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Research Note

Superluminal motions with oblique shocks

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Abstract. We discuss the conditions for oblique shocks in extragalactic jets to produce apparent superluminal motions by the scissors effect. It is shown that diffusive acceleration is still possible for particular orientation of the magnetic field with respect to the main flow. The interpretation of superluminal motions in VLBI jets in this context yields constraints on the physical parameters of the shock and jet. This model is more satisfactory than the simple beaming model, but the lack of clear evidence of contraction motions in VLBI jets is a severe constraint.

Key words: extragalactic jets – VLBI jets – superluminal motions – first-order Fermi particle acceleration – oblique shocks

1. Introduction

The understanding of compact radio sources and extragalactic jets requires very high resolution observations. The VLBI provides us with parsec-scale details of these objects, and the major discovery is the predominance of superluminal motions (Porcas, 1986; Zensus and Pearson, 1988). This certainly reveals a physical property of the radio sources (Blandford, 1986) which is not yet understood. Explaining these observations would be a great step toward the understanding of the nature of extragalactic jets and their propagation. Several models were developed (see reviews by Blandford et al., 1977; Scheuer, 1984). The currently accepted interpretation is based on the beaming model, which involves the relativistic aberration of a very fast blob moving nearly toward us.

Whereas some other observations find a natural explanation in relativistic expansion, this simple model has some difficulties with the existence of unbeamed sources (Barthel, 1989). It has also the two important problems of the very large deprojected size of some superluminal radio sources (e.g. 4C 34.47 in Barthel et al., 1989) and of the brightness boosting (Scheuer, 1984; Blandford, 1986; Marscher, 1986).

The exact nature of these very fast blobs is not clear (Lind and Blandford, 1985), but they are believed to be of the same kind as knots in kiloparsec-scale jets, i.e. shocks which accelerate electrons through a first-order Fermi type process (Drury, 1983; Blandford and Eichler, 1987). These shocks should have a speed very close to c and propagate in the main direction of the jet.

In this paper, we consider shock fronts which are propagating at some angle with respect to the flow direction. Numerical simulations have shown that such shocks should be very common in jets (Norman et al., 1982; Falle and Wilson, 1985). We envisage a scissors effect between this shock front and a linear structure parallel to the flow. Acceleration of electrons and synchrotron emission are supposed to be allowed at the intersection of the shock and this feature, because of the presence there of the relativistic electrons or the magnetic field. The scissors effect has been used in screen models or some models of the Christmas trees' type (Blandford et al., 1977; Scheuer, 1984), but we consider here that this phenomenon is internal to the jet.

Section 2 presents the basis of the model. We present in Sect. 3 the physical relations allowing the Fermi acceleration. A discussion of application of this model to VLBI jets is given in Sect. 5, while the conclusion is in Sect. 6.

2. The model of “superluminal oblique shocks”

We consider first the scissors effect between a shock front propagating at U_o and a linear feature parallel to the main direction of the jet. The speed $U_{||}$ of the intersection point along the jet is:

$$U_{||} = \frac{U_o}{\cos \delta_o}, \quad (1)$$

where δ_o is the angle between the normal of the shock front and the linear feature (Fig. 1 a). (Throughout this paper, the speeds will be expressed in units of c .) For a convenient choice of U_o and δ_o , $U_{||}$ can be greater than the speed of light. Note that U_o and δ_o are directly related to the physics of the jet (Fraix-Burnet and Biermann, 1989).

Second, we identify the intersection point with an emitting knot. We assume that this emission is synchrotron from relativistic electrons which are accelerated (Bridle and Perley, 1984) through the diffusive shock acceleration mechanism (first-order Fermi acceleration; see reviews by Drury, 1983; Blandford and Eichler, 1987).

