DO THE MILDLY SUPERLUMINAL VLBI KNOTS EXCLUDE ULTRARELATIVISTIC BLAZAR JETS?

Gopal-Krishna,1 Samir Dhurde,2 and Paul J. Wiita3

Received 2004 July 16; accepted 2004 October 4; published 2004 October 13

ABSTRACT

We compute the effective values of apparent transverse velocity and flux boosting factors for the VLBI radio knots of blazars by integrating over the angular distributions of these quantities across the widths of jets with finite opening angles but constant velocities. For high bulk Lorentz factors ($\Gamma > 10$), variations across the jet can be quite large if the opening angle, $\omega$, is even a few degrees on subparsec scales. The resulting apparent speeds are often much lower than those obtained from the usual analyses that ignore the finite jet opening angles. We can thus reconcile the usually observed subluminal or mildly superluminal speeds with the very high ($\approx 20$) $\Gamma$ factors, required by the inverse Compton origin and rapid variability of TeV fluxes, as well as by intraday radio variability. Thus it is possible to associate the VLBI radio knots directly with shocks in the ultrarelativistic main jet flow, without invoking very rapid jet deceleration on parsec scales or extremely unlikely viewing angles.

Subject headings: BL Lacertae objects: general — galaxies: active — galaxies: jets — galaxies: nuclei — quasars: general — radio continuum: galaxies

1. INTRODUCTION

In order to avoid excessive photon-photon collisions, the highly variable TeV emission from blazars has been interpreted in terms of inverse Compton radiation emerging from ultrarelativistic jets with bulk Lorentz factors, $\Gamma \sim 15–100$ (e.g., Krawczynski et al. 2002; Piner & Edwards 2004; Ghisellini et al. 2004). Earlier, very high values of $\Gamma \sim 100$ were inferred from the intraday radio variability (IDV), which is a common feature of blazars (Wagner & Witzel 1995; Kraus et al. 2003). It now appears that the bulk of this IDV may arise from interstellar scintillations (e.g., Kedziora-Chudczer et al. 2001; Bignall et al. 2003). Nonetheless, the required microarcsecond angular sizes of the scintillating components would still need $\Gamma > 30$, and probably substantially larger, in order to reconcile apparent brightness temperatures, $T_B \sim 10^{13}–10^{14}$ K (Blandford 2001; Rickett et al. 2002) with the canonical limit of $T_B < 10^{12}$ K needed to avoid the inverse Compton catastrophe (e.g., Kellermann & Pauliny-Toth 1969). Direct evidence for high values of $T_B$ comes from the VLBI Space Observatory Program survey (Horiuchi et al. 2004). Standard models for gamma-ray bursts also invoke bulk ultrarelativistic jet flows with $\Gamma \sim 100–1000$ (e.g., Sari et al. 1999; Meszáros 2002).

In contrast, the only direct probe of extragalactic jet motion, namely, the radio knots detected by VLBI, reveal typical proper motions corresponding to apparent speeds, $v_{app} \equiv c \theta_{app}$, of $5c–10c$ or less (Jorstad et al. 2001; Cohen et al. 2003; Giovannini 2003). Recent measurements have shown that roughly one-third to one-half of the VLBI components measured in TeV blazars are found to be subluminal or even essentially stationary (Piner & Edwards 2004; Giroletti et al. 2004). As emphasized by Piner & Edwards (2004), the apparent lack of relativistically moving shocks that are assumed to be responsible for the high-energy flaring activity, and are convincingly seen in most EGRET blazars (Kellermann et al. 2004), is intriguing.

