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Influence of the jet opening angle on the derived kinematical parameters of blazar jets having uniform and stratified bulk motion

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ABSTRACT
We present analytical modelling of conical relativistic jets, in order to evaluate the role of the jet opening angle on certain key parameters that are inferred from VLBI radio observations of blazar nuclear jets. The key parameters evaluated are the orientation angle (i.e., the viewing angle) of the jet and the apparent speed and Doppler factor of the radio knots on parsec scales. Quantitative comparisons are made of the influence of the jet opening angle on the above parameters of the radio knots, as would be estimated for two widely discussed variants of relativistic nuclear jets, namely, those having uniform bulk speed and those in which the bulk Lorentz factor of the flow decreases with distance from the jet axis (a 'spine–sheath' flow). Our analysis shows that for both types of jet velocity distributions the expectation value of the jet orientation angle at first falls dramatically with increases in the (central) jet Lorentz factor, but it levels off at a fraction of the opening angle for extremely relativistic jets. We also find that the effective values of the apparent speeds and Doppler factors of the knots always decline substantially with increasing jet opening angle, but that this effect is strongest for ultra-relativistic jets with uniform bulk speed. We suggest that the paucity of highly superluminal parsec-scale radio components in TeV blazars can be understood if their jets are highly relativistic and, being intrinsically weaker, somewhat less well collimated, in comparison to the jets in other blazars.

Key words: blazars: general – galaxies: active – galaxies: jets – galaxies: nuclei – galaxies: radio continuum

1 INTRODUCTION

Although Very Long Baseline Interferometry (VLBI) monitoring of the radio knots in blazar jets has revealed several sources containing knots with apparent speeds v_{app} in excess of $25c$ (e.g., Kellermann et al. 2004; Piner et al. 2006), the typical speeds for blazars known to emit the highest energy γ-ray photons (TeV blazars) are found to be much more modest, with $v_{app} < 5c$, and their radio knots are often subluminal (e.g., Edwards & Piner 2002; Piner & Edwards 2004). The glaring contrast with the very large bulk Lorentz factors in the parsec-scale blazar jets ($\Gamma > 30c$), as inferred from TeV flux variations (e.g., Krawczynski, Coppi & Aharonian 2002), has been highlighted by several authors (e.g., Giroletti et al. 2004; Gopal-Krishna, Dhurde & Wiita 2004; Piner & Edwards 2004, 2005; Levinson 2006). Similar ultra-relativistic bulk Lorentz factors have also been inferred from the intraday radio variability of some blazars (e.g., Rickett, Kedziora-Chudczer & Jauncey 2002; Macquart & de Bruyn 2006) and, more directly, from VLBI measurements of the brightness temperatures of several blazar nuclei (e.g., Horiuchi et al. 2004; cf., Kovalev et al. 2005). The large mismatch between the estimates of Γ derived from these different types of observations has led some authors to postulate a dramatic jet deceleration between sub-parsec and parsec scales (e.g., Georganopoulos & Kazanas 2003; cf., Piner & Edwards 2005). An alternative approach has been to invoke a 'spine–sheath' configuration for the jets such that the fast spine close to the jet axis is surrounded by an appropriately slow moving sheath (e.g., Baan 1980; Komissarov 1990;

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Laing 1993; Meier 2003; Ghisellini, Tavecchio & Chiaberge 2005).

These considerations recently led us to undertake an analytical study which showed that the modest apparent speeds of the knots of blazars, which are mostly unresolved by VLBI, can be reconciled with the extremely relativistic bulk motion inferred for TeV, and some other, blazars as noted above, if one considers a modest full opening angle ($\omega \sim 5^\circ$–10°) for the parsec-scale jets (Gopal-Krishna, Dhurde & Wiita 2004, hereafter Paper I). We also showed that the actual viewing angles, θ, of such *conical* jets from the line-of-sight can be substantially larger than those commonly inferred (e.g. Jorstad et al. 2005) by combining the flux variability and the VLBI proper motion data (Gopal-Krishna, Wiita & Dhurde 2006, Paper II). Direct support for the assumption of *conical* parsec-scale jets comes from the VLBI imaging of the nuclear jets in the nearest two radio galaxies, M87 (Biretta, Junor & Livio 2002) and Centaurus A (Horiuchi et al. 2006).

