ny Alesund 20 m (Norway), Onsala 20 m (Sweden), and Westford 18 m (Massachusetts) telescopes. Typically, four scans of ∼3 minutes were made, with bandwidths of 16 MHz for the first two epochs, 32 MHz for the 8 GHz observations of the last two epochs, and 64 MHz for the 15 GHz observation in 1996 April. Right-circular polarization is recorded for all RRFID observations. An image from the 1995 April 12 epoch at 8.4 GHz was published by Fey & Charlot (1997).

The 5 GHz VSOP observation, in 1998 April, was made over a 13 hr period with the *HALCA* satellite, the VLBA, and the Effelsberg 100 m (Germany) telescope. Interferometric fringes to the satellite were detected from tracking passes totaling 7 hr. In the standard VSOP observing mode, 32 MHz of the 2 bit–sampled, left-circular polarization data is recorded. Although made at the lowest frequency considered here, the long baselines to the orbiting telescope result in the synthesized beam size for this observation being the smallest of these data. The VSOP data considered here were combined with a 1.6 GHz VSOP observation 1 day later to derive a spectral index map of the source (Edwards et al. 2000a).

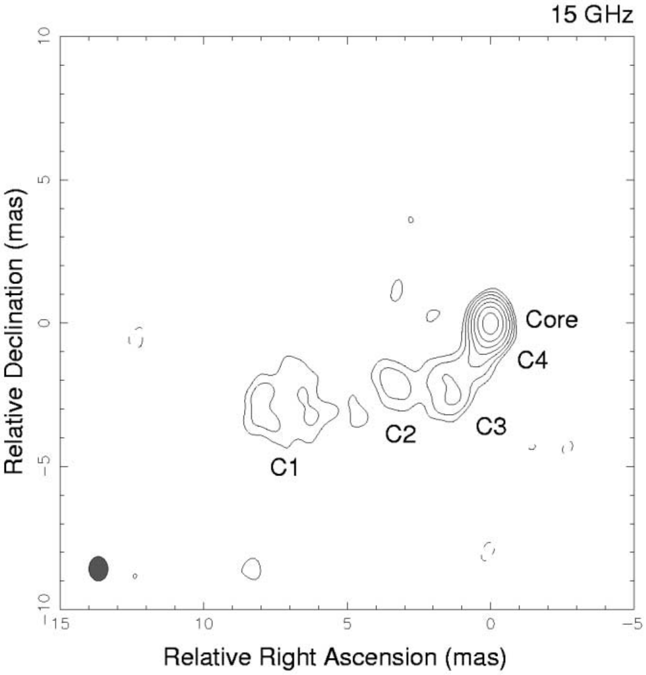

Fig. 1.—Image of Mrk 501 at 15 GHz from the RRFID observation in 1996 April. The positions of the core and jet components are indicated (see Table 2 for details). The beam, 0.85 × 0.66 mas (FWHM) at a position angle of 2°, is shown at the bottom left-hand corner. The contours are −1% (*dashed*), 1%, 2%, 4%, 8%, 16%, 32%, and 64% of the map peak of 485 mJy beam^{-1}.

3. ANALYSIS

The data were fringe-fitted in AIPS, and we have imaged all data ourselves using the DIFMAP package. Beams were calculated using natural weighting (uvweight $= 0, -1$ in DIFMAP), with the exception of the VSOP observation for which uniform weighting (uvweight $= 2, 0$ in DIFMAP) is more appropriate (Hirabayashi et al. 2000). An image from the 15 GHz RRFID observation in 1996 April is shown in Figure 1.

Model fitting of the images was carried out in DIFMAP. As an inspection of Figure 1 reveals, at most epochs four jet components were required, in addition to the core, to provide a good representation of the data. We have labeled these C1–C4, with C1 being the component farthest from the core. Circular Gaussian components were fitted at all epochs. Full details of the model fits are given in Table 2. Reduced χ^2-values for the fits are not given in the table since they are dependent on the way the data from the different programs were reduced. Thus, while model fits represent a minimum in χ^2 for the given number of components, the comparison of χ^2-values between data from different programs is potentially misleading (see also Piner et al. 1999).