One possible explanation for the slow VLBI components of the TeV blazars would be a dramatic deceleration of the jet between subparsec and parsec scales (e.g., Georganopoulos & Kazanas 2003); but then the problem becomes understanding how such a deceleration is avoided in the case of EGRET blazars for which distinctly higher apparent speeds are measured (Piner & Edwards 2004; Kellermann et al. 2004). Essentially perfect alignment (to within $1^\circ$) of the TeV blazar jets in our direction is another possible way out; however, given their substantial number, angles of a few degrees are much more likely (Piner & Edwards 2004). Other attempts to explain the relatively slow apparent motions of the knots involve postulating a spine and sheath geometry for the jets, as was proposed for FR I type sources (e.g., Sol et al. 1989), such that the radio knots are frequently associated with the slower moving outer layer (Komissarov 1990; Laing et al. 1999; Chiaberge et al. 2000; Ghisellini et al. 2004). Some support for this picture comes from the limb-brightening marginally observed in a few parsec-scale jets (e.g., Giovannini 2003; Giroletti et al. 2004).

Here we argue that the observed mildly superluminal, or even subluminal, speeds of the parsec-scale VLBI knots do not necessarily demand that the knots be associated exclusively with an outer sheath; the knots may well be formed by shocks occurring in the energetic ultrarelativistic flow of the spine. Nor is any overall slowing, or an extraordinarily close alignment, required to account for the observed substantial fraction of slow VLBI knots. Since the jets on the parsec scale are likely to be a few degrees wide, if they are pointed close to our direction and have a high bulk Lorentz factor, one expects very large variations of the apparent velocity and Doppler boosting across the face of the jet or blob. The calculations that we present here show that when the distribution of apparent velocity across the jet cross section is weighted by the corresponding Doppler boosting factor distribution, as is appropriate when the jet cannot be transversely resolved, there can be a marked overall reduction in the resulting apparent velocity, compared to the usually assumed case in which both the Doppler boosting factor and the apparent velocity are taken to be constant across the jet. Therefore, the Lorentz factors, $\Gamma \geq \beta_{app}$, usually inferred from the VLBI motion data often may be gross underestimates of the actual bulk (or pattern) Lorentz factors.
2. THE MODEL

We now compute the boosting-weighted apparent velocity $v_{\text{app},w}$ and observed flux density $S_{\nu,w}$. The standard Doppler boosting factor for a jet is $\delta = |\Gamma(1 - \beta \cos \theta)|^{-1}$, where $\beta \equiv v/c$, $\theta$ is the angle between the jet’s axis and the observer’s line of sight, and $\Gamma \equiv (1 - \beta^2)^{-1/2}$ (e.g., Scheuer & Readhead 1979). The observed flux, $S_{\nu,w}$, is related to the emitted flux, $S_{\nu,e}$ via $S_{\nu,e} = \delta^{-\alpha}\times S_{\nu,w}$, where $n = 2$ for a continuous jet but $n = 3$ for a discrete “plasmoid” or shocked emitting region (as the VLBI components are usually treated), and $\alpha$ is the spectral index, defined by $S \propto \nu^{-\alpha}$. For simplicity, we assume $\alpha = 0$ for the VLBI knots and ignore the cosmological effects implemented through factors of $(1 + z)$. We further ignore any possible distinction between a bulk velocity and a pattern speed; none of these simplifications affects our qualitative argument.

The apparent transverse velocity of a knot in the jet is

$$v_{\text{app}} = \frac{v \sin \theta}{1 - \beta \cos \theta},$$

and the maximum value of $v_{\text{app}} = \Gamma c$ when $\theta = 1/\Gamma$. Since the typical values of $v_{\text{app}}$ are under $10c$, the usual statistical studies of VLBI component velocities seem to imply that the dominant bulk (or pattern) Lorentz factors are also less than $10$ (e.g., Vermeulen & Cohen 1994; Kellermann et al. 2004).

But if the jet has a finite opening angle, $\omega$, corresponding to a solid angle, $\Omega$, as opposed to an infinitesimal opening angle, then each small element of the jet cross section is boosted by a different amount because of having a different misalignment from the line of sight, even if all elements have exactly the same bulk velocity, as we assume here. Hence, we must integrate over the solid angle of the jet to obtain the boosting-weighted values of the key observed quantities. The weighted flux is

$$S_{\nu,w} = \int_{\Omega} \delta^\prime(\Omega') S_{\nu}(\Omega')\ d\Omega' \equiv A(\theta) S_{\nu},$$

where we have suppressed the subscript $\nu$ and, in the second equality, explicitly taken $S_{\nu}$ to be independent of $\Omega'$ and defined the mean amplification factor, $A(\theta)$.