Our focus in this paper is on making a quantitative comparison of the predictions for two widely discussed jet forms (i.e., those with uniform Γ and those with velocities decreasing away from the jet axis, the spine–sheath types), of the extents to which some key parameters of the VLBI radio knots in blazar jets would be influenced by the jet opening angle. The three main jet parameters examined are the apparent speed (β_{app}) of the knot, its Doppler factor (δ) and the viewing angle (θ) to the jet axis from our line-of-sight. Although discussed specifically for blazar jets, the present results are also relevant for γ-ray burst sources (GRBs) which too are believed to arise from extremely relativistic jets, with $\Gamma > 100$, and with even larger solid angles (e.g., Mészáros 2002; Liang et al. 2006, and references therein).

2 COMPUTATION OF THE APPARENT PARAMETERS FOR CONICAL JETS

Following the analytical prescription of Papers I & II, we approximate a radio knot with a circular disc-shaped region of uniform intrinsic synchrotron emissivity, and thus uniform surface brightness, presumably arising from a shock in the jet (e.g., Marscher & Gear 1985; Hughes, Aller & Aller 1985). See Fig. 1.

We define the angle between the axis of the jet and the line-of-sight from the stationary core of the blazar to the observer to be θ and the velocity parameter of the knot along the jet to be $\vec{\beta} \equiv \vec{v}/c$. Because we will consider jets with finite opening angles, and thus with a range of viewing angles to different portions of them, we use the more general form of the usual relations,

$$\delta = \frac{1}{\Gamma(1 - \vec{\beta} \cdot \hat{n})}, \quad (1)$$

where $\Gamma = (1 - \beta^2)^{-1/2}$ and $\hat{n}$ is the unit vector along the sight line;

$$\vec{v}_{app} = \frac{\vec{v} \times \hat{n}}{(1 - \vec{\beta} \cdot \hat{n})} \quad (2)$$

In Papers I & II we considered that each portion of the surface of the knot, denoted by the differential solid angle, $d\Omega'$, will have an angle to the observer's line of sight that can range between $\theta - \omega/2$ and $\theta + \omega/2$. Then the values of δ and v_{app} arising from each $d\Omega'$ patch vary (unlike for the commonly considered case where the jet is assumed to be a pencil beam with $\omega = 0$). Here we generalize those results by considering the possibility that the magnitude of the bulk velocity, $c\beta$, might also vary as a function of the angular distance (r) of that patch from the jet axis.

The following basic relations are used for computing the *effective* values, $\beta_{\rm eff}$ and $\delta_{\rm eff}$, for a knot, as would be determined from VLBI observations which are unable to resolve the width of the jet (i.e., knot):

$$S_{obs} = \int_{\Omega} \delta^p(\Omega') S_{em}(\Omega') d\Omega' \equiv A(\theta) S_{em}; \quad (3)$$

$$\delta_{\rm eff} = A^{\frac{1}{p}}(\theta); \quad (4)$$

$$\vec{\beta}_{\rm app,eff} = \frac{1}{S_{obs}} \int_{\Omega} \vec{\beta}(\Omega') \delta^p(\Omega') S_{em}(\Omega') d\Omega'. \quad (5)$$

Here, S_{em} and S_{obs} are the emitted and the (Doppler boosted) observed flux densities, respectively, $\Omega' = \vec{\beta} \cdot \hat{n}/\beta$ denotes the location on the knot given by the direction cosine between the local velocity and the line of sight to the nucleus (which is no longer merely $\cos\theta$), Ω is the entire solid angle subtended by the knot, $A(\theta)$ is the flux boosting factor averaged over the radio knot's cross-section, and p is defined later in this section. Although we allow for a functional dependence for S_{em} in Eqs. (3) and (5) our computations assume that S_{em} is actually independent of Ω' (i.e., a uniform intrinsic surface brightness across the knot).

In principle, several peaks in a VLBI jet could belong to a common shock/knot yet appear separate only because of their different apparent velocities (owing to their different velocity vectors within a cone). In some cases, this approach has already suggested extremely large bulk Lorentz factors (> 100, cf., Jorstad et al. 2004); however, there is usually a bias against accepting and reporting such extreme speeds. Moreover, such associations are unlikely to be the norm, since there is good evidence that individual bright VLBI knots arise from discrete ejection events in the nucleus, since their trajectories can mostly be extrapolated to begin from the core at the times of emission of discrete flares observed at millimetre wavelengths (e.g., Savolainen et al. 2002). Secondly, due to limited resolving power, the apparent motion of individual VLBI knots is commonly determined by monitoring the shift in the "centroid" position of a given knot (e.g., Cohen et al. 2007). To give expression to this practical situation, we have computed the flux weighted speed (Eq. 5). Clearly, this would no longer be required when the spatial resolution and the dynamic range of the VLBI image undergoes a substantial improvement.