Third, we define the observed speed U_{obs} which is related to $U_{||}$ by the relativistic aberration:

$$U_{\text{obs}} = \frac{U_{||} \sin \theta_o}{(1 - U_{||} \cos \theta_o)}, \quad (2)$$

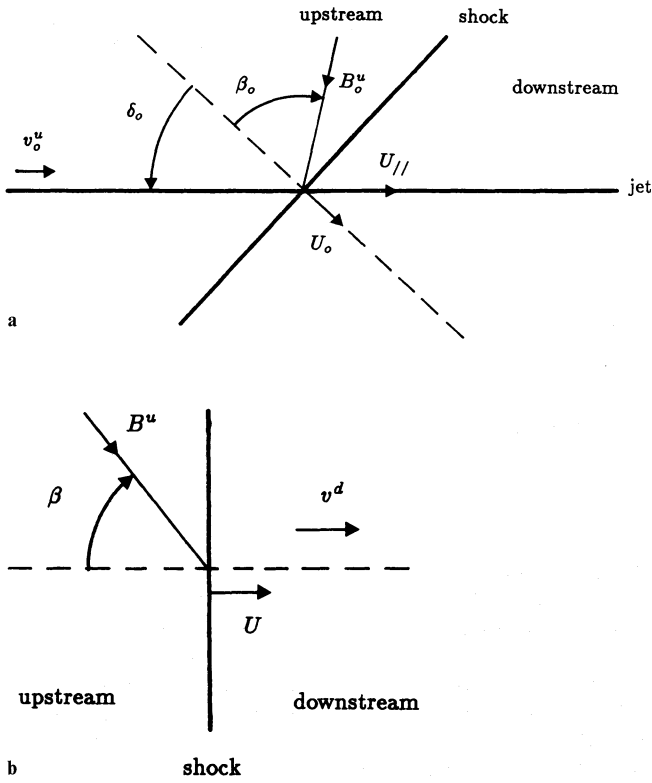


Fig. 1 a and b. Sketch of the shock configuration for the model in the frames of **a** the observer and **b** the upstream fluid. The angles are positive counterclockwise and vectors are positive as shown

where θ_o is the angle between the jet and the line of sight. These three processes constitute the model of “superluminal oblique shocks”.

Three types of configurations are possible for the linear feature. First, if we follow the very simple scheme of the model, the jet itself could define the linear feature, while the shock propagates in an external medium. The simplest medium is the cocoon made of material expelled from the jet at the bow shock (Blandford and Rees, 1974; Norman et al., 1982). Numerical simulations by Norman et al. (1982) have shown that oblique shocks occur in the cocoon from interaction with the surrounding medium, and that these shocks penetrate the jet. Our model thus predicts that the knots would be localised near the surface of the jet.

Shocks propagating in the thermal plasma of the jet are a second type of configuration. Our model then requires that the linear feature would be defined by the localisation of the relativistic electrons or the magnetic field. The simplest structure is that of a hollow cylinder, the relativistic electrons or the magnetic field being inside the hollow core or on the cylinder. Such a structure has been suggested in the M87 jet on very high resolution radio maps (Owen et al., 1987) and high resolution optical polarization maps of this jet also support this picture (Fraix-Burnet et al., 1989). In addition, Sol et al. (1989) developed a model where relativistic electrons are injected in the core of a thermal jet.

Finally, the linear feature can be fictitious and this characterizes the third type of configurations. The intersection of two propagating oblique shocks moves along a line at the speed $U_{||}$. Such crossings shocks are present in two-dimensional numerical simulations (Norman et al., 1982; Falle and Wilson, 1985), but the

physics of the acceleration mechanism in this configuration is certainly more complex than assumed in the present model.

3. The Fermi acceleration

Hudson (1965) showed that first-order Fermi acceleration is not possible when the speed of the shock front along the magnetic field lines is larger than c . The present model thus a priori requires that the magnetic field must not be aligned with the jet. In this section, we establish the physical conditions implied by the acceleration of particles. Most calculations in this paper are derived from Fraix-Burnet and Biermann (1989) and Fraix-Burnet (1989), but we consider in this paper the case $U_{||} \gtrsim 1.0$ (Eq. (1)).