We then perform an integration of the (boosted) flux–weighted apparent velocity over the jet cross section to obtain the weighted observed value of the apparent velocity of the jet,

$$\beta_{\text{app},w} = \frac{1}{S_{\nu,w}} \int_{\Omega} \beta(\Omega') \delta^\prime(\Omega') S_{\nu} \ d\Omega'.$$

Note that the resultant vector is along the line joining the directions of the blazar nucleus and the center of the jet’s cross section. In Figure 1 we show the dependence of $\beta_{\text{app},w}$ on $\theta$ for $\Gamma = 10, 50,$ and $100$, taking $n = 3$.

For any combination of $\Gamma, \omega, \text{ and } n$ we can now compute the probability distribution of $\beta_{\text{app},w}$. For this an integration needs to be done over strips of solid angle represented by concentric annuli with radii $\theta$ around the source direction. There will be an unique value of $\beta_{\text{app},w}$ for each such annulus, which is given by the magnitude of equation (3). This value will be weighted by the number of sources for that annulus that would be visible in a flux-limited sample. This number, or when normalized, this probability, $p(\theta; \Gamma, \omega, n)$, will be proportional to both the solid angle of the annulus and the enhancement of the source counts due to Doppler boosting, $A$, averaged over the jet’s cross section, when the latter is centered on that annulus. We ignore any contribution from a counterjet, which should be extremely deboosted. The enhanced surface density of these core-dominated sources, which are detected in high-frequency (centimeter-wavelengths) flux-limited surveys, is proportional to $\Lambda^q$, where $q$ is the exponent in the integrated counts of radio sources (e.g., Cohen 1989). $N(S, dS) \propto S^{-q} dS'$; we take $q = 3/2$, which is strictly applicable for Euclidean space but is a good approximation for these core-dominated radio source samples (e.g., Fomalont et al. 1991). The number of sources seen in a flux-limited sample for a particular misalignment angle $\theta$ will thus be related to the solid angle subtended by that annulus, multiplied by $\Lambda^q$. We find the probability to be

$$p(\theta)d\theta \propto \sin \theta \Lambda^q(\theta)d\theta.$$

Fig. 1.—Top panels: Distributions of $\beta_{\text{app},w}$ against $\theta$ for $\Gamma = 10$ (left), 50 (center), and 100 (right). Results for jet opening angles, $\omega = 0^\circ, 1^\circ, 5^\circ,$ and $10^\circ$, are shown. Bottom panels: Cumulative probability for $\beta_{\text{app},w} > \beta$ for the same values of $\Gamma$ and $\omega$. In the left panels the results for $\omega = 0^\circ$ and $1^\circ$ are indistinguishable, so only the latter are labeled.
Equation (4) can also be used to provide the distribution of $\beta_{app}$ since there is a unique value of it for every $\theta$.

Our key result is shown in Figure 1, where the probability of observing any $\beta_{app}$ greater than a given value is shown; this is obtained by integrating equation (4) and subtracting the normalized cumulative probability distribution function from unity. Distributions for the canonical case of a narrow cylindrical jet, $\omega = 0$, are plotted for comparison.

The results for $n = 2$, which are applicable to the continuous jet case, are quite similar: the locations of the peaks in the $\beta_{app}$ curves are hardly shifted, but the maximum values at those peaks are somewhat lower because of the weaker boosting. The cumulative probabilities decline slightly less rapidly than those plotted in Figure 1 for low $\beta$ but more rapidly at high $\beta$ (because of the lower peak values), thus yielding fewer very low values of $\beta_{app}$ for given $\Gamma$ and $\omega$.

3. DISCUSSION AND CONCLUSIONS

We have presented computations indicating that a significant reduction in the apparent motion can be expected for VLBI radio knots associated with an ultrarelativistic jet by taking into account the jet’s opening angle. On the parsec scale that could be identified with the collimation regime, the jets are likely to be at least several degrees wide; they may be substantially wider, as indicated for the best resolved case of M87 (Junor et al. 1999).