The positions of all model-fitted jet components are plotted as a function of time in Figure 2. In order to determine the uncertainty in the component location for the purposes of de-

TABLE 2
Gaussian Model Fits to Source Components

Epoch	Frequency (GHz)	Component ID	S^{a} (mJy)	r^{b} (mas)	P.A.^{b} (deg)	a^{c} (mas)
1995 Apr 8	15	Core	489	…	…	0.17
		C4	114	0.75	172.1	0.63
		C3	84	2.32	147.7	1.25
		C2	57	4.01	133.1	1.95
		C1	62	7.45	113.0	2.58

Note.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

[a] Flux density.

[b] Polar coordinates of the center of the Gaussian relative to the core. The position angle is measured from north through east.

[c] FWHM of the Gaussian.

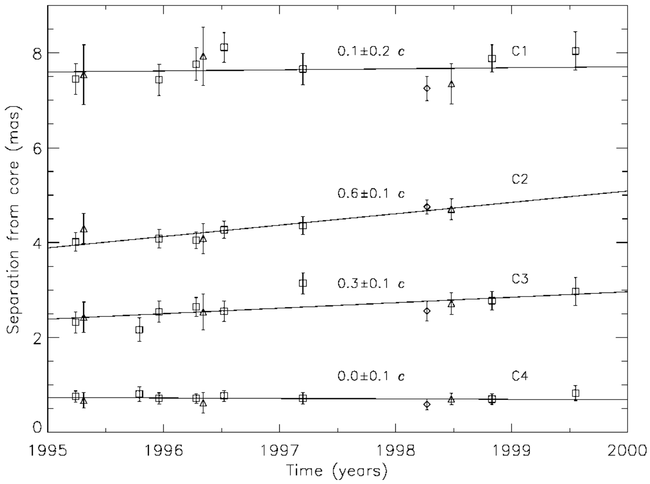

FIG. 2.—Component positions and weighted linear fits to component motions. The squares denote 15 GHz observations, the triangles denote 8 GHz observations, and the diamonds are used for the 5 GHz VSOP observation. Note that the two observations in 1996 April have been offset from each other in the plot for clarity.

termining component motions, we have projected the beam major axis onto the line joining the component and core and then taken a fraction of this projected length as the error in position. For the extended, outermost component, C1, we conservatively adopted half a projected beamwidth for the uncertainty. For C2 and C3, we used one-quarter of the projected beamwidth, and for the innermost component, C4, we used one-eighth of the beamwidth. Motions were determined by weighted linear fits to the data. As shown in Figure 2, both C1 and C4 show little evidence of motion over the 4.28 yr period. Both C2 and C3 show clear evidence of motion, with an apparent component speed for C2 of $(0.6 \pm 0.1)c$ and for C3 of $(0.3 \pm 0.1)c$. The apparent speeds along the jet, as opposed to radial separations, are, within errors, the same. These speeds supersede the preliminary values reported in Piner et al. (2002).

4. DISCUSSION

Our component locations agree well with those reported from a contemporaneous 5 GHz observation made in 1996 June as part of the VLBA Prelaunch Survey (Fomalont et al. 2000). We can also extrapolate our derived motions and compare them with model fits to the 5 GHz observations at epochs 1987.4 (Gabuzda et al. 1992) and 1989.3 (Gabuzda et al. 1994). The extrapolated motion of C3 is consistent with the positions of the K2 of Gabuzda et al. (1992, 1994), assuming uncertainties ~3 times larger than the ±0.1 mas adopted by these workers. The K1 of Gabuzda et al. (1992, 1994), with similarly increased uncertainties, is consistent with the extrapolated motion of C2, particularly if the speed of C2 lies at the lower end of the range determined in § 3 (assuming a constant motion). These identifications were qualitatively suggested by Edwards et al. (2000b) but are quantitatively borne out by the fuller analysis presented here.