The nominal viewing angle, θ, to the jet axis measures the angular offset of the circular radio disc's centre (i.e., the jet axis) from the direction of the AGN core (Fig. 1). The probability distribution of the viewing angle, $\mathcal{P}(\theta)$ (see Eq. 7 below), is used to compute the expectation value of θ for any particular combination of Γ, ω, p and q, with the last two parameters defined below.

The integration was carried out numerically by dividing the circular radio disc (i.e., the radio knot) of diameter ω and centred at θ into small pixels of angular size equal to 0.01ω. For each pixel (i, j) in the disc, its angular off-

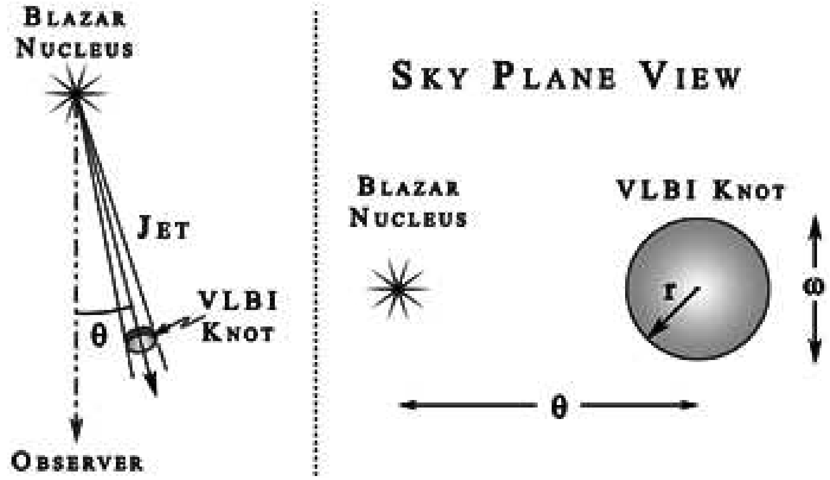

Figure 1. Cartoon of a relativistic jet of mis-alignment angle θ and full opening angle ω. A uniform radio knot in the jet appears as a disc on the plane of the sky, the centre of which marks the location of the jet's axis and therefore lies at an angular separation θ from the line-of-sight to the nucleus.

set from the AGN core was computed and combined with the jet's bulk Lorentz factor at that location (see below), in order to find: the Doppler factor $\delta_{i,j}$, the apparent velocity, the vector $\vec{\beta}_{app(i,j)}$; the flux boosting factor, $A_{i,j}$, taken to be $\delta^p_{i,j}$; and the product of the last two terms (which amounts to the apparent velocity of the pixel, weighted by its apparent flux). Finally, for each of these parameters, the average taken over all the pixels across the radio disc was evaluated and this was taken taken to be the *effective* value of that parameter (e.g., $A_{\rm eff}$) for the entire radio knot. Note that the effective value of δ for the knot is then $\delta_{\rm eff} = A^{1/p}_{\rm eff}$, where we have usually set $p = 3$, widely used for compact discrete sources (e.g., Lind & Blandford 1985) and we have assumed the knot to have a flat spectral index for simplicity; taking other values for the spectral index would make no qualitative difference to our results. We also consider the case where $p = 2$, appropriate for smooth flows. The motion of each pixel is taken to be ballistic (see, e.g., Kaiser 2006).

For the case of spine–sheath type jets, too, the (transverse) shock is assumed to cover the jet's entire cross-section with uniform intrinsic emissivity. In the absence of any specific form argued for in the literature, we adopt an exponential approximation:

$$\Gamma(r) = \Gamma_0 e^{-2rq/\omega}, \qquad (6)$$

where r is the angular separation from the centre of the radio disc/knot (i.e., from the jet axis). We evaluated results for such stratified jets, taking two representative values for q (1 and 2). The choice of the minimum Γ_0 allowed is then dictated by the constraint that the corresponding $\Gamma(r = \omega/2)$ remains above the physical limit of $\Gamma = 1$.

Note that the probability of finding a jet at a viewing angle θ, in a flux-limited sample, is given approximately by (Paper I; Cohen 1989):

$$\mathcal{P}(\theta)d\theta \propto \sin\theta \; A^{\frac{3}{2}}_{\rm eff}(\theta) \; d\theta, \qquad (7)$$

where the exponent $\frac{3}{2}$ is the typical slope of integral source counts at centimetre wavelengths (e.g., Fomalont et al. 1991) and $A_{\rm eff}$ was taken from the present computations (see above). Eq. (7) was numerically evaluated from $\theta = 0^\circ$ to 90° and then used to compute the expectation values $\langle\theta\rangle$ for different combinations of Γ_0, ω, p and q.

