QUASI-TWO-DIMENSIONAL COSMIC JETS

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INTRODUCTION

One of the major discoveries in solar physics over the past decade has been the association of coronal holes with high-speed solar wind streams (Zirker 1977 and references therein). On the other hand, advances in X-ray and radio instrumentation (e.g., *Einstein*, VLA, VLBI, etc.) in the past few years have allowed detailed observations of collimated outflows from rather more distant objects, such as young stars and active galaxies (Beer 1981, Lada 1982, Ferrari and Pacholczyk 1983 and references therein). The remarkable structural similarities between jets of magnetized gas from our Sun, other active stars, and active galactic nuclei suggest that these phenomena may be manifestations of similar hydrodynamic processes operating on both small and large scales. In this article, we shall use the experience gained by studying the nearest known astrophysical jet -- high-speed solar wind streams -- to address some of the problems of astrophysical jet acceleration and collimation associated with objects as diverse as SS 433, star-forming molecular clouds and, in particular, jets associated with galaxies and quasars.

MODEL ASSUMPTIONS AND GOVERNING EQUATIONS

The three questions that we have chosen to address in the context of the jet phenomenon are:

(i) the initial acceleration of the jet within the inner regions of the "power source";
(ii) the collimation of the accelerated ionized gas;
(iii) the physical mechanism(s) responsible for the *in situ* particle reacceleration, and corresponding multiwavelength emission from the bright knots along the jet axis.

In the case of extragalactic jets, these questions are motivated by the rich collection of observational data available in the optical and radio and, recently, at X-ray wavelengths (cf. Heeschen and Wade 1982, Ferrari and Pacholczyk 1983). These observations show that jets are highly collimated and that the nonthermal emission is peaked in bright knots along the jet axis; and imply that the jets originate deep within the "power center". From the theoretical point-of-view, several ideas have been proposed to account for jet acceleration and collimation (see review talks by A. Ferrari and C. Norman in these Proceedings). For our purposes, however, we will assume (with Rees *et al.* 1982) that a

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central mass is surrounded by an accretion disk (Fig. 1). Two narrow channels are formed along the rotation axis of the system (Abramowicz and Piran, 1981). This disk "throat" is not empty, however, because wave and radiation pressure acting on the plasma which diffuses inward from the disk "walls" initiate an outward flow above some stagnation distance z_o. A Parker-type wind then emerges from the throat.

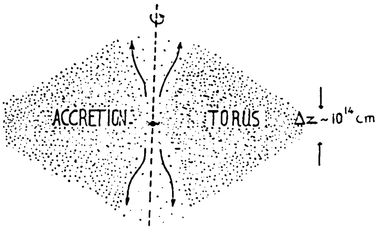


Figure 1

Along the symmetry axis of the channel, the flow speed v(z,t) and density $\rho(z,t)$ are governed by the familiar hydrodynamic conservation equations for mass and momentum (Parker 1963, Kopp and Holzer 1977, Habbal and Tsinganos 1983),

$$\frac{\partial}{\partial t}(\rho A) + \frac{\partial}{\partial z}(\rho v A) = 0 , \tag{1}$$

$$\frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial z} = -\frac{\partial P}{\partial z} - \frac{GM}{z^2} + \rho D(z,t) , \tag{2}$$

where A(z,t) is the (macroscopic) channel cross-sectional area and $\rho D(z,t)$ represents the local momentum deposited by waves, radiation, etc., emitted by the accretion disk or the central object. The study of the energetics of the flow is temporarily postponed by assuming a polytropic equation of state $P = k\rho^{\alpha}$. In the following, however, we will further simplify the problem by assuming an isothermal flow, $\alpha = 1$, and hence a constant sound speed v_s. The flow $v \equiv \partial \Phi/\partial z$ is then governed by the following single equation

$$\frac{\partial^2 \Phi}{\partial t^2} + 2v \frac{\partial^2 \Phi}{\partial z\, \partial t} + (v^2 - v_s^2) \frac{\partial^2 \Phi}{\partial z^2} + v\left(\frac{GM}{z^2} - \frac{2v_s^2}{z}\right) = \frac{\partial \Delta}{\partial t} + v\frac{\partial \Delta}{\partial z} , \tag{3}$$

where

$$\Delta(z,t) = v_s^2 \ln f(z,t) + \int D(z,t)dz \tag{4}$$

represents the total effect of nonthermal momentum addition (either directly, via D(z,t), or indirectly, via non-spherical expansion such that $f(z,t) = A(z,t)/z^2$).

