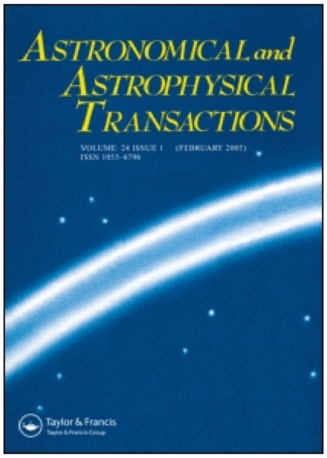

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MAGNETIC COLLIMATION OF RELATIVISTIC JETS

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We briefly outline a scenario for the magnetic collimation of outflows from AGN and other astrophysical compact objects, based on recent numerical simulations of axisymmetric 3-D MHD outflows from the central parts of these objects. It follows from our results that magnetic self-collimation of a relativistic plasma is negligibly small if all the outflow is relativistic. However, a tightly collimated inner relativistic jet can be indirectly formed by an exterior nonrelativistic but collimated disk-wind.

KEY WORDS Relativistic plasmas, MHD, jets, AGN

1 INTRODUCTION

Superluminal galactic objects (Mirabel and Rodriguez 1999) and AGN (Begelman *et al.*, 1984, Pelletier *et al.*, 1996) seem to eject relativistic plasma in the form of jets propagating at large distances from their source. Several problems arise in connection with such observations of relativistic jets. For example, it is necessary to find a mechanism for the initial ejection of the plasma, its subsequent acceleration to relativistic speeds and finally its collimation into highly directed outflows (jets). In this paper we shall restrict ourselves only to the problem of plasma collimation.

Among all possible mechanisms for the collimation of cosmic outflows, magnetic collimation seems to be the most interesting since it operates in ordinary conditions that may easily be realised in all different sources of observed jets (Lovelace, 1976; Blandford, 1976; Bisnovatyi-Kogan and Ruzmaikin, 1976). As a matter of fact, an analysis of the full set of the MHD equations shows that collimation is a rather general property of magnetised outflows from rotating objects (Heayvaerts and Norman, 1989; Chiueh *et al.*, 1991; Bogovalov, 1995). Thus, a magnetised and superfast wind will inevitably be partially collimated into a jet directed along the rotation and magnetic axis at large distances from the source in comparison to all characteristic dimensions of the system e.g., the size of the accretion disk. This collimation has been shown to occur when the flow is non-dissipative, the magnetised central object is rotating, the total magnetic flux of one polarity reaching infinity in open field lines is finite, the polytropic index of the plasma exceeds unity and the pressure of the ambient matter is low enough such that it cannot terminate the wind before the formation of the jet. Also, non-polytropic exact MHD families of solutions have been found where the outflow is cylindrically collimated asymptotically (Vlahakis and Tsinganos, 1998, Sauty *et al.*, 1999). Note that this result is independent of the detailed properties of the central source. Hence, collimation occurs spontaneously due to internal Lorentz forces acting in the magnetised plasma which is ejected from the rotating source. For this reason it is often referred to as the process of magnetic self-collimation.

A numerical investigation of this process and the ensuing characteristics of jets produced via this mechanism in the cold (Bogovalov and Tsinganos, 1999) or hot limits (Tsinganos and Bogovalov, 2000), for nonrelativistic as well as relativistic conditions (Bogovalov, 1997; Bogovalov, 2001) has verified the feasibility of this mechanism. However, these calculations have also demonstrated a general shortcoming of the mechanism of magnetic self-collimation. Namely, the mass flux in the jets formed from a uniformly rotating object appears to be uncomfortably low in comparison to the total mass flux from the initially non-rotating and non-collimated wind. For relativistic winds this problem is especially acute, since calculations in the simplest models give a ratio of the mass flux in the jet over the mass flux in the wind from the central source of the order of only 10^{-3} (Bogovalov, 2001). In this paper we present a model which can provide collimation of a larger part of the outflow into the jet due to magnetocentrifugal forces.