Results of the above numerical computations are displayed in Figs. 2–4, for both uniform Γ jets ($q = 0$) and for the stratified jets ($q = 1$ and 2). Fig. 2 shows the expectation values of θ, computed for a range of Γ, for three representative values of ω ($1^\circ, 5^\circ$ and 10°) and for $p = 2$ and $p = 3$. Figs. 3 and 4 display, for $p = 3$ and 2, respectively, the dependence of $\beta_{\rm eff}$ and $\delta_{\rm eff}$ on the jet opening angle ω, for three values of Γ_0 (20, 50 and 100). Analytical expressions for the curves fitted to the computed data points are given inside each of the panels. Note that any given point along these curves refers to the corresponding expectation value of θ for that point, as computed using the values of Γ_0, ω, p and q for that point.

3 DISCUSSION

Fig. 2 shows a steep initial decline of $\langle\theta\rangle$ with increasing Γ_0, regardless of the chosen values of ω or q. This decline continues until the regime of ultra-relativistic jets ($\Gamma_0 \gtrsim 30$) is reached, whereafter $\langle\theta\rangle$ becomes essentially independent of Γ_0. The near constancy of $\langle\theta\rangle$ for extremely relativistic jets is particularly striking for the conical jets having a uniform Γ and at least a moderate opening angle ($\omega \sim 5^\circ$–10°). Further, in this ultra-relativistic regime, the tendency for $\langle\theta\rangle$ to increase with ω is found to accelerate with the increase in the opening angle ω. Interestingly, these trends found for the uniform Γ jets are also shared by both representative forms of spine–sheath jets considered here. Quantitatively, for $\omega = 5^\circ$, ultra-relativistic jets of all the three forms (i.e., $q = 0, 1$ and 2), have $\langle\theta\rangle$ in the narrow range from 1° to 2°. The corresponding range of $\langle\theta\rangle$ for $\omega = 10^\circ$ jets is 2° to 4°, for all Γs above ~ 30. From Fig. 2, it is also evident that in a typical radio flux-limited sample of blazars, a larger opening angle of an ultra-relativistic jet would correspond to a considerably larger $\langle\theta\rangle$; hence a milder fore-shortening due to projection is typically expected (see Paper II for an

