A RELATIVISTIC WIND-TYPE MODEL FOR THE GENERATION OF VLBI JETS [+]

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ABSTRACT

We discuss wind-type solutions for flows from accretion funnels, and show under what physical conditions such flows can become supersonic and relativistic already very close to the stagnation point within the funnel. The acceleration is due to radiation emitted by the funnel walls, while the location of the transonic points is also affected by the geometrical shape of the funnel's cross-section.

I. INTRODUCTION

VLBI observations and variability time scales suggest that the central engine powering active galactic nuclei and the associated radio sources has dimensions of the order of our solar system ($\lesssim 10^{14}$ cm). In addition, supersonic jets ejected from active nuclei appear to be accelerated and collimated inside the deep cores: in some cases, the process can be extremely efficient, as suggested by superluminal expansion. These facts suggest the existence of accretion disks orbiting around massive black holes (Rees 1982). Several models have been proposed along these lines, wherein acceleration is produced either by radiation pressure forces or by electromagnetic processes in the vicinity of such disks.

Here we discuss some preliminary results of a hydrodynamical study of steady flows emanating from accretion funnels. We demonstrate the importance of the geometrical shape of the funnel in determining the final flow pattern, and discuss how, for identical boundary conditions, more than one physical solution may be allowed, some of which involve shocks. The general framework of this model has been presented elsewhere (Ferrari et al., 1983). Here we address the acceleration of an optically-thin, isothermal wind in the relativistic regime, assuming a simplified disk structure and radiation field within the funnel, as appropriate to VLBI jets and, perhaps, superluminal sources.

II. PHYSICAL PARAMETERS AND FLUID EQUATIONS

The conservation equations for particle number and energy-momentum give the following single equation for the dimensionless flow speed $\tilde{\beta}=v/c$ along the axis z of the jet:

$$\frac{d\beta^2}{d\xi} = \frac{1}{\gamma^4\left(1 - \frac{\beta_{so}^2}{\beta^2}\right)}\left[2\beta_{so}^2\gamma^2\frac{1}{A(\xi)}\frac{dA(\xi)}{d\xi} - \frac{b}{\xi^2} + \frac{D}{\rho c^2}\right] , \tag{1}$$

In this notation, $\xi = z/z_0$ is the dimensionless coordinate along the stream-lines, $A(\xi)$ is the cross-sectional area of the funnel, β_s is the dimensionless sound speed v_s/c, $b = GM/2z_0^2 c^2$, and the subscript "o" indicates quantities calculated at the base of the funnel z_0, which we fix as the flow's stagnation point (for example, $z_0 = 10^5$). Note that an isothermal equation of state has been assumed.

In Eq. (1) the first term on the right represents the effect of transverse pressure from the boundaries on the flow in terms of an integral average over the cross-sectional area (this requires a prompt response of the plasma to transverse perturbations). In this sense, the mathematical model is called "quasi-two-dimensional". The second term represents the gravitational attraction of the central mass, while the third represents the effects of nonthermal momentum deposition, which we assume to be due to radiation. A complete treatment of the problem would involve solving a radiative transfer equation; however, restricting ourselves to the case of a radiation field in an optically-thin plasma, we shall use the results of Schmidt-Burgk (1978):

$$\frac{D}{\rho c^2} = \frac{gb\gamma^3}{A(\xi)} \left[H(\xi)(1 - \beta)^2 - \beta[J(\xi) - H(\xi)](1 + f) \right] , \qquad (2)$$

where J, H, K, are the zeroth, first and second moments of the radiation field (averaged over frequencies), as measured in its rest frame. We recall that J is related to the total flux and H to the collimated part, and that K is the angular distribution of the collimated radiation:

$$f = \frac{K - H}{J - H} , \quad g = \frac{J_0}{J_{Edd}} . \qquad (3)$$

The presence of an anisotropic radiation field is due to the effect of the funnel walls (Sikora 1981).

We assume, with Piran (1982), a non-spherically symmetric shape for the funnel. Immediately above the stagnation point the funnel has a constant opening angle, i.e., $A(\xi) \propto \xi^2$; beyond this region, the opening angle increases parabolically, and $A \propto \xi^4$. Finally, at the exit of the funnel, we consider a sudden expansion, with $A \propto \xi^{2n}$, and n possibly very large. Further out, we allow for the possibility that n decreases again, perhaps to $n = 1$, if external conditions lead to recollimation (via magnetic or thermal pressures).

In this geometry, we can write the radiation field moments in the following form:

$$H(\xi) = \frac{1}{A(\xi)} \left(1 - \alpha(\xi,\epsilon) \right), \quad f(\xi) = \frac{1}{A(\xi)} \left(1 - \frac{2}{3}\alpha(\xi,\epsilon) \right), \quad \alpha(\xi,\epsilon) = \frac{1 - \epsilon}{\cosh \left(\dfrac{\xi - 1}{\xi_c - 1} \right)^m} \qquad (4)$$

for $m \geq 1$, where ϵ is a coefficient between 0 and 1 defining the level of collimation, and ξ_c is a typical (dimensionless) distance of the order of the disk geometrical thickness above which the radiation field becomes essentially isotropic. These expressions are valid within the accretion funnel; above the disk, we simply assume that the radiation field decays spherically. Finally, the remaining moment $J(\xi) \propto 1/A(\xi)$.

III. RESULTS

We shall not present all details of our calculations here; instead we shall simply focus on the qualitative trends of the solutions of the hydrodynamic equation (1) as applied to our astrophysical problem. The steady-state solutions are found by determining the positions of the zeroes of the term enclosed by square brackets on the right-hand-side of Eq. (1). The relevant solutions form a subset of those which make a transition from subsonic to supersonic flow at these points, because some of these critical points correspond to flow topologies which do not correspond to physical solutions. As discussed by Habbal and Tsinganos (1983) and by Ferrari *et al.* (1983), it is straightforward to find the physically relevant critical points, and then to integrate the corresponding solutions. A sample topology is given in Fig. 1 for a mildly relativistic case, with $T = 10^8$ K and $M = 10^8$ $M_\odot$.

