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Jet deflections in radio galaxies

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Abstract. Convincing evidence for the interaction between jets and their environments has been found in many extragalactic radio sources. In some radio galaxies these interactions appear to cause the jet to be deflected, not completely stopped or disrupted. This paper presents a simple model which accounts for jet deflections with oblique shocks in a relativistic flow. Using the model in conjunction with measurements of jet deflection angles, it is possible to derive estimates of pre and post-shock jet speeds as well as the strength and obliquity of the shocks. The model is applied to two radio galaxies, PKS 1308−441 and 3C 277.3. A range in shock strength of 2 – 30 and jet Lorentz factors of 2 – 5 are required to explain the data for these two sources.

Key words: shock waves – galaxies: individual: PKS 1308−441, 3C 277.3 – galaxies: active – galaxies: jets – radio continuum: galaxies

1. Introduction

One of the processes which occurs in radio galaxies which can strongly affect their appearance is the interaction of jet with galactic and intergalactic environment. There are several different forms of interaction possible: the interaction between the head of the high-power jet and intergalactic medium in Fanaroff-Riley type II sources; the interaction and possible entrainment of galactic material in the low-power jets of Fanaroff-Riley type I sources (e.g. Bicknell 1994); and the possibility that some interactions between jets and galactic environments completely halt the jet advance and confine the radio source to sub-galactic dimensions, as postulated for GHz peaked-spectrum and compact steep-spectrum sources (e.g. Stanghellini et al. 1993).

In some radio galaxies, however, jet interactions appear to play a more subtle role, not halting or disrupting the jet completely, but changing its direction by up to a few tens of degrees, through a jet deflection. This type of behavior is noted in three radio galaxies. A well known example is 3C 277.3 (van Breugel et al. 1985). More recently PKS 1308−441 (Jones 1996) and PKS 2152−699 (Tadhunter et al. 1988; Wilson 1995, private communication) have been shown to have many characteristics in common with 3C 277.3. All three radio galaxies have jets which undergo a change of direction on the kpc-scale. At the change of direction a bright, discrete, hot spot of radio emission is present in the jet and is coincident with a hot spot of optical emission. In two of these objects for which the optical hot spot has been investigated spectroscopically, 3C 277.3 and PKS 2152−699, strong emission lines at the source redshift and large velocity gradients are seen. In the two sources for which the kpc-scale radio jets are well observed, PKS 1308−441 and 3C 277.3, the jets widen following the hot spots and changes in the jet polarization occur. In all three sources the jets continue to form a radio lobe some distance from the hot spots.

These facts taken together suggest a mechanical interaction between the jets in these sources and clouds of gaseous material in the host galaxies, or perhaps extragalactic clouds near the galaxy. That the jets are not completely disrupted and do not form a radio lobe at the point of interaction suggests that the interaction is comparatively minor, a glancing blow which is not enough to destroy the collimation of the jet but enough to change its direction significantly.

One way to change the direction of a jet is through an oblique shock within the jet, a planar shock which lies at some angle to the jet flow. The component of jet velocity parallel to the shock is unchanged as the jet traverses the shock but the component of jet velocity perpendicular to the shock is decreased, causing the jet to change its direction, the jet becoming more parallel to the shock.

In the next section, a simple model describing oblique shocks in a relativistic jet is developed which can be used to estimate some of the physical parameters in the jets of radio galaxies which undergo jet deflections, in particular the jet speed, the strength of the shock, and the obliquity of the shock. This model has previously been used to explain the deflection of the jet in PKS 2152−699 (Tingay et al. 1996). Here the model will be described in more depth and applied to data for two more radio galaxies, PKS 1308−441 and 3C 277.3.