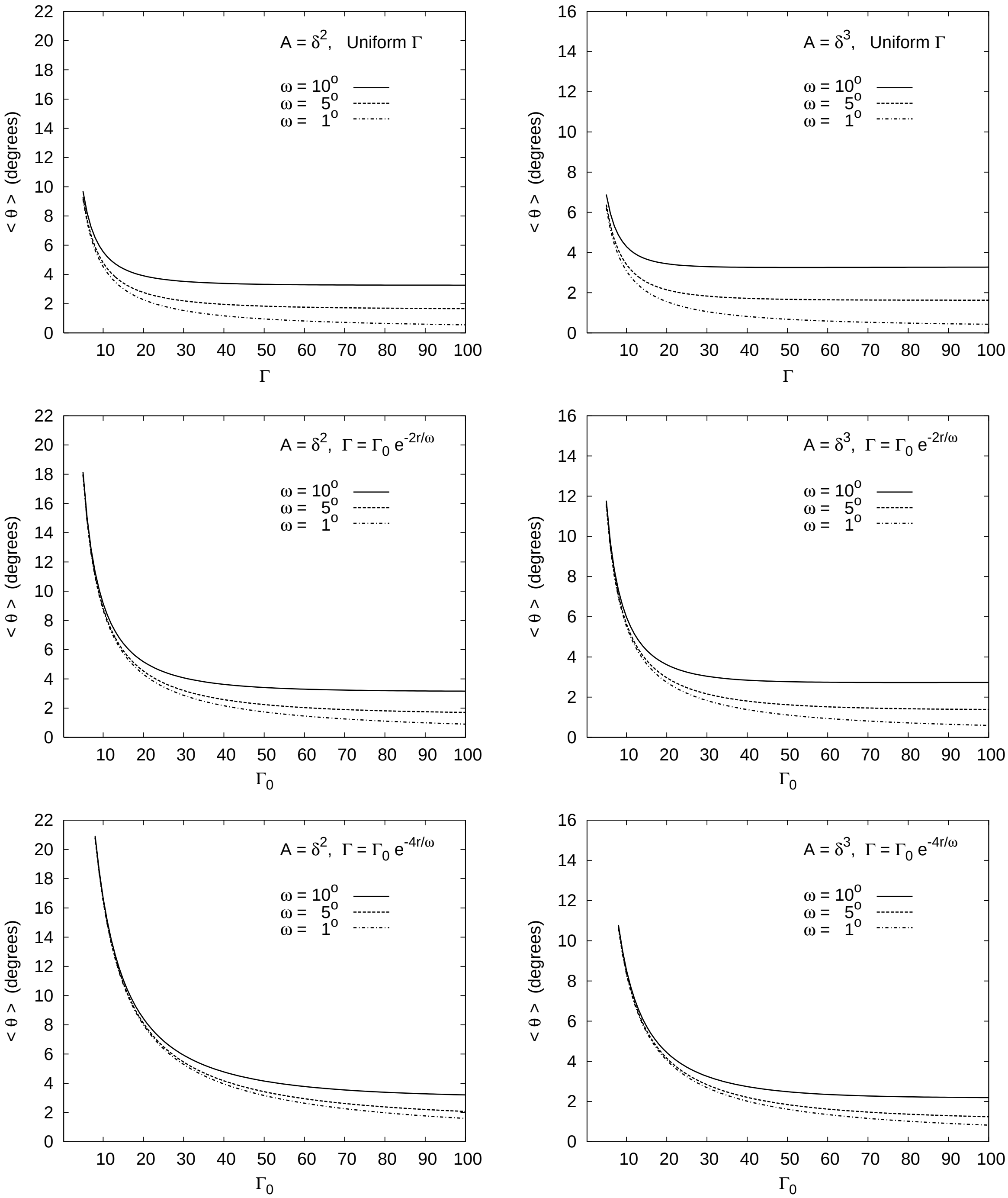

Figure 2. Expectation values of the viewing angle, $\langle\theta\rangle$, against the jet (central) Lorentz factor, Γ_0, for uniform (top) and transversely structured (middle and lower panels) jets. The left panels correspond to $p = 2$ and the right to $p = 3$. Solid, dashed and dot-dashed lines are for $\omega = 10°, 5°$, and $1°$, respectively.

expanded discussion of this last point for uniform velocity jets).

We now examine the influence of ω on the *effective* apparent speed of a radio knot, c$\beta_{\rm eff}$, and its *effective* Doppler factor, $\delta_{\rm eff}$ (Eqs. 4 & 5). These are displayed in Fig. 3 ($p = 3$) and in Fig. 4 ($p = 2$) for the computed expectation values $\langle\theta\rangle$ (which is a function of ω, Γ_0, p and δ and hence varies along each curve, as explained above). Good analytical fits to simple exponential curves were found to all the computed values of $\beta_{\rm eff}$ and they are quoted within those figures. Exponential functions also gave good fits to all but two of the 18 cases considered for $\delta_{\rm eff}$; in those cases the displayed polynomial fits were found to be substantially better.

Firstly, it is seen that the decline of $\beta_{\rm eff}$ with ω is sharper for the knots associated with jets of higher Γ (for both uniform and stratified types). On the other hand, for