For this situation, we find that the apparent transverse velocity peaks at lower values, and these peaks can occur at significantly greater angles to the line of sight than they do for the usually assumed case of an infinitesimally small jet opening angle on parsec scales (Fig. 1). These trends become stronger for high $\Gamma$, for then $v_{app,max}$ is sharply peaked around some $\theta > 1/\Gamma$. A reversal of the sign of contributions to $v_{app,max}$ arising from some parts of the jet’s cross section occurs if $\theta < \omega/2$.

The resulting cancellation, which is further enhanced because of the sharply declining Doppler boost with $\theta$, can often lead to a fairly drastic reduction in the apparent velocity of the knots, as compared to the canonical peak value of $\beta_{max} = \Gamma$ (Fig. 1).

In the core-dominated samples that are characteristic of BL Lac objects, the usual expectation, based on $\omega = 0$ jets, is to find sources with $v_{app}$ widely distributed up to $\Gamma$, but with the distribution actually skewed toward the higher part of that range (as shown in Fig. 1; see also Vermeulen & Cohen 1994). Thus, when the $v_{app}$ measured for VLBI knots are frequently less than 10c, one of the following conclusions discussed in § 1 is usually drawn: bulk $\Gamma$-values are modest; pattern velocities due to shock motions are slower than the jet flow; the VLBI knots are associated with a slower sheath of the jet; or the angle to the line of sight is extremely small. While all of these are possible, here we have shown that none is necessary; rather, if the jet has a modest full opening angle ($\omega$) on the scales probed by VLBI, then there is a very large reduction in the probability of measuring apparent velocities motions approaching $\Gamma c$. For instance, even for the extreme case of $\Gamma = 100$ and a modest jet opening angle, $\omega = 5^\circ$, over 73% of the radio components would be detected with $v_{app} < 10c$, while for $\omega = 10^\circ$, over 87% would fall into this category. Over 41% (for $\omega = 5^\circ$) and over 69% (for $\omega = 10^\circ$) would actually be seen as subluminal sources. Similarly, for $\Gamma = 50$ and $\omega = 5^\circ$, over 64% of the sources would be detected with $v_{app} < 10c$, the median value is $\beta_{app} = 6$, and still some 15% would appear as subluminal sources.

Therefore, the predominance of marginally superluminal or even subluminal VLBI knots among TeV blazars does not imply that these radio knots cannot be physically associated with their ultrarelativistic jets. Instead, a combination of high $\Gamma$ factors and modest jet opening angles can just as well explain the preponderance of low $v_{app}$-values. At the same time, high $\Gamma$ factor jets (greater than 15) are needed by the standard one-zone models to efficiently produce the TeV photons by inverse Compton scattering (such relatively modest values emerge from models only when dereddening of the TeV spectrum by the IR background is ignored), and higher values ($\Gamma > 40$) are usually required when the TeV spectrum is appropriately dereddened (e.g., Krawczynski et al. 2002; Ghisellini et al. 2004). Only multizone (rapidly decelerating or spine-sheath) models can give satisfactory fits to TeV blazar spectra with $\Gamma \sim 15$, even with dereddening (Georganopoulos & Kazanas 2003; Ghisellini et al. 2004).

The applicability of our interpretation is not restricted to TeV blazars. Relatively slow proper motions ($v < 3c$) are now known to occur frequently among the radio-selected samples of quasars (for instance, the 2 cm Very Long Baseline Array survey; Kellermann et al. 2004). In our picture, such slow motions would not be at variance with the values of $\Gamma > 30$, which seem to be needed to explain the scintillating radio components of IDV blazars (e.g., Blandford 2001). The values of $\theta$ for all blazars should be small but are more likely to be a few degrees rather than less than 1°, as shown by the Monte Carlo simulations of Lister & Marscher (1997) and by the detection of quiescent X-ray emission (Giebels et al. 2002), so explaining the slow apparent motions through extremely precise jet alignment is a less attractive alternative.