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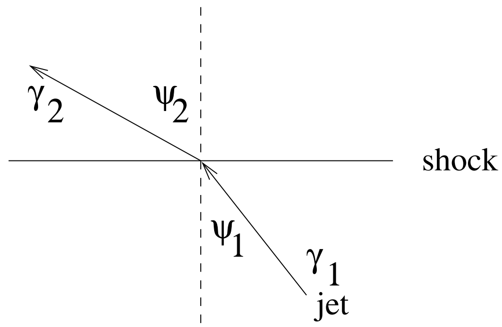

Fig. 1. Relationship between the jet and oblique shock.

2. The model

Bicknell (1994) sets up the equations describing oblique shocks, for a relativistic jet and an ultrarelativistic equation of state [1],

$$tan\psi_2 = tan(\psi_1 + \theta_d) = \left(\frac{3p_2/p_1 + 1}{3 + p_2/p_1}\right) tan\psi_1. \quad (1)$$

The subscripts refer to the jet upstream of the shock (1) and downstream of the shock (2): ψ are the angles between the jet directions and the shock normal, p is the pressure in the jet, and θ_d is the angle through which the jet is deflected in traversing the shock, $\psi_2 - \psi_1$ (see Fig. 1; γ is the jet Lorentz factor).
The strength of the shock can be characterized by the compression $1/k = p_2/p_1$, which can also be written as, following Eq. 1,

$$1/k = \frac{tan\psi_1 - 3tan(\psi_1 + \theta_d)}{tan(\psi_1 + \theta_d) - 3tan\psi_1}. \quad (2)$$

Following Bicknell (1994), the x (perpendicular to shock) and y (parallel to shock) components of the jet velocity with respect to the shock can be calculated,

$$\beta_{1x} = \frac{1}{\sqrt{f(k) + tan^2\psi_1}}, \quad (3)$$

$$\beta_{2x} = \frac{1}{\sqrt{g(k) + tan^2(\psi_1 + \theta_d)}}, \quad (4)$$

$$\beta_{1y} = \beta_{1x}tan\psi_1 = \beta_{2x}tan(\psi_1 + \theta_d) = \beta_{2y}, \quad (5)$$

where $f(k) = \frac{3(3+1/k)}{(3/k+1)}$ and $g(k) = \frac{3(3/k+1)}{(3+1/k)}$. The model takes as input a measurement of the jet deflection, θ_d. For each value of shock obliquity, ψ_1, a compression, $1/k$, can then be calculated, leading to the calculation of β_1 and β_2, hence γ_1 and γ_2.

The range in shock obliquity for which valid solutions can be calculated is limited and depends on the degree on deflection in the jet. This can be illustrated by considering Eq. 2, which should only be evaluated for physically meaningful values of compression i.e. $1/k > 1$. Figs. 2, 3, and 4 show plots of the compression against shock obliquity for three different jet deflection angles, 20°, 30°, and 40°, respectively. All solutions of Eq. 2 are shown, not just those which are physically meaningful. For a jet deflection of 20° in Fig. 2, the range in shock obliquity over which $1/k > 1$ is approximately 12° to 58°. For a jet deflection of 30° in Fig. 3, it can be seen that there is no point at which $1/k > 1$ is satisfied (note that when θ_d = 30 and ψ_1 = 30, the denominator of Eq. 2, $tan(\psi_1 + \theta_d) - 3tan\psi_1$, is identically zero and a singularity occurs, $1/k = -\infty$). Finally, for a jet deflection of 40° in Fig. 4, again there is no range over which $1/k > 1$ is satisfied. It can be shown from Eq. 2 that for $\theta_d \geq 30$, $1/k < 0$ for all values of ψ_1.