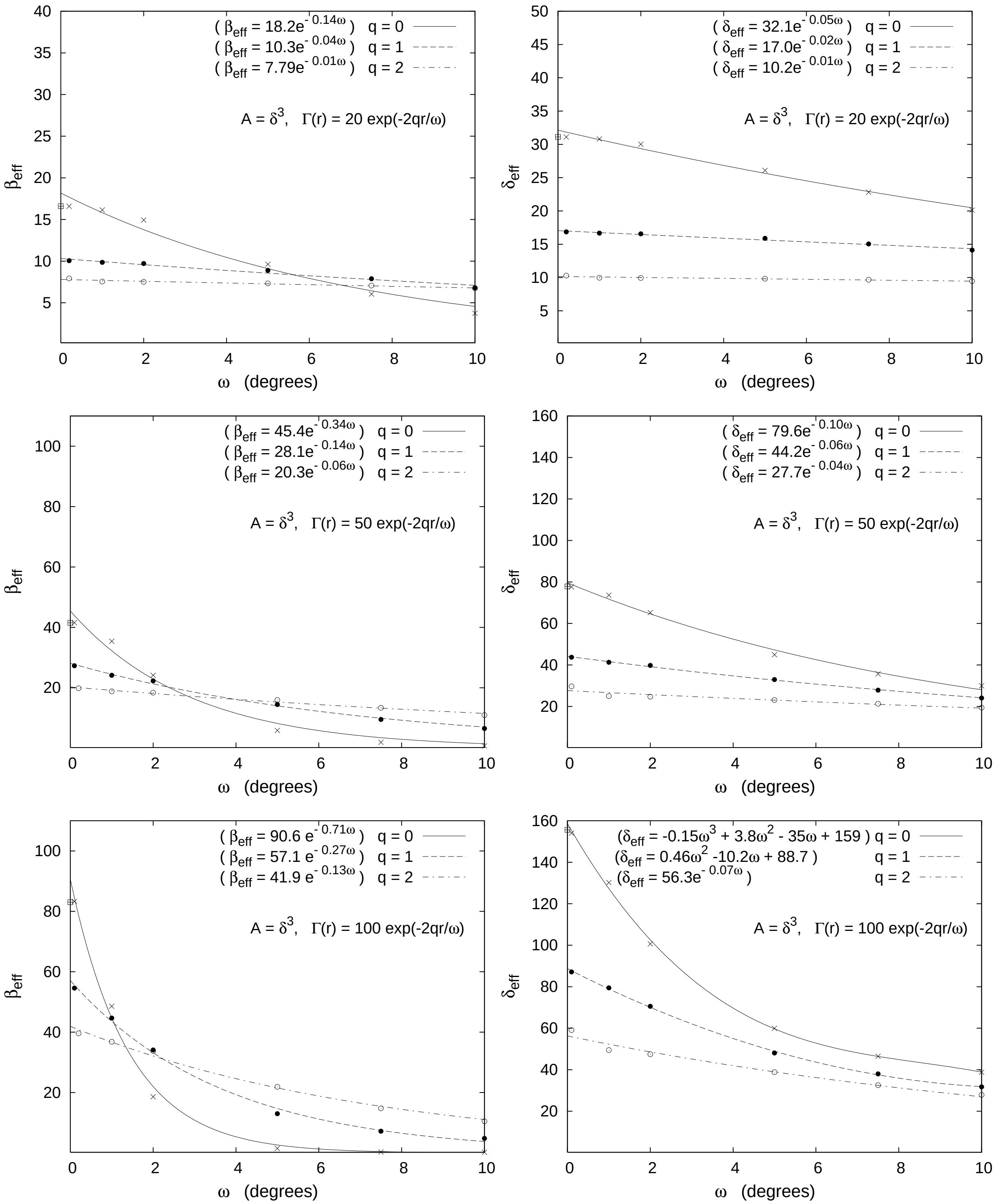

Figure 3. The effective speeds (left) and effective Doppler factors (right) as functions of the full opening angle of the jet, with $p = 3$. The top, middle and bottom panels correspond to $\Gamma_0 = 20, 50$, and 100, respectively. The $\times$ symbols, closed circles and open circles are the computed values for $q = 0, 1, 2$, respectively. The solid, dashed and dot-dashed curves give the corresponding labelled exponential function fits to the results except that polynomial fits are given to the $\delta_{\rm eff}$ values for the $\Gamma_0 = 100$ and $q = 1, 2$ cases. In each panel, the open square symbol gives the usual result for $\omega = 0$ and constant Γ.