We recall that essentially all models for gamma-ray bursts also invoke very high $\Gamma$ factors for their jets (e.g., Mészáros 2002). If the processes that accelerate jets on these very different scales are basically similar, then this observation from gamma-ray bursts may provide further support for the high $\Gamma$ scenario in quasars and blazars (e.g., Kundt & Gopal-Krishna 2004).

Although our picture explains the preponderance of slow velocities, there is always a tail to the computed $v_{app}$ distribution that extends up to a substantial fraction of $\Gamma c$. While the highest well-measured values of $v_{app}$ do reach up to 35–40c (Cohen et al. 2003; Kellermann et al. 2004), there is a strong possibility of bias against picking out VLBI components showing anomalously high apparent velocities. The difficulty in tracking such fast-moving knots in the usually sparsely temporally sampled databases is compounded by their expected rapid fading.

Upper limits on $\omega$ for powerful blazars can be set, since the total jet power, $L_j$, is related to the inferred bolometric luminosity $L_{bol}$ via $L_j = (L_{bol}/\Omega) (4\pi) = L_{bol} \omega^2 \epsilon^2$, with $\epsilon$ the efficiency of converting jet power into radiation. Since $\epsilon < 0.1$ is expected and $L_j$ should not exceed the Eddington limit, we have $\omega < 0.37[(e/0.1)(M_{bol} / 10^9 M_\odot) / (L_{bol} / 10^{44} \text{ ergs s}^{-1})]^{1/2}$; here $\omega$ is in radians and we have scaled $L_{bol}$ to the supermassive black hole mass, $M_{bol}$, by typical values. Unless $\epsilon < 0.01$, $\omega > 5^\circ$ should be allowed for even very powerful blazars.

It is interesting to examine our picture in the context of the “spine+sheath” model of the jet, e.g., as proposed by Chaberge et al. (2000) to bring the data into accord with the orientation-based unification model (e.g., Gopal-Krishna 1995; Urry & Padovani 1995). By considering the nuclear emission in radio, optical, and X-ray bands from BL Lac objects and their presumed misaligned counterparts, the FR I type radio galaxies, they inferred that a mildly relativistic ($\Gamma = 1–2$) sheath component is the prime contributor to the observed
nuclear emission from FR I type radio galaxies. At the same time they showed that the spectral energy distribution of the beamed counterparts, i.e., BL Lac objects, all the way from radio to gamma rays can be modeled in terms of a relativistic spine component moving with a bulk Lorentz factor $\Gamma$. Still higher $\Gamma$-values have been estimated in several studies, particularly for TeV blazars, as mentioned above.

In this work we have only discussed the spine component and tried to address the question: can such large $\Gamma$-values be reconciled with the statistics of superluminal motion of the VLBI knots of blazars/BL Lac objects, which suggest a typical $\Gamma \sim 3$ (e.g., Piner & Edwards 2004; Kellermann et al. 2004)? We have argued that the discrepancy can be resolved by considering a modest opening angle ($\sim 5^\circ$) for the jet/spine on parsec scales. The blazar observations can then be understood without invoking a rapid jet deceleration on such small scales, or relegating the VLBI knots exclusively to a slower sheath (and thus totally decoupling them from the shocks occurring within the spine), or postulating extremely unlikely viewing angles for the jet.

The main question addressed here can be rephrased as follows: if indeed the fast spine component alone is relevant for the observed blazar emission, then how large a typical Lorentz factor can be reconciled with their VLBI data? We have argued that even when the VLBI knots are associated with shocks in the spine itself, their usually observed modest speeds ($v_{app} \sim 3–5c$) would not be inconsistent with $\Gamma > 30–50$ of the spine, provided one takes into account a $5^\circ–10^\circ$ opening angle of the spine on the parsec scale. Thus, the VLBI results can be reconciled with the TeV and IDV observations indicating such large $\Gamma$ factors ($\Gamma \sim 3$).