2 NUMERICAL SIMULATIONS OF A RELATIVISTIC PLASMA OUTFLOW

At the present time the only convenient method to obtain a steady state for the plasma outflow is through numerical simulation. In particular, the solution is attained in two steps. In the first step we obtain the solution in the nearest zone containing all critical surfaces and in the second we solve the problem in the far zone which spans the extremely large distances from the source encountered in many jets (Bogovalov and Tsinganos, 1999).

We use the model of a star with an initially monopole-like magnetic field, which is the simplest model which can be used for the investigation of the process of magnetic collimation. The steady state outflow of the relativistic plasma in this model is defined by two dimensionless parameters. One of them is $\sigma = (R_f/R_l)^2$, where $R_f = \sqrt{(B_0 R_\star)^2/4\pi\rho_0 c U_0}$ is the initial fast magnetosonic radius, R_l is the light cylinder radius, and B_0, ρ_0 and U_0 are the values of the magnetic field, plasma density and four-velocity on the stellar surface. The plasma is assumed cold. Another parameter is $\alpha = \sqrt{\sigma}/U_0$. A more detailed discussion of the physical meaning of these parameters is given in Bogovalov (1999).

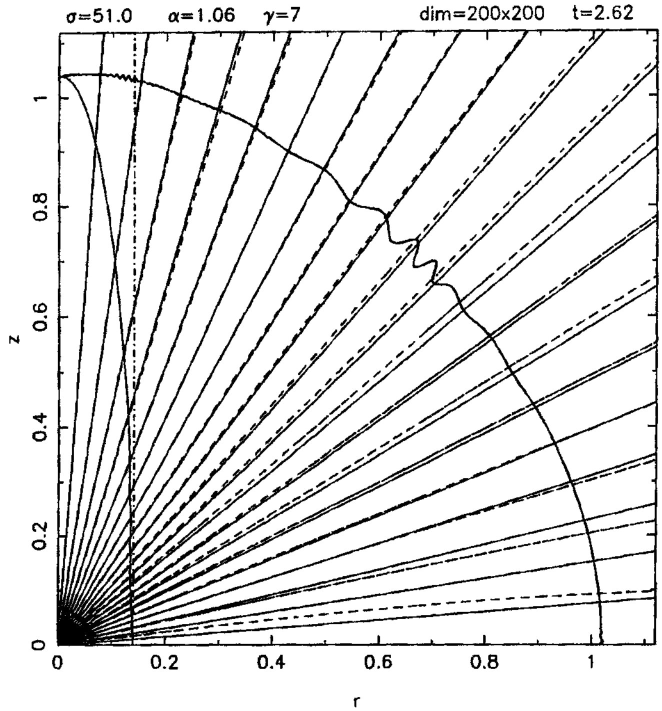

Figure 1 The steady state relativistic plasma outflow in the nearest zone for the parameters σ, α, the initial Lorentz-factor, the dimension of the lattice and the duration of the simulation in units R_f/v_0 is indicated at the top of the figure. The axes z and r are the axes of rotation and the equator, respectively. The coordinates are given in units of R_f. The star is located at the left lower corner of the figure. Solid lines outgoing from the star indicate the lines of the poloidal magnetic field. Dashed lines indicate the lines of the poloidal electric currents generated by rotation. The thick (thin) solid line indicates the fast (Alfvén) MHD surface. The vertical dashed-dotted line shows the light cylinder.

The result of the numerical simulation of the outflow for $\gamma_0 = 7$ and in the nearest zone is shown in Figure 1. Evidently, the collimation of the plasma outflow in the nearest zone is practically nonexistent. Similarly, in the far zone shown in Figure 2, the collimation is extremely weak and the wind expands practically radially.

However, this does not mean that the relativistic plasma is not self-collimated. A more detailed inspection of the flow near the axis of rotation shows that a thin jet-like structure is actually formed in the wind. Figure 3 demonstrates the dependence with the distance from the axis of rotation of the poloidal magnetic field normalized to its value at the axis, for two values of z. An approximate analytical solution which follows from the theory of self-collimation of magnetised winds is shown in this figure as well. Comparison of the numerical results with the theoretical prediction shows that the theory correctly predicts the structure of the relativistic wind at large distances from the source.