For values of the physical parameters typical of active galactic nuclei, the Parker-type wind would become supersonic at a distance $z_p = GM/2\beta_{so}^2 c^2$, i.e., very far from the core, contrary to the observations quoted above. The presence of a sudden expansion of the funnel substantially modifies this classical solution, introducing new critical points near the location at which the maximum expansion occurs, so that the first two terms on the right side of Eq. (1) are in balance. The flow becomes supersonic, and collimated, at the exit of the throat of the disk. In addition, if the radiation field within the funnel is sufficiently intense (corresponding to $L \gtrsim 0.5 L_{Edd}$) and well-collimated ($\epsilon \gtrsim 0.7$), an additional transonic point appears before the exit of the funnel.
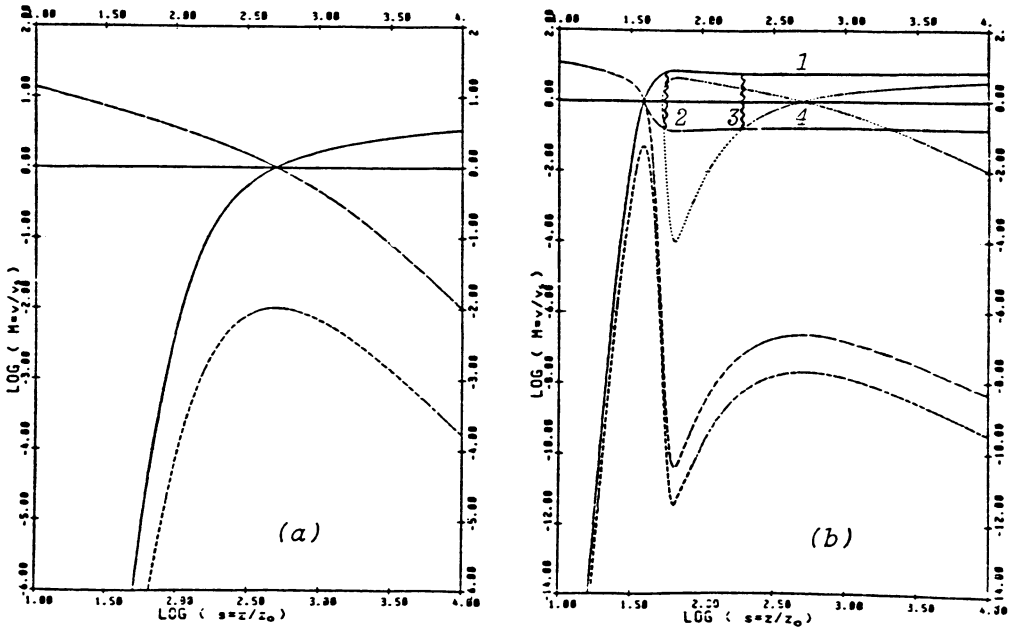

Fig. 1 - Topologies for mildly relativistic winds.

(a) Wind without nonthermal momentum addition ($D = 0$ and $A(\xi) \propto \xi^2$); the Parker-type critical point occurs at $\xi = 500$. (b) Wind with nonthermal momentum addition peaked at $\xi = 50$; one branch [1] becomes supersonic at $\xi = 39$; two additional solutions exist, which revert to subsonic flow at shocks [2,3], and again become supersonic at the Parker-type critical point [4].

The existence of additional transonic points also offers the possibility of distinct degenerate solutions corresponding to the same boundary and initial conditions. As shown in Fig. 1 (see also Ferrari *et al.*, 1983), steady solutions exist in which the flow becomes supersonic initially at the inner critical point, and then reverts to subsonic flow by an isothermal shock discontinuity, reaching the branch crossing the second transonic point. These configurations can be obtained in our problem for ϵ in the range 0.7 to 0.8 and for $L \sim L_{Edd}$. The presence of solutions with shocks is very interesting because they may be related to enhanced particle acceleration and variability effects when boundary conditions allow the flow to jump from one branch to another.

Finally, we have studied the conditions under which the flow can become relativistic after crossing the critical point. The geometrical effect does not seem to be able to provide enough momentum addition, unless one considers implausibly large expansion factors for the cross-sectional area A, and the quasi-two-dimensional theory becomes questionable. However, the radiation energy density inside the funnel can be much larger than that corresponding to the Eddington luminosity because of the geometrical concentration of the radiation field emitted from the walls in a narrow funnel (Piran 1982). In that case, radiation pressure suffices and, using $L \cong 50\ L_{Edd}$, allows to reach $\beta \gtrsim 0.9$.

IV. CONCLUSIONS

We have shown how straightforward wind theory allows a rather complete analysis of the hydrodynamics of flows from active galactic nuclei. A number of important effects have yet to be included in our analysis, such as the effect of rotation of the flow about its axis (which is likely to enhance collimation); the role played by magnetic fields (especially in determining the boundary conditions at the exit of the disk throat); the possibility of mass addition to the flow (because mass is likely to be added to the jet flow by "evaporation" and entrainment of matter from the funnel walls); and, finally, departures from isothermality. For example, the use of a more general polytropic equation increases the complexity of the topologies, and, following some preliminary results, tends to increase the momentum addition requirements to reach large supersonic velocities. However, even within the limits of the present work, our results appear to be a good guide for interpreting experimental data and for suggesting directions in the numerical simulations.

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