Hence, from this analysis, there is a limited range in shock obliquity for each valid value of jet deflection which allows

[1] the power of 1/2 in Eq. 1 in Bicknell (1994) is a typographical error (Bicknell 1995, private communication)

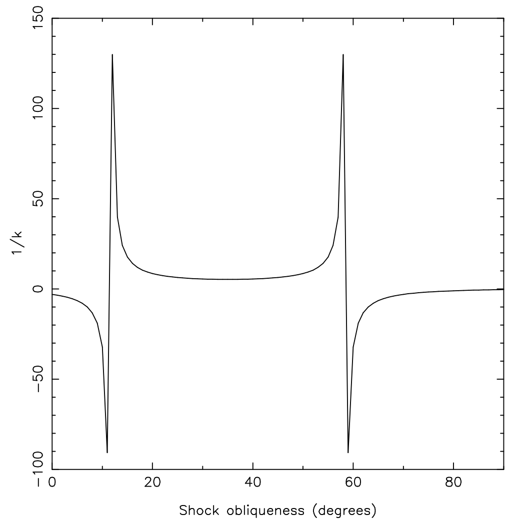

Fig. 2. Physical and non-physical values of compression, $1/k$, calculated for a jet deflection angle of 20° and shock obliquity between 0 and 90°.

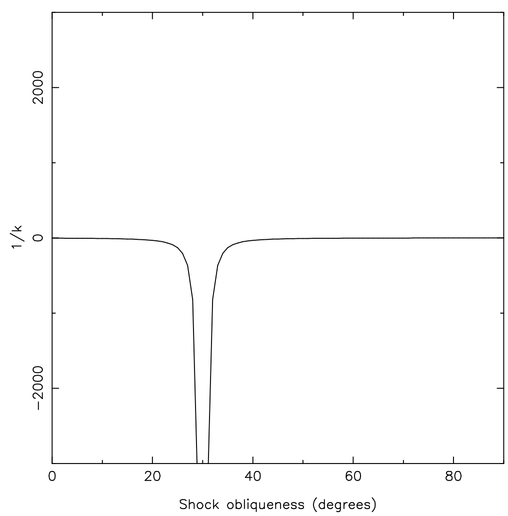

Fig. 3. Non-physical values of compression, $1/k$, calculated for a jet deflection angle of 30° and shock obliquity between 0 and 90°.

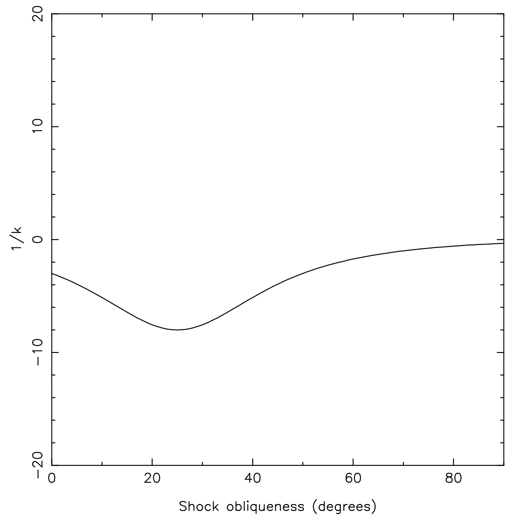

Fig. 4. Non-physical values of compression, $1/k$, calculated for a jet deflection angle of 40° and shock obliquity between 0 and 90°.

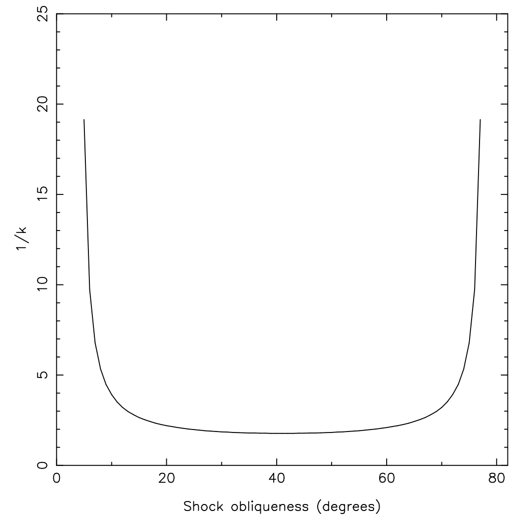

Fig. 5. Compression, $1/k$, calculated for a jet deflection angle of 8° and shock obliquity between 0 and 90°.

physically meaningful solutions. In addition the model can produce a maximum jet deflection of 30°.