3.1. Dynamics

Figure 1a, b define the parameters of the shock in the reference frames of the observer (subscript “o”) and of the upstream fluid (no subscript) respectively. The subscript “s” stands for the reference frame of the shock front and the superscripts “u” and “d” for upstream and downstream quantities. For simplicity and reason of symmetry, $U_o, v_o^u, \cos \delta_o$ and $\cos \beta_o$ (Fig. 1a) will be taken positive.

The compression ratio of the shock is given by:

$$r = \frac{v_{s\perp}^u}{v_{s\perp}^d} = \frac{(1 - v^d U)}{(1 - v^d/U)}, \quad (3)$$

where $v_{s\perp}^u$ and $v_{s\perp}^d$ are the fluid speeds perpendicular to the shock front. U and v^d are the speeds of the shock front and the downstream fluid respectively (Fig. 1b). U is related to the parameters in the observer frame by:

$$U = \frac{U_o - v_o^u \cos \delta_o}{\sqrt{(\cos \delta_o - v_o^u U_o)^2 + \sin^2 \delta_o (1 + v_o^{u2})}}. \quad (4)$$

Because we are interested to the case $U_{||} \gtrsim 1$, we shall assume $U_{||} > v_o^u$ without restricting the discussion. Then (1) and (4) yield:

$$U > 0. \quad (5)$$

It can be shown that this inequality implies $v_{s\perp}^u < 0$. The only possibility for a physical shock is thus $v_{s\perp}^d < 0$. This is to say the “upstream” and “downstream” fluids should be redefined in the shock front frame, but we keep this denomination however. Now, the real physical compression ratio is $1/r$, and hence $r < 1$. $v_{s\perp}^d < 0$ also implies that $v^d < U$ and this inequality provides a condition on the shock speed in the upstream frame, using (3):

$$U^2 < r. \quad (6)$$

Equations (3) and (6), together with $r < 1$, imply in turn $v^d < 0$. The condition (6) can be transformed into a condition on δ_o :

$$\frac{U_o}{U_{||}} = \cos \delta_o > F_r(U_o, v_o^u) \quad (7)$$

with

$$F_r(U_o, v_o^u) = \frac{U_o}{v_o^u} - \sqrt{\frac{r}{1-r}} \frac{(1 - U_o^2)(1 - v_o^{u2})}{v_o^{u2}}.$$

In addition, $F_r(U_o, v_o^u)$ as a function of v_o^u presents a minimum only for $U_o^2 > r$, and its value is:

$$F_{\min} = \sqrt{\frac{U_o^2 - r}{1 - r}}. \quad (8)$$

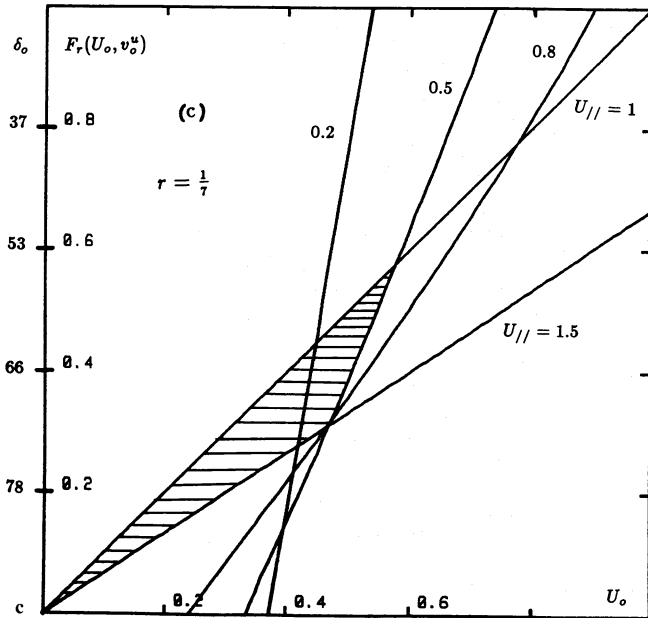
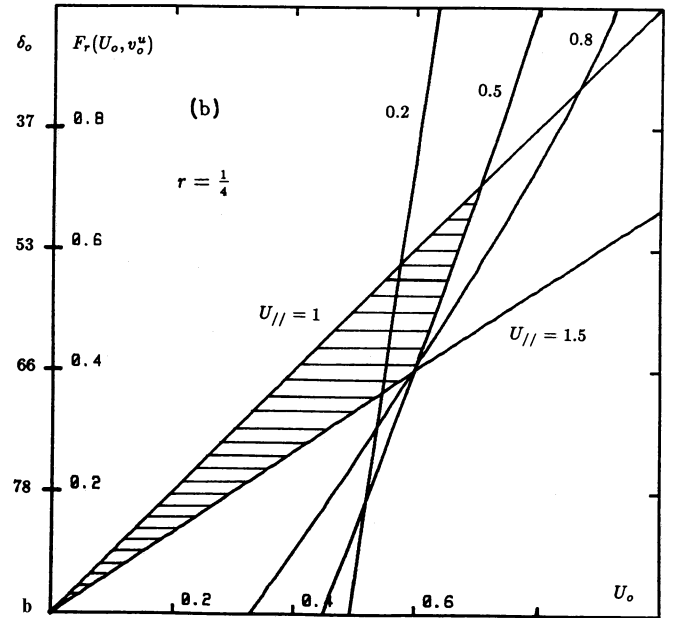
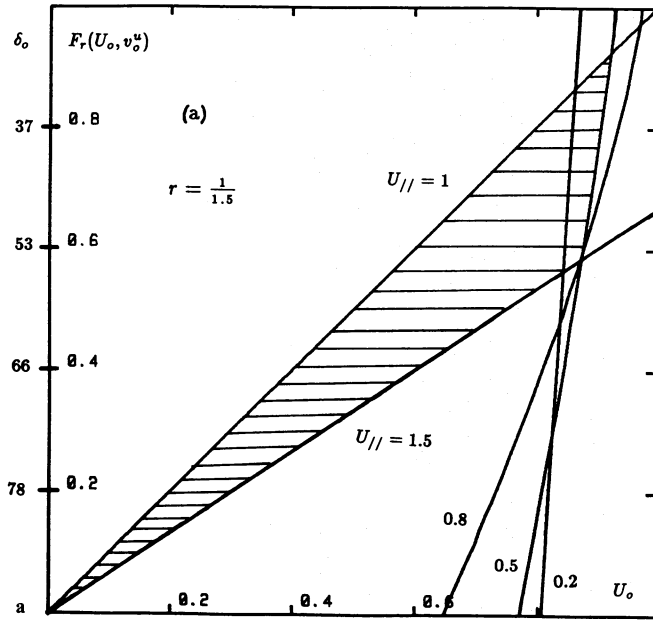


Fig. 2a–c. $F_r(U_o, v_o^u)$ given by inequality (7) versus U_o for different values of v_o^u (0.2, 0.5 and 0.8) and for compression ratios of **a** 1.5, **b** 4, and **c** 7. The corresponding angle δ_o is also given in degrees in ordinates. The hatched region corresponds to the allowed ranges for δ_o and U_o for $v_o^u = 0.5$ and $1 < U_{||} < 1.5$

This yields the following necessary conditions to inequality (7) in the case $U_o^2 > r$:

$$\frac{U_o}{U_{||}} > F_{\min} \Leftrightarrow U_{||} < U_o \sqrt{\frac{(1-r)}{(U_o^2-r)}}. \quad (9a)$$

When $U_{||} > \sqrt{1-r}$, this is also equivalent to:

$$U_o < U_{||} \sqrt{\frac{r}{(U_{||}^2+r-1)}}. \quad (9b)$$

The function $F_r(U_o, v_o^u)$ is plotted in Fig. 2 for $v_o^u = 0.2, 0.5, 0.8$ and $r = 1/1.5, 1/4$ and $1/7$. For illustration, a hatched region in the case

$v_o^u = 0.5$ and $1 < U_{||} < 1.5$ shows the allowed range for $\cos \delta_o$ and U_o . The curves in Fig. 2 put the constraints on the geometrical and dynamical parameters of the jet and the shock.