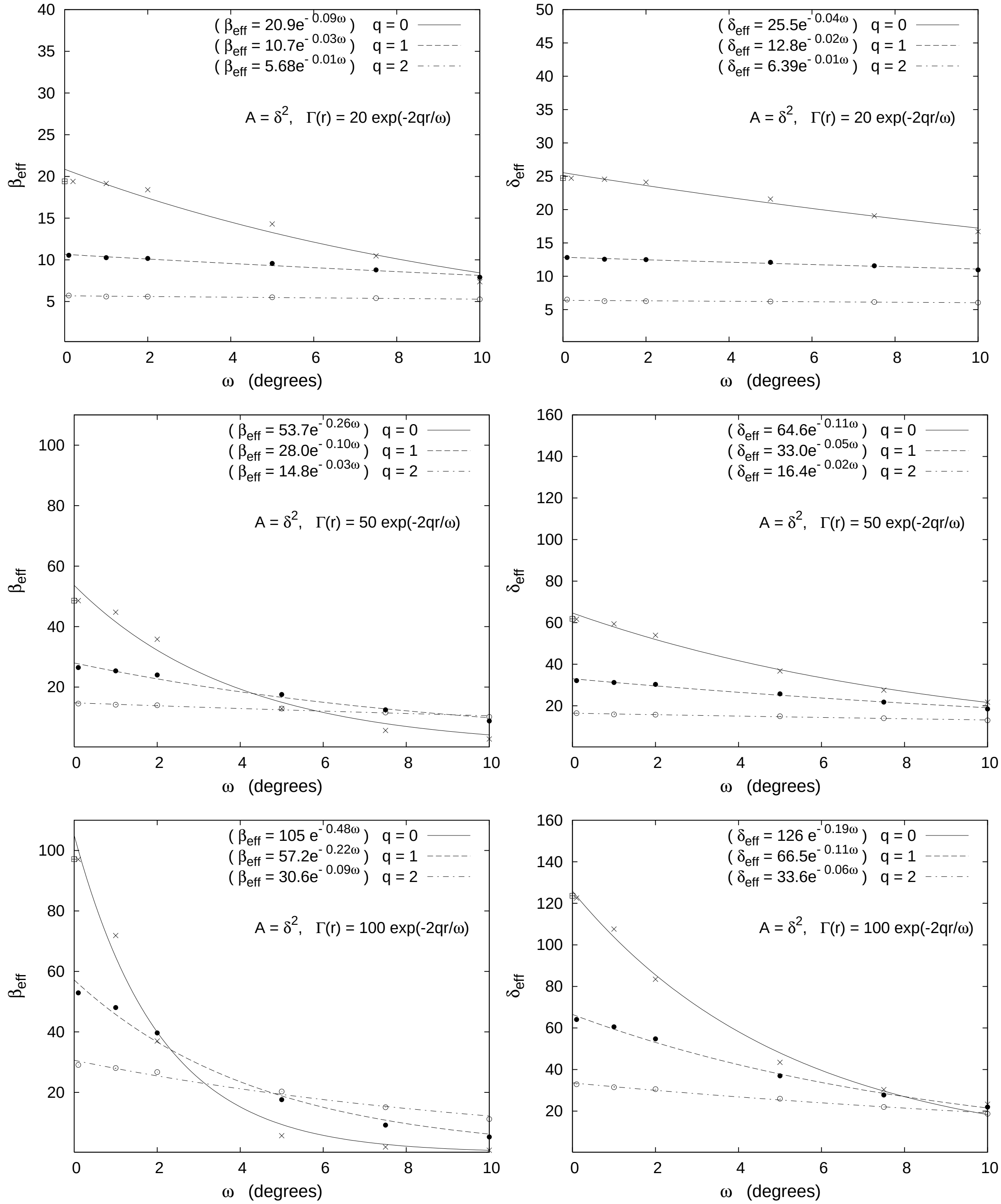

Figure 4. As in Fig. 3 for $p = 2$, except that exponential fits are made to all results.

well collimated jets (i.e., $\omega \lesssim 0.5^\circ$), $\beta_{\rm eff}$ for the uniform Γ case would typically be 1.5 to 2 times higher than for the $q = 1$ and between 2 and 4 times higher for the $q = 2$ (the two spine–sheath cases). Thus, the fastest *spine* component of the jet flow, which is near the jet axis, would be substantially concealed in the VLBI measurements.

It is interesting to note that the much sharper fall of $\beta_{\rm eff}$ with ω found for the uniform Γ case (especially in Fig. 2) ensures that already for modest jet opening angles, the value for $\beta_{\rm eff}$ of such jets would drop below the corresponding values for both of the spine–sheath models considered here. For $p = 3$ this crossover is seen to occur near $\omega = 6^\circ, 2.5^\circ$ and 1.3°, for $\Gamma_0 = 20, 50$ and 100, respectively, such that beyond these modest jet opening angles, $\beta_{\rm eff}$ rapidly approaches mildly relativistic (or, even sub-relativistic) values in the case of extremely relativistic jets with uniform Γ.

This steep fall of $\beta_{\rm eff}$ was first pointed out in Paper I for the case of uniform Γ jets and we find here a similar, albeit milder, dependence for the stratified ultra-relativistic jets as well (Figs. 3 and 4). It is also worth noting that while for well collimated ultra-relativistic jets $\beta_{\rm eff}$ is more strongly suppressed (relative to the uniform Γ case) when Γ is more peaked towards the axis (i.e., $q = 2$); the opposite is found for the jets having a significant opening angle ($\omega \sim 2^\circ$ to $\sim 10^\circ$), with the exact cross-over value of ω depending on Γ_0 and p. In summary, provided the conical jet is moderately wide ($\omega \sim 10^\circ$), the measured apparent speeds of the VLBI knots would typically remain under $10c$, even if Γ_0 were extremely large (~ 100), *not only for the uniform Γ jets but even for the stratified jets.*

The right columns of Figs. 3 and 4 illustrate the ω-dependence of the 'effective Doppler factor' ($\delta_{\rm eff}$) for the uniform Γ jets and for the two stratified jet forms; recall that $\delta_{\rm eff}$ is the cube root (for the $p = 3$ case), or square root (for $p = 2$) of the flux boosting factor, $A_{\rm eff}$, averaged over the radio knot (Eq. 4). Again, each point of these profiles is meant for the corresponding value of $\langle\theta\rangle$, as discussed above. It is seen that for cases of very good collimation ($\omega \leqslant 0.5^\circ$), the uniform Γ jets would typically have 2 to 4 times larger $\delta_{\rm eff}$ compared to the stratified jets, implying roughly an order-of-magnitude stronger Doppler boost. As expected for stratified jets, a sharper spine–sheath contrast (i.e., a larger q) leads to a lower $\delta_{\rm eff}$.