The speeds of C1 and C4 are formally consistent with zero; i.e., they appear to be stationary components. Before considering this further, we reconcile this result for C4 with the observations of Marscher (1999), who reported the detection at 22 GHz of a resolved component between 0.5 and 1 mas from the core, with an apparent motion derived from three epochs between 1997 April and August of 0.96 ± 0.1 mas yr^{-1}, corresponding to $(2.3 \pm 0.2)c$. This location is consistent with our C4; however, we do not see such rapid motion over the 4 yr period. The motion reported by Marscher (1999) corresponds to 0.27 mas in the 0.29 yr the observations spanned. In our data, C4 ranges between 0.59 mas from the core (1998 April 7) and 0.83 mas from the core (1999 July 19), a range of 0.21 mas, similar in magnitude to that of Marscher (1999). Any attempt at further interpretation is complicated by the fact that there are likely to be frequency-dependent offsets in the separation of components from the core (see, e.g., Lobanov 1998) in our data, which would be most important for C4.

Stationary components have been reported for a number of sources in the past, with a detailed study being made as part of the multiepoch monitoring program of Jorstad et al. (2001b). The monitoring revealed that the superluminal speeds detected for these of EGRET-detected blazars were much faster than for the general population of bright compact radio sources; however, evidence was also found for at least one stationary component in 27 of the 42 sources (Jorstad et al. 2001b). Jorstad et al. suggested that the stationary components within several parsecs of the core were associated with standing recollimation shocks caused by pressure imbalances at the boundary between the jet and the surrounding medium. In contrast, the stationary components farther from the core tended to be associated with bends in the parsec-scale jet. There is support for this scenario in our data. C4 is located at a projected distance of ~0.5 pc from the core and is quite plausibly associated with a recollimation shock. C1, on the other hand, is an extended component, which 1.6 GHz VLBI imaging has revealed is associated with a significant change in the jet from a bright "spine" to a limb-brightened morphology (Giovannini et al. 1999).

If we assume that our fastest observed pattern speed (0.6*c* for C2) reflects the bulk apparent speed of the jet, then we can solve for the intrinsic speed and angle to the line of sight, provided we also have an estimate of the Doppler-beaming factor. A Doppler factor $\delta \sim 10$ is inferred from the TeV observations of this source (e.g., Tavecchio, Maraschi, & Ghisellini 1998). The VSOP observations yield our best measurement of the radio-core brightness temperature, 4×10^{11} K. This is consistent with a Doppler factor of ~10 if the source is in equipartition (Readhead 1994), but it is also consistent with lower Doppler factors if equipartition is violated (Kellermann 2002). If we accept the values of 0.6*c* and 10 for the apparent bulk speed and Doppler factor, respectively, then the Lorentz factor of the Mrk 501 jet is $\gamma = 5$ ($v = 0.98c$), and its angle to the line of sight is $\theta = 0\overset{\circ}{.}7$. Such a small angle to the line of sight may be expected of a gamma-ray blazar, although subluminal apparent speeds are in general not expected (see the Monte Carlo simulations of Lister 1999).

Alternative kinematics that do not place such tight constraints on the angle to the line of sight assign the Doppler-factor measurement to the TeV-emitting region (on the light-day size scale) and the apparent bulk speed to the VLBI jet (on the light-year size scale) and allow a change in the bulk Lorentz factor or angle to the line of sight in the intermediate region. If the jet in the TeV-emitting region has, e.g., $\theta = 5°$ and $\gamma = 7$ (enforcing $\delta = 10$), then a decrease in the Lorentz factor to $\gamma = 2$ would reproduce the observed apparent speed in the VLBI jet. Such a deceleration of electron-positron jets close to the core is proposed by Marscher (1999) for the TeV blazars. A change in angle to the line of sight, perhaps accompanying the large bend in the jet seen ~2 mas from the core, cannot by itself reproduce the observed values; a jet with $\delta = 10$ has a minimum Lorentz factor of 5, and a jet with $\gamma = 5$ can only have an apparent speed of 0.6*c* in the large-angle solution for $\theta > 90°$. Any set of kinematic parameters must also be constrained by the one-sided appearance of the source; the example above with $\theta = 5°$ and $\gamma = 2$ would have a jet-to-counterjet brightness ratio greater than ∼200, somewhat higher than the limit that can be placed from our observations.

Similar values for the Doppler factor and apparent jet speed apply to the other well-studied TeV blazar, Mrk 421 (Piner et al. 1999). From these two sources, it appears that TeV blazars as a class may either have very small angles to the line of sight ($\theta < 1°$) or may decelerate significantly between the TeV-emitting region and the parsec scale.