There are two fundamental properties of the above governing equation of motion (3) which are of particular interest to our problem:

(I) The time-dependent Eq. (3) is a second order *hyperbolic* partial differential equation. As a result, perturbations in the flow might "break", and hence develop shocks. For example, suitable changes in the magnitude of Δ have been shown numerically to lead to shock formation (Habbal *et al.* 1983, Tsinganos *et al.* 1983).

(II) The time-independent form of Eq. (3) is the familiar Mach number equation (Parker 1963). For appropriate forms of Δ, however, its solution topologies are characterized by multiple critical points, possibly degenerate transonic solutions, and possible standing shocks, as it can be seen from the following results.

RESULTS

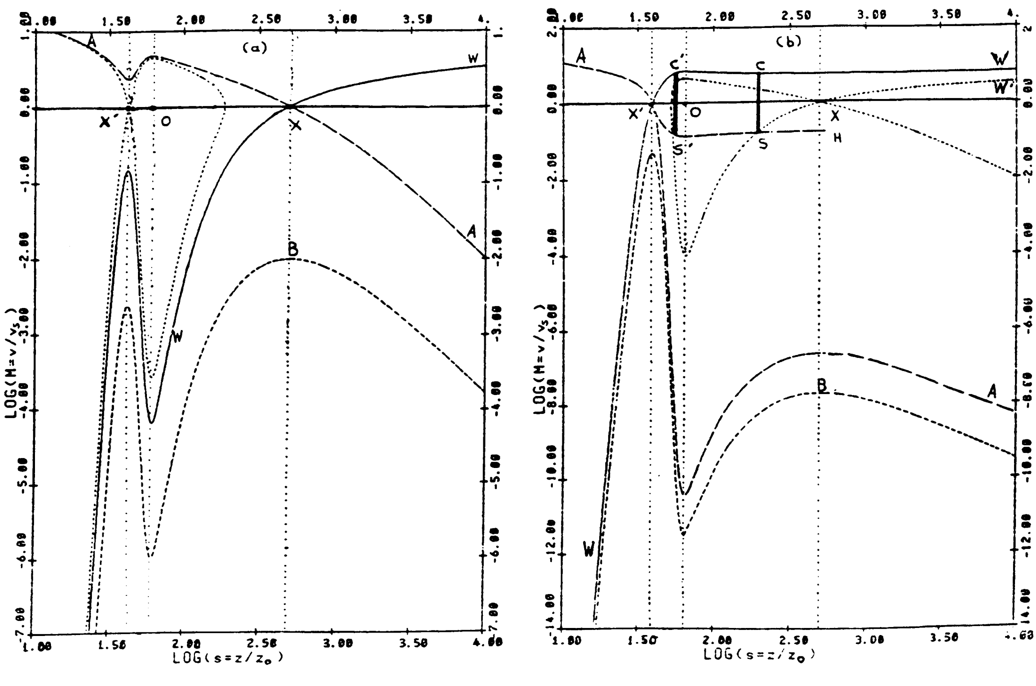
The following figures 2 and 3 are plots of the steady solutions of Eq. (3) for a gaussian form of the nonthermal momentum deposition D(s) ,