3. Application to data

It needs to be pointed out here that θ_d refers to the *intrinsic* jet deflection angle. In general, for real objects, only the projected deflection angle is observed, which may be greater or less than the intrinsic value, depending on the three dimensional orientation of the radio galaxy with respect to us. Therefore, where possible, the observed deflection angle should be de-projected.

3.1. PKS 1308−441

PKS 1308−441 is a giant radio galaxy (z=0.051) which is intermediate in morphology between the FR-I and FR-II classes (Fanaroff & Riley 1974), although its luminosity lies below the FR-I/FR-II break (Jones 1996). Jones (1996) has imaged PKS 1308−441 with the Molonglo Observatory Synthesis Telescope at 843 MHz and with the Australia Telescope Compact Array at 1.37 and 2.37 GHz. The images show a core and jets extending to the NW and the SE. Approximately 2′ from the core, along the SE jet, a bright hot spot can be seen, after which the position angle of the jet changes by approximately 8°. At the position of the radio hot spot a diffuse optical object has been found. Jones (1996) calculates that the probability of a chance coincidence of the radio and optical objects is 0.005. The already large size of this source implies that its jets lie close to the plane of the sky. It follows that projection effects are not likely to be large and that the intrinsic deflection angle is near 8°.

The model for jet deflections described above was given θ_d = 8 as input and the compression, pre-shock (upstream) jet speed, and post-shock (downstream) jet speed were found as a function of shock obliquity. These results are shown in Figs. 5, 6, and 7, respectively.

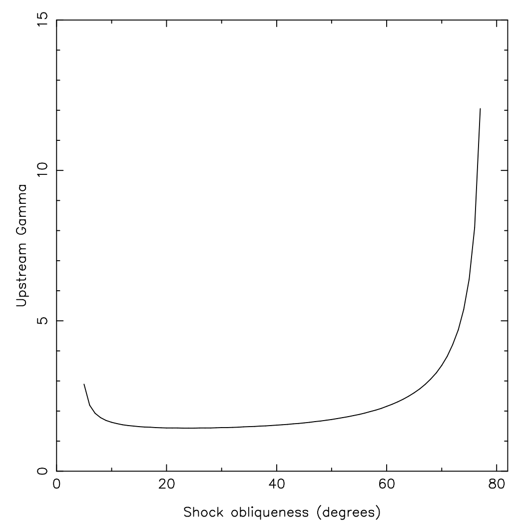

Fig. 6. Upstream Lorentz factor, γ_1, calculated for a jet deflection angle of 8° and shock obliquity between 0 and 90°.

From Figs. 5, 6, and 7, it is apparent that the required jet deflection can be achieved easily in a variety of conditions, with shock obliquities over a wide range, 10° – 70°. In this range weak shocks are generated, 2 – 5, and pre-shock jet Lorentz factors of only 2 – 4 are required. In the small region of parameter space outside this range where the deflection of 8° is still allowed, stronger shocks, up to 20, and faster jet Lorentz factors, up to 12, are required. The weak shock, slow jet solutions are consistent with the low radio power and transitional FR-I morphology of this radio galaxy.

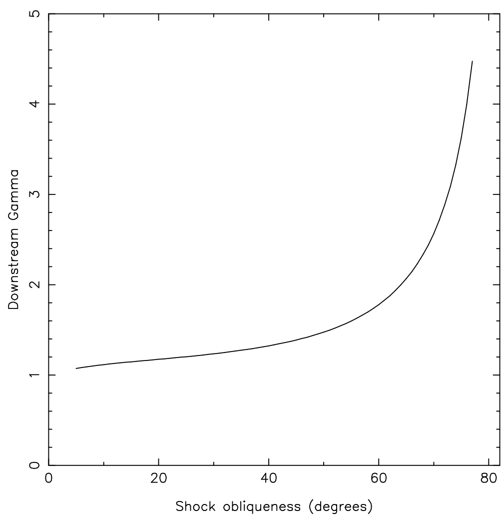

Fig. 7. Downstream Lorentz factor, γ_2, calculated for a jet deflection angle of 8° and shock obliquity between 0 and 90°.