3.2. Magnetic field

The condition for the first-order Fermi acceleration to work is given by (Hudson, 1965):

$$\frac{U}{\cos \beta} < 1 \quad (10)$$

and β (Fig. 1 b) is related to the parameters in the observer frame by:

$$\cos \beta = \frac{\cos \beta_o - v_o^u U_o \cos(\beta_o - \delta_o) + v_o^{u2} \sin \delta_o \sin(\beta_o - \delta_o)}{\sqrt{(\cos \delta_o - v_o^u U_o)^2 + \sin^2 \delta_o (1 - v_o^{u2})} \sqrt{1 - v_o^{u2} \sin^2(\beta_o - \delta_o)}}. \quad (11)$$

Thus, using (4) and (11), (10) can be expressed only with observed parameters:

$$\frac{U_o}{\cos \beta_o} < x, \quad (12)$$

where

$$x = \frac{1 + v_o^u / \cos \beta_o [\cos \delta_o \sqrt{1 - v_o^{u2} \sin^2(\beta_o - \delta_o)} + v_o^u \sin \delta_o \sin(\beta_o - \delta_o)]}{v_o^u \cos(\beta_o - \delta_o) + \sqrt{1 - v_o^{u2} \sin^2(\beta_o - \delta_o)}}. \quad (13)$$

Note that when the magnetic field is parallel to the jet, i.e. $\beta_o = \delta_o$, we have $x = 1$, so that $U_{||} > 1$ (Eq. (1)) contradicts with (12): no particle acceleration is allowed with a superluminal motion in this case.

The curve $x \cos \beta_o$ versus β_o is plotted in Fig. 3 for different values of δ_o and v_o^u . The allowed region for U_o given by (12) is below the curves and the range of allowed values for β_o depends on U_o . But the magnetic field tends to be preferentially oriented roughly perpendicularly to the flow ($\beta_o \simeq \delta_o - 90^\circ$).

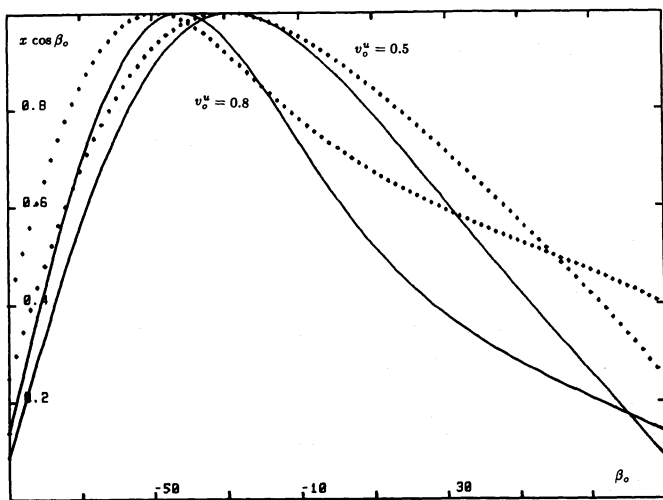


Fig. 3. $x \cos \beta_0$ ((12) and (13)) versus β_0 (degrees) for two values of v_0^u and for $\delta_0 = 60^\circ$ (dotted line) and 80° (solid line)

4. Discussion

The previous section shows that it is possible to have $U_{||} > 1$ with Fermi acceleration, and Figs. 2 and 3 give the required conditions on the parameters. In this section, we consider the application of this model to VLBI jets.

Zensus and Pearson (1988) compiled the observations of VLBI motions, made of 39 blobs (for 26 sources) plus 7 for which the speed is still uncertain. While the sample is heterogeneous and certainly not complete (see cautions about these data in Zensus and Pearson, 1988), it is instructive to see that the apparent speeds are as large as about 14, but there is a significant maximum between 3 and 4. One speed is stated to be negative, and relatively few (7) are subluminal.