$$D(s) = D_o\exp[-(s-s_m)^2/\sigma^2] \tag{5}$$

Fig. 2 corresponds to the galactic case ($M=10^8$ M_o, $T=10^8$ K, $z_o=10^{15}$ cm). In 2a the parameters of nonthermal momentum addition are $D_o=10$ dyn/gm, $s_m=50$, $\sigma=10$, and in 2b $D_o=20$ dyn/gm, $s_m=50$, $\sigma=10$. In (a) the wind solution crosses the outermost critical point at s=500 while in (b) the innermost one at s=39.6. The wind solution corresponds to the branch WXW in (a) and WX'W in (b); the accretion solution to branch AXA in (a) and AX'A in (b); and the "breeze" solution to branch B. The subsonic branch XSS'H satisfies the Rankine-Hugoniot relation $M_1M_2=1$ with respect to the supersonic branch X'C'CW in (b). The vertical solid lines CS and C'S' denote the position of the standing shocks. In (a) the jet becomes supersonic at the outermost critical point, as in the case of a Parker-type galactic wind. In (b) however enough nonthermal momentum has been added to the subsonic portion of the unperturbed wind such that the jet becomes supersonic much earlier, at the inner critical point X'. Note the presence of three (degenerate) solutions -- two of them being discontinuous -- for the same initial velocity: the two discontinuous solutions WX'C'S'SXW' and WX'CSXW' occur because the shock transitions C'S' and CS connect the inner transonic solution WX'W to the outer transonic branch crossing the critical point X.

Fig. 3 is the analogous jet outflow from a stellar object ($M=M_o$, $T=10^6$, $z_o=10^{11}$ cm). The continuous curve in Fig. 3a is the familiar Parker-type solution with D=0 and one critical point at s = 4.8. Two new critical points are added in Figure 3b; however, the flow still remains subsonic for s < 4.8. In 3c-3d the flow becomes supersonic at the innermost critical point, s =2.7. Fig 3c contains the two shock transitions C'S' and CS as in 2b. These shocks are not allowed for the values of the flow parameters of Fig 3d.

Figure 2



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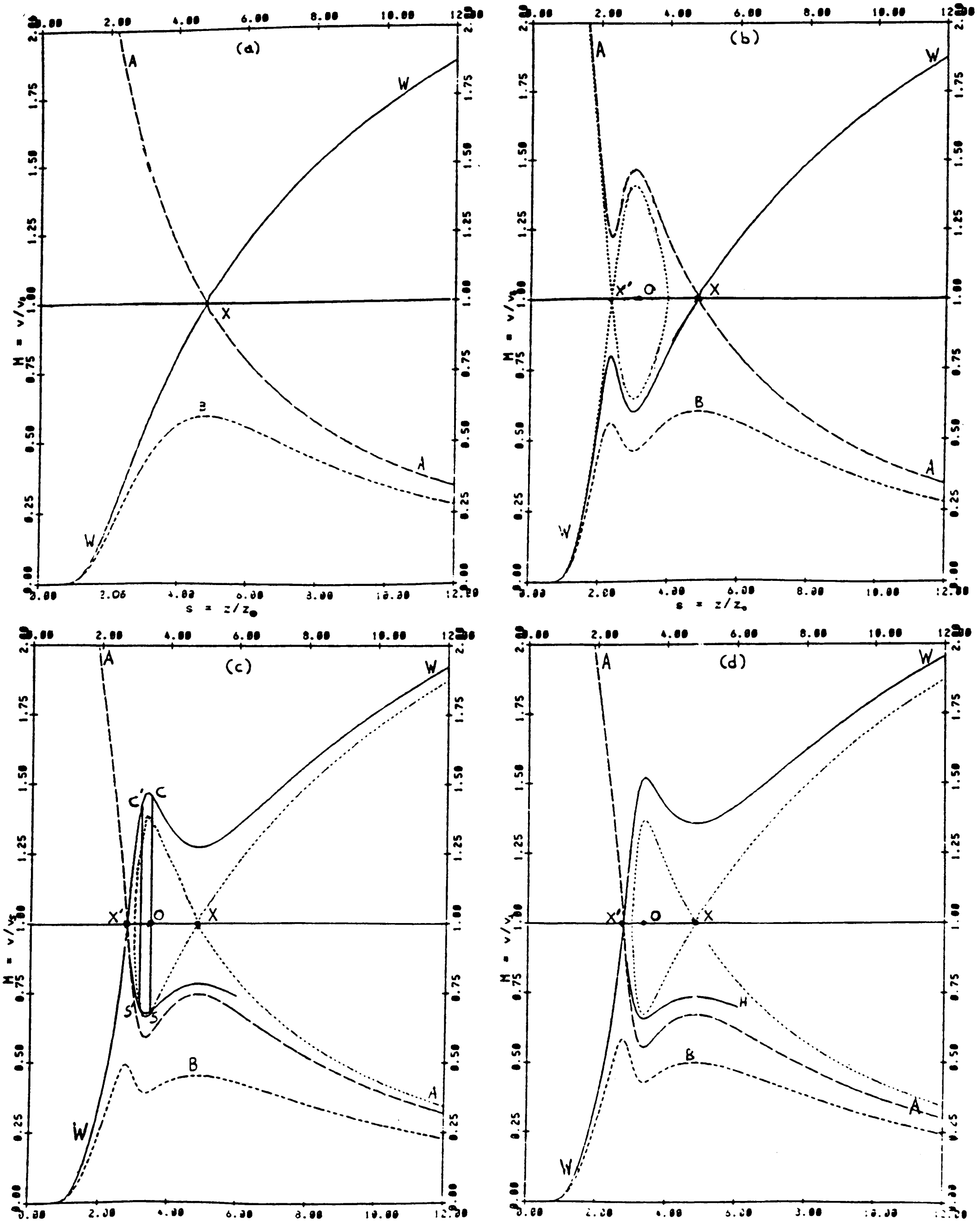