Further, as for $\beta_{\rm eff}$, a significant reduction in $\delta_{\rm eff}$ with ω is the typical expectation for both kinds of jet, the dependence being stronger for extremely relativistic jets, particularly the uniform Γ type (Figs. 3 and 4). This leads to a situation where extremely relativistic jets of both uniform and stratified Γ types end up with comparable $\delta_{\rm eff}$ values, once ω exceeds about 5°, although the $\delta_{\rm eff}$ values for the uniform jets do remain larger than those for the stratified jets over the wide parameter space considered here. These still very high values of $\delta_{\rm eff}$ mean that rapid variability in TeV γ-ray emission is to be expected in any of our ultrarelativistic models as the variability timescale is proportional to $\delta_{\rm eff}^{-1}$. Significant changes in TeV fluxes on sub-hour timescales have been reported for Mrk 421 (e.g., Błażejoski et al. 2005).

Often, VLBI observations reveal different apparent speeds for the radio knots in the same jet. This is usually interpreted by postulating that the knots reflect 'pattern speeds' which can be substantially different from the underlying speed of the jet (e.g., Vermeulen & Cohen 1994; Cohen et al. 2007). In our picture, such variations can be readily understood in terms of surface brightness distributions across the different knots being dissimilar. Moreover, the observed lack of sources with large apparent speeds but low brightness temperatures (e.g., Kovalev et al. 2005; Homan et al. 2006) also suggests that the intrinsic pattern speed should be broadly correlated to the jet's bulk speed.

As noted in Paper I, for the case of fully collimated jets the bulk Lorentz factor would have to quickly drop by 1 to 2 orders of magnitude between sub-parsec (TeV) and parsec (radio–VLBI) scales in order to reconcile the very large Doppler factors inferred from the compactness argument with the marginally superluminal (even sub-luminal) motion observed for the VLBI knots (Sect. 1). At present there is no direct observational evidence for such drastic deceleration (and the concomitant dissipation) occurring on sub-parsec scales in blazar nuclei. Rather, for Cygnus A, where sub-pc radio knot motions can be measured from millimetre VLBI and the jets are close to the plane of the sky (so that small changes in direction would not yield significant apparent speed changes) the evidence favors modest acceleration, not deceleration, on the sub-pc scale (Bach et al. 2005). One aim of our model is to eliminate the need for such a massively rapid deceleration.

A key question is: why is the Lorentz factor dichotomy so striking only for TeV blazars (e.g., Piner & Edwards 2004)? Essentially all blazars show two correlated peaks in their spectral energy distributions and are now usually classified by the frequency at which the lower frequency (synchrotron) peak is strongest (e.g., Padovani & Giomni 1995; Sambruna, Maraschi & Urry 1996). Now, according to the popular scheme unifying high energy peaked (HBL) and low energy peaked blazars (LBL) (e.g., Sambruna et al. 1996; Fossati et al. 1998), TeV emission, which is an HBL characteristic, would be more common among lower luminosity blazars. This hypothesis has been supported by a recent study, which indicates that the synchrotron peaks for powerful blazars (the Flat-Spectrum Radio Quasars) all remain below the rather high energy ($\gtrsim 1$ keV) which is characteristic of HBLs and TeV blazars (Padovani 2007).

We also recall that extragalactic jets tend to be less well collimated for lower luminosity sources, although this is only well established on the kpc scales where their opening angles can be routinely measured (e.g., Bridle 1984). Opening angles on sub-pc scales can be measured fairly unambiguously only for very nearby sources such as M87 (Biretta et al. 2002) and Centaurus A (Horiuchi et al. 2006) where the jets lie rather close to the plane of the sky; both of these are indeed relatively weak sources with wide jets. On the scale of nuclear jets Blandford (1993) gives a theoretical argument for this weak/wide correlation. Assuming it does hold, then the correlation between HBL properties and intrinsically weaker jets would mean that the jet opening angle should be larger for TeV emitting jets. Likely consequences of this are: (a) the probability of detecting TeV blazars would be enhanced, since, even though the TeV emission itself is probably beamed very sharply, its effective beaming angle is in fact much larger, and actually more like the jet opening angle (see, Phinney 1985; Blandford 1993; Begelman, Rees & Sikora 1994); (b) the wider jet would mean a bigger reduction in the apparent velocity of the radio knot (Paper I and Figs. 3 and 4). We suggest that the combination of these factors is probably responsible for the intriguing preference of TeV blazars to display slower motions of their VLBI knots.

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