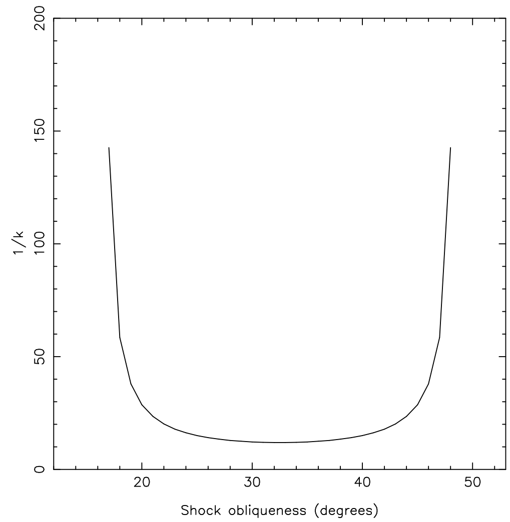

Fig. 8. Compression, $1/k$, calculated for a jet deflection angle of 25° and shock obliquity between 0 and 90°.

3.2. 3C 277.3

3C 277.3 has been observed with the VLA at 1.4, 4.9, and 15 GHz by van Breugel et al. (1985). It has a radio power which puts it above the FR-I/FR-II break and it lies at a red shift of 0.0857. Like PKS 1308−441, 3C 277.3 has a jet which is interrupted by a bright hot spot, after which the jet changes direction by approximately 30° and increases its width. Strong emission line gas is associated with this hot spot (designated K_1 by van Breugel et al. [1985]). Spectroscopic observations of the optical emission at the hot spot shows strong velocity changes in the direction parallel to the jet direction and small velocity changes perpendicular to the jet direction. A similar finding has been made for PKS 2152−699 (Tadhunter et al. 1988)

As shown in §2 a jet deflection of $\theta_d \geq 30$ is impossible under the model described. In the case of 3C 277.3 the jets may be inclined to our line of sight in such a way as to make the projected deflection angle appear greater than what it is intrinsically, although no information is available to allow an estimate of what the inclination is. Simulations were undertaken to determine if this situation is likely, taking an intrinsic deflection angle, exploring all possible jet orientations and determining all possible projected (observed) deflection angles. It was found that intrinsic deflection angles of $< 30°$ were projected into apparent deflection angles of $> 30°$ for $\sim$30% of all possible jet orientations, over a range in inclination angle between 0° and 75°. A single representative case was then simulated, an intrinsic deflection of 25° projected as an apparent deflection of 30° (to match the observed deflection angle). This deflection could be achieved for $\sim$10% of all possible orientations of the jet, over a range in jet inclination of 0° to 60°. In both simulations the small jet inclination angles were more favorable than the large inclination angles.

Figs. 8, 9, and 10 show the model results for an intrinsic jet deflection of 25°. A range in shock obliquity of approximately 20° – 45° is supported for 3C 277.3. In this range compressions of between 15 and 30 and pre-shock jet Lorentz factors of between 3 and 5 are required. Outside this range the compressions required quickly rise to approximately 150 and the Lorentz factors to over 10.