Figures 3a-3d: Mach number $M=v/v_s$ *vs.* distance $s=z/z_o$, (v_s= 140 km/s, $z_o=10^{11}$ cm) for Parker-type outflows from a stellar object of mass $M=M_o$ and temperature $T=1.2 \times 10^6$ K in a channel of cross-section A(s) and/or with momentum addition D(s). The parameters [D_o dyn/gm, s_m, σ] of the nonthermal momentum deposition D(s) [cf. Eq. (4)] are [0, 3, 0.3], [3000, 2.5, 0.5], [2700, 3, 0.3] and [3000, 3, 0.3] in (a), (b), (c), and (d), respectively.

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SUMMARY

There are two novel and interesting features of the above solutions of the wind equations which are introduced either by the geometry of non-radial flow tube expansion, or by direct momentum addition within the flow. The *first* is that the flow can become supersonic much closer to the central "power source" than without some effective momentum deposition; the funnel of an accretion disk offers the appropriate environment for beam collimation and non-thermal momentum addition. The *second* has to do with the propagation of the jet outside the nuclear region. As a result of hydrodynamic or hydromagnetic instabilities, the functional dependence of the cross-sectional area of the jet on the linear distance from the source may differ substantially from $A(z) \propto z^2$, opening the possibility for shocks to exist in the external region as well (as illustrated in Fig. 2b). These shocks in turn may be associated with local acceleration of particles (cf., Blanford and Ostriker 1978), resulting in the nonthermal emission associated with the bright knots aligned along the axis of, for example, M87.

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DISCUSSION

BENFORD : What is collimating the beam?

TSINGANOS : The geometry of the funnel and the rotation of the beam around the z-axis are expected to assist collimation.

BRATENAHL : This modeling is interesting, but have you checked the existence of shocks in the coronal holes?

TSINGANOS : Yes, we are looking into this question. The cross-sectional area $A(z,t)$ of the flow tube is a function of the time t and the height z; and in numerical simulations we indeed obtained the shocks for suitable temporal variations of the cross-section $A^*(z,t)$ and/or $D^*(z,t)$. We should expect therefore shocks to occur in the inner solar wind for $A(z,t) = A^*(z,t)$ and/or $D^*(z,t)$. It would be interesting to look at the white light or radio data from the solar corona for observational signatures of these shocks.