The problem attached to screen models such as those involving the scissors effect is that a non negligible proportion of apparent contraction motions should be observed. No clear evidence for contraction motions has been found yet, thus we take 20% as a firm upper limit to their proportion. This corresponds to a population of randomly oriented radiosources with $U_{||} = 1.5$, which can be considered as an upper limit implied by the observations. In order not to increase the number of subluminal speeds, we take $U_{||} \geq 1.0$. The allowed range for δ_0 and U_0 is then given in Fig. 2 (hatched region).

For a uniform distribution of $U_{||}$ between 1.0 and 1.5 in a population of randomly oriented radiosources, the proportions of subluminal and negative speeds are respectively $\simeq 40\%$ and $\simeq 10\%$. These values are modified by a selection effect due to the limited resolution: for a given $U_{||}$, phenomena in jets which are too close to the line of sight are unresolved. Conversely, for a given θ_0 , higher $U_{||}$ (hence globally higher U_{obs}) are favoured. This results in a decrease of the subluminal and negative speed proportions, favouring $U_{\text{obs}} > 2$. We finally expect $\simeq 5\text{--}10\%$ of contracting motions and $\simeq 30\text{--}40\%$ of subluminal ones. Among 39 observed speeds, this would correspond respectively to $\simeq 2\text{--}4$ and $\simeq 12\text{--}16$, which is reasonably close to the data.

Although the comparison of models assuming so crude distributions with a somewhat cautious sample may be meaningless. $U_{||} < 1$ (beaming model) would yield at least 50% of randomly oriented radiosources with $U_{\text{obs}} < 1$. The beaming model eliminates nearly all these subluminal motions by consider-

ing light amplification effects that are not taken into account in this paper. The problem with the present model could come from the negative speeds, but the interpretation of such motions (if actually observed) would be very difficult with the beaming model, as is the observation of apparently stationary blobs together with superluminal ones (4C 39.25 in Shaffer, 1984; Shaffer and Marscher, 1986). Conversely, such behaviours seem easy to explain in the present model. Very high U_{obs} can also be easily produced because it goes to ∞ for $\cos \theta_0 = 1/U_{||}$ (Eq. (2)). The observation of $U_{\text{obs}} \gtrsim 20$ would not be surprising in this context, whereas it could in firm the beaming model.

The last parameters of the present model is the direction of the magnetic field, which is not much constrained (i.e. $\beta_0 < \delta_0$) in the case $\delta_0 = 60^\circ$ and $U_{||} \simeq 1.1$ (Fig. 3). But the magnetic field must be more perpendicular to the flow as $U_{||}$ and v_0^u increase. For example, $U_{||} = 1.5$, $\delta_0 = 60^\circ$ and $v_0^u = 0.8$ imply $\beta_0 \lesssim -10^\circ \simeq \delta_0 - 70^\circ$. The very few polarization data seem to show no systematic orientation with respect to the jet direction in VLBI blobs (Roberts and Wardle, 1986). A study of the correlation between magnetic field orientation and the speed in several blobs of the same source, would be helpful to test the present model.

6. Conclusion

First-order Fermi acceleration of electrons has been studied in the case of a scissors effect between an obliquely propagating shock front and a linear feature, both inside the jet. This process is possible within some conditions which have been expressed with the parameters of the jet and the shock in the observer frame. One observable requirement is that the magnetic field must not be aligned with the jet direction.

Applied to VLBI observations of parsec-scale jets, we find the following predictions assuming a population of randomly oriented radiosources:

- $1.0 \lesssim \frac{U_0}{\cos \delta_0} \lesssim 1.5$,
- $\simeq 5\text{--}10\%$ of observed speeds should be negative (contraction),
- $\simeq 30\text{--}40\%$ should be subluminal,

Because it abandons the common geometrical property of the radiosources required by the beaming model (near alignment with the line of sight) in favor of a common physical property (the existence of adequate shocks), the present model solves some problems set by the beaming model. As a corollary, the physical parameters of the jet are quite directly related to the observations. Although it does not eliminate the problem of negative speeds implied by screen models, the “superluminal oblique shocks” model makes some predictions which could be checked in the future.

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