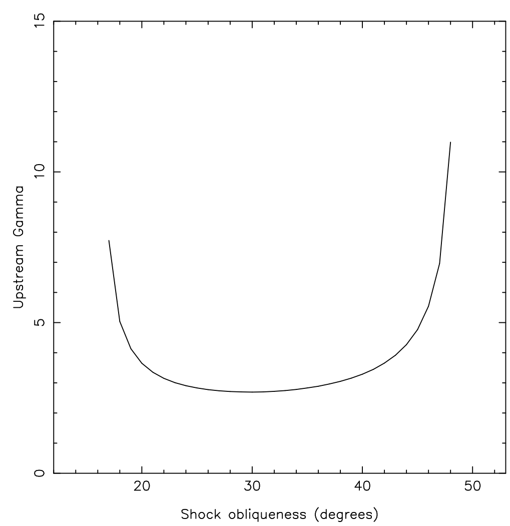

Fig. 9. Upstream Lorentz factor, γ_1, calculated for a jet deflection angle of 25° and shock obliquity between 0 and 90°.

The choice of a larger or smaller intrinsic deflection angle for 3C 277.3 is possible, with the consequence of more or less extreme shock parameters, respectively. For example, if the intrinsic jet deflection is increased, allowing the observed apparent deflection to occur over a larger fraction of jet orientations then stronger shocks and more highly relativistic bulk flows are required. Conversely, if the intrinsic deflection is decreased then the chance of observing a 30° apparent deflection is lessened, requiring a special orientation for the source.

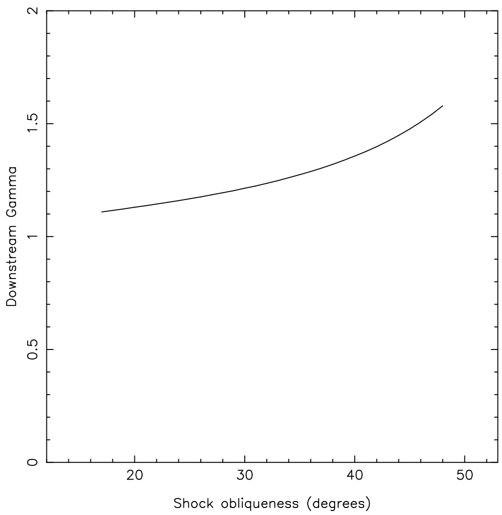

Fig. 10. Downstream Lorentz factor, γ_2, calculated for a jet deflection angle of 25° and shock obliquity between 0 and 90°.

Thus, although the simple shock model can explain the apparent deflection in 3C 277.3 over a reasonable range in parameter space and jet orientation, which is consistent with observations, the model is perhaps at the limit of its applicability for this source.

4. Conclusions

A simple model for the deflection of a relativistic jet via oblique shocks has been developed. Given a jet deflection, the model can estimate the shock strength and jet speed as a function of shock obliquity. Not all values of shock obliquity are valid and the range of valid solutions decreases as the degree of jet deflection increases. The model can generate jet deflections up to 30° and is applicable to radio galaxies in which a minor interaction between jet and environment causes a small but significant deviation of the jet. Jet deviations due to heavier interactions are likely to produce stronger and more complex jet bending and this model cannot be used to model these more complex situations.

This model has now been applied to apparent jet deflections in three similar radio galaxies: PKS 1308−411; PKS 2152−699 (Tingay et al. 1996); and 3C 277.3. It has been found that to model the apparent jet deflections in these sources (8°, 20°, and 30°, respectively) that a wide range in shock strength from weak ($1/k$ = 2) to strong ($1/k$ = 30) is required and that a moderate range in jet Lorentz factor is required, from 2 to 5. For 3C 277.3 the jet needs to be inclined $< 75°$ to our line of sight to bring the intrinsic deflection angle under the 30° model limit. The parameterization chosen for 3C 277.3 requires somewhat special but not overwhelmingly unlikely conditions, indicating that the simple shock model is perhaps near its limits of validity for this source.

The estimates of jet Lorentz factor made above are easily consistent with observations of the speeds in pc-scale radio jets (e.g. Vermeulen & Cohen 1994). Perhaps, as suggested by Bridle & Perley (1984) for high power radio galaxies, jet speeds remain relativistic on kpc-scales and Lorentz factors at least in the lower part of the range 2 – 5, estimated above, would seem plausible.

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