It is notable that no new component has emerged from the core after the prolonged TeV high state in 1997. A component with a speed similar to that of C2 or C3 would now be ∼0.5 mas from the core and would have been detected at the latter epochs. This suggests that events that give rise to extended TeV (and associated X-ray) activity are different in nature to those that result in the production of new VLBI components (see also Marscher 1999). Mrk 421 and Mrk 501, for which the inverse Compton component of the SED peaks at TeV energies, have subluminal component speeds and apparently no new component emerging after epochs of TeV activity. In contrast, sources with the inverse Compton component of the SED peaking at GeV energies tend to have the emergence of new, superluminal, VLBI components associated with GeV flaring states (Jorstad et al. 2001a). The detection of more TeV gamma-ray sources by the next generation of air Cerenkov telescopes will enable these apparent trends to be investigated more quantitatively.

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REFERENCES

Catanese, M., & Weekes, T. C. 1999, PASP, 111, 1193

Conway, J. E., & Wrobel, J. M. 1995, ApJ, 439, 98

Edwards, P. G., Giovannini, G., Cotton, W. D., Feretti, L., Fujisawa, K., Hirabayashi, H., Lara, L., & Venturi, T. 2000a, PASJ, 52, 1015

Edwards, P. G., Piner, B. G., Unwin, S. C., Wehrle, A. E., Murphy, D. W., Hirabayashi, H., & Fujisawa, K. 2000b, in Astrophysical Phenomena Revealed by Space VLBI, ed. H. Hirabayashi, P. G. Edwards, & D. W. Murphy (Sagamihara: ISAS), 235

Falomo, R., Kotilainen, J. K., & Treves, A. 2002, ApJ, 569, L35

Fey, A. L., & Charlot, P. 1997, ApJS, 111, 95

Fomalont, E. B., Frey, S., Paragi, Z., Gurvits, L. I., Scott, W. K., Taylor, A. R., Edwards, P. G., & Hirabayashi, H. 2000, ApJS, 131, 95

Gabuzda, D. C., Cawthorne, T., Roberts, D. H., & Wardle, J. F. C. 1992, ApJ, 388, 40

Gabuzda, D. C., Mullan, C., Cawthorne, T. V., Wardle, J. F. C., & Roberts, D. H. 1994, ApJ, 435, 140

Giovannini, G., Feretti, L., Venturi, T., Cotton, W. D., & Lara, L. 1999, in ASP Conf. Ser. 159, BL Lac Phenomena, ed. L. O. Takalo & A. Sillanpää (San Francisco: ASP), 439

Hirabayashi, H., et al. 1998, Science, 281, 1825 (erratum 282, 1995)

Hirabayashi, H., et al. 2000, PASJ, 52, 955

Jorstad, S. G., Marscher, A. P., Mattox, J. R., Aller, M. F., Aller, H. D., Wehrle, A. E., & Bloom, S. D. 2001a, ApJ, 556, 738

Jorstad, S. G., Marscher, A. P., Mattox, J. R., Wehrle, A. E., Bloom, S. D., & Yurchenko, A. V. 2001b, ApJS, 134, 181

Kellermann, K. I. 2002, Publ. Astron. Soc. Australia, 19, 77

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

Lister, M. L. 1999, Ph.D. thesis, Boston Univ.

Lobanov, A. P. 1998, A&A, 330, 79

Marscher, A. P. 1999, Astropart. Phys., 11, 19

Mufson, S. L., et al. 1984, ApJ, 285, 571

Piner, B. G., Edwards, P. G., Fodor, S., & Rector, T. A. 2002, Publ. Astron. Soc. Australia, 19, 114

Piner, B. G., Unwin, S. C., Wehrle, A. E., Edwards, P. G., Fey, A. L., & Kingham, K. A. 1999, ApJ, 525, 176

Quinn, J., et al. 1996, ApJ, 456, L83

Readhead, A. C. S. 1994, ApJ, 426, 51

Tavecchio, F., Maraschi, L., & Ghisellini, G. 1998, ApJ, 509, 608

Wills, D., & Wills, B. J. 1974, ApJ, 190, 271