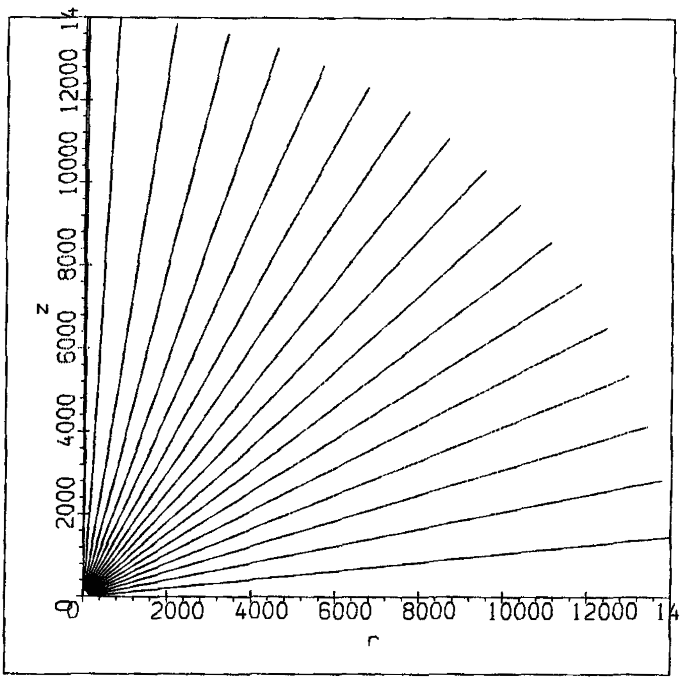

Figure 2 The relativistic plasma flow in the far zone for $\alpha = 1.0$ and $\sigma = 51$. The coordinates are expressed in units of R_f.

The transverse scale of the jet-like flow is very small compared to the distance to the source. This is why this jet is not visible in Figure 2. It follows from Figure 3 that the magnetic flux in the jet is of the order 10^{-3} of the total magnetic flux in the wind. The mass flux density is proportional to the poloidal magnetic field. Therefore, the mass flux in the jet is of the order of 10^{-3} of the total mass flux in the wind from the source. This value is uncomfortably small for astrophysical applications. Therefore, it is important to find conditions which provide magnetic collimation of a significant part of the wind into the jet.

3 MODEL WITH HIGH MASS FLUX IN THE JET

A comparison of the degree of collimation of the relativistic plasma with the degree of collimation of the nonrelativistic plasma shows that the relativistic plasma is much more weakly collimated than the nonrelativistic one. A discussion of the difference in the physics of collimation of the relativistic and nonrelativistic plasma is given in Bogovalov (2001). Here we suggest a model which provides collimation of all the flux of the relativistic plasma from the source. This model includes the central source which ejects uncollimated relativistic plasma and an accretion disk.

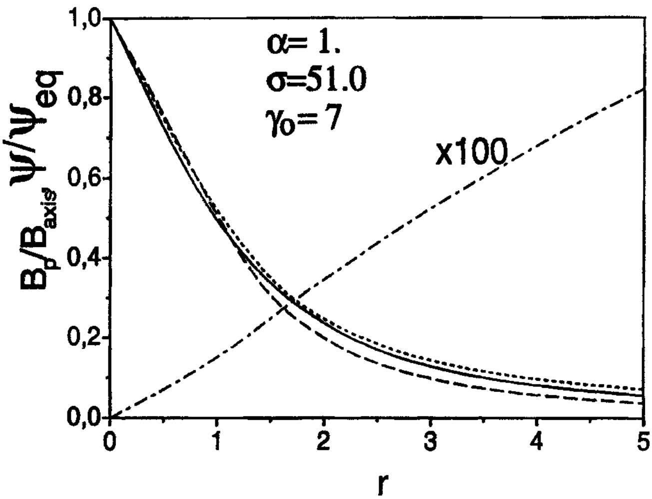

Figure 3 The dependence of the poloidal magnetic field across the jet at $z = 1121R_f$ (solid line) and at $z = 140R_f$ (dotted) compared with the prediction of the analytical theory (dashed line). The dash-dotted line shows the ratio of the magnetic flux to the total magnetic flux in the upper hemisphere multiplied by a factor 100. The distance to the axis of rotation r is expressed in units of R_f. The radius of the jet in these units is $1/\alpha = 1$.