One prediction of this picture is that when adequate resolution and sensitivity are achieved so as to be able to transversely resolve the fastest moving VLBI scale knots, then different portions of those knots would sometimes evince different apparent velocities because variations across the jet opening angle could then be detected. If sufficient dynamic range also becomes available, such components might be seen to fragment, or, perhaps more likely, appear to be smeared out quickly.

S. D. is grateful to NCRA for a Project Studentship. P. J. W. appreciates the hospitality provided at NCRA and at Princeton University. P. J. W.’s efforts were partially supported by RPE funds at GSU.

REFERENCES

Bignall, H. E., et al. 2003, ApJ, 585, 653
Blandford, R. D. 2001, in ASP Conf. Ser. 250, Particles and Fields in Radio Galaxies, ed. R. A. Laing & K. M. Blundell (San Francisco: ASP), 487
Chiaberge, M., Celotti, A., Capetti, A., & Ghisellini, G. 2000, A&A, 358, 104
Cohen, M. H. 1989, in BL Lac Objects, ed. L. Maraschi, T. Maccacaro, & M.-H. Ulrich (Berlin: Springer), 13
Cohen, M. H., Russo, M. A., Homan, D. C., Kellermann, K. I., Lister, M. L., Vermeulen, R. C., Ros, E., & Zensus, J. A. 2003, in ASP Conf. Ser. 300, Radio Astronomy at the Fringe, ed. J. A. Zensus, M. H. Cohen, & E. Ros (San Francisco: ASP), 177
Fomalont, E. B., Windhorst, R. A., Kristian, J. A., & Kellermann, K. I. 1991, AJ, 102, 1258
Georganopoulos, M., & Kazanas, D. 2003, ApJ, 594, L27
Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2004, A&A, submitted (astro-ph/0406093)
Giebels, B., et al. 2002, ApJ, 571, 763
Giovannini, G. 2003, NewA Rev., 47, 551
Giroletti, M., et al. 2004, ApJ, 600, 127
Gopal-Krishna. 1995, Proc. Natl. Acad. Sci., 92, 11399
Horiiuchi, S., et al. 2004, ApJ, in press (astro-ph/0407069)
Jorstad, S., Marscher, A. P., Mattox, J. R., Werhle, A. E., Bloom, S. D., & Yurchenko, A. V. 2001, ApJS, 134, 181
Jorstad, S., Marscher, A. P., Mattox, J. R., Werhle, A. E., Bloom, S. D., & Yurchenko, A. V. 2001, ApJS, 134, 181
Kedziora-Chudczer, L. L., Jauncey, D. L., Wieringa, M. H., Tzioumis, A. K., & Reynolds, J. E. 2001, MNRAS, 325, 1411
Kellermann, K. I., & Pauliny-Toth, I. I. K. 1969, ApJ, 155, L71
Kellermann, K. I., et al. 2004, ApJ, 609, 539
Komissarov, S. S. 1990, Soviet Astron. Lett., 16, 284
Kraus, A., et al. 2003, A&A, 401, 161
Krawczynski, H., Coppi, P. S., & Aharonian, F. 2002, MNRAS, 336, 721
Kundt, W., & Gopal-Krishna. 2004, J. Astrophys. Astron., submitted (astro-ph/0406318)
Laing, R. A., Parma, P., de Ruiter, H. R., & Fanti, R. 1999, MNRAS, 306, 513
Lister, M. L., & Marscher, A. P. 1997, ApJ, 476, 572
Mészáros, P. 2002, ARA&A, 40, 137
Piner, B. G., & Edwards, P. G. 2004, ApJ, 600, 115
Rickett, B. J., Kedziora-Chudczer, L., & Jauncey, D. L. 2002, ApJ, 581, 103
Sari, R., Piran, T., & Halpern, J. P. 1999, ApJ, 519, L17
Scheuer, P. A. G., & Readhead, A. C. S. 1979, Nature, 277, 182
Sol, H., Pelletier, G., & Asseo, E. 1989, MNRAS, 237, 411
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Vermeulen, R. C., & Cohen, M. H. 1994, ApJ, 430, 467
Wagner, S., & Witzel, A. 1995, ARA&A, 33, 163