We assume that a nonrelativistic wind is emitted from this accretion disk. This wind is magnetised and indirectly collimates the relativistic wind from the central source. A sketch of this model is presented in Figure 4.

It is easy to understand that all the relativistic wind from the central source will be collimated in this model. Let us consider the limiting case where the central source does not rotate and only the accretion disk is in Keplerian rotation. The theory of magnetic self-collimation of rotating outflows (Heyvaerts and Norman, 1989; Chiueh *et al.*, 1991; Bogovalov, 1995) predicts that at large distances from the central source there should be at least one field line which is directed along the axis of rotation. The root of this field line should be in rotation with finite angular velocity. It follows from this result that at least one magnetic surface of the nonrelativistic wind will be directed along the axis of rotation. All the mass flux including the relativistic outflow surrounded by this surface will then also be collimated.

4 DISCUSSION

The model that we suggest here consists of a central object which ejects relativistic plasma and an accretion disk which is the source of a nonrelativistic disk-wind. Actually this model is not new. A similar model has been suggested by Sol *et al.* (1989) in relation to AGN. Shu *et al.* (1991) on the other hand, have proposed an ejection

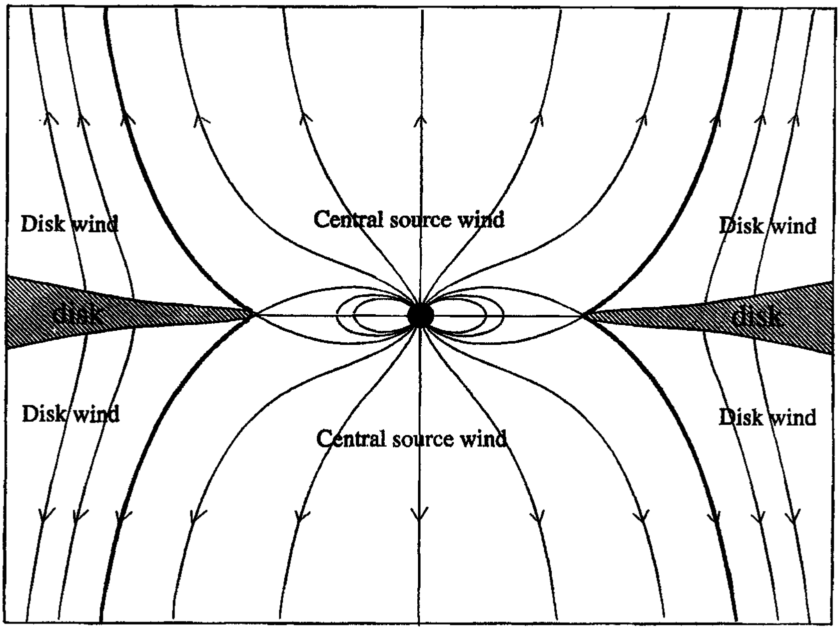

Figure 4 Sketch of our model which can provide collimation of all the relativistic plasma flow from the central source. The model includes the central source and the accretion disk. The magnetised nonrelativistic wind from the accretion disk collimates the relativistic plasma emitted from the central regions of the source.

mechanism of the mass supplied by the accretion disk in the context of YSO's. We do not specify here the mechanism for the plasma ejection from the central source. The nonrelativistic wind may be accelerated from the accretion disk, for example, via the Blandford and Payne (1982) mechanism. Here we emphasized the new role which the disk-wind may play. This wind itself does not produce the relativistic jet, but only serves as the collimator of the initially uncollimated central relativistic wind. An investigation of the collimation of nonrelativistic plasma in this model has been already investigated numerically in the framework of this model (Bogovalov and Tsinganos, 2001). It was shown that the wind from the central source can indeed be totally collimated along the axis of rotation. Similar investigations for relativistic outflows will be published elsewhere.

Acknowledgements

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