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Parameter study in disk-jet systems: Magnetization

P. Tzeferacos([1]), A. Ferrari([1])([2]), A. Mignone([1])([3]), C. Zanni([4]),
G. Bodo([2]) and S. Massaglia([1])

([1]) *Dipartimento di Fisica Generale, Università di Torino*
Via Giuria 1, 10125 Torino, Italy
([2]) *Department of Astronomy and Astrophysics, University of Chicago - Chicago, USA*
([3]) *Osservatorio Astronomico di Torino - Viale Osservatorio 20, 10025 Pino Torinese, Italy*
([4]) *Laboratoire d'Astrophysique de Grenoble - 414 rue de la Piscine*
BP 53, 38041 Grenoble, France

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Summary. — In this study we discuss the impact of the magnetic field's strength onto the characteristics of solutions in models where both the collimated outflow and the accretion disk are treated consistently. We perform an analysis on the range of magnetic field by non-relativistic 2.5 dimension numerical simulations using the PLUTO code. The main results are that magnetic fields around equipartition with plasma pressure allow for steady super-fast-magnetosonic collimated jet solutions; magnetic fields below equipartition correspond to intermittent collimated outflows, whereas above equipartition cases lead to sub-alfvenic winds. This allows to conclude that the configuration proposed by Blandford and Payne to interpret supersonic jets is viable both for equipartition and weaker magnetic fields.

PACS `97.10.Gz` – Accretion and accretion disks.
PACS `97.10.Me` – Mass loss and stellar winds.
PACS `97.21.+a` – Pre-main sequence objects, young stellar objects (YSO's) and protostars (T Tauri stars, Orion population, Herbig-Haro objects, Bok globules, bipolar outflows, cometary nebulae, etc.).
PACS `98.58.Fd` – Jets, outflows and bipolar flows.

1. – Introduction

From the mid seventies Lovelace [1] and Blandford [2] showed that a force-free poloidal field anchored in a astrophysical Keplerian disk can extract energy and angular momentum creating a Poynting flux jet. This idea was developed in the MHD regime by Blandford and Payne [3], who showed how Poynting jets can transfer energy and momentum to outflowing matter via a magneto-centrifugal mechanism, capable of reaching super-fast-magnetosonic speeds. In these studies the disk was treated as a fixed boundary and no self-consistent treatment of the inflow/outflow dynamics was attempted. More recent works, for example Ferreira and Pelletier [4], Ferreira [5] and Casse and Ferreira [6] have studied analytic "cold" and "warm" steady state outflow solutions and linked them to thin accretion disks; they conclude that super-fast-magnetosonic outflows can be obtained with plasma β values around unity, for a limited range of Prandtl numbers and larger toroidal diffusivity.

Numerical simulations allow instead to investigate time-dependent solutions, often still limited to the study of the outflow treating the disk as a boundary condition [7-9], or referred to the entire disk-jet system but for very short timescales [10, 11]. Casse and Keppens [12] have followed the evolution of an accretion-ejection system for longer timescales but without using an energy equation replaced by a simple polytropic equation of state; more recently they updated their work including non-adiabatic effects [13].

In this work we address the problem of the stationarity of the inflow/outflow dynamics on the basis of compressible MHD numerical simulations, analyzing the effects of the most relevant physical parameters with respect to the possibility of reaching steady state solutions over long time scales of integration. In a previous paper, Zanni *et al.* [14] have discussed the importance of resistive effects. Here we concentrate on the strength and configuration of the initial magnetic field associated with the accretion disk. Simulations have been performed in a 2.5D resistive framework, utilizing the numerical code PLUTO [15].

2. – Model description

In order to model the accretion ejection system we solve numerically the equations of resistive magnetohydrodynamics, neglecting all transport coefficients but magnetic resistivity η_m. The latter is parametrized following the Shakura and Sunyaev [16] paradigm. We allow for anisotropy in the magnetic diffusion through a tensor representation of η_m and we specify the toroidal diffusion to be three times stronger than the poloidal. Even though we solve the energy equation, we presume that the heating caused by Ohmic dissipation is completely radiated. This is done to avoid a rise in the disk's entropy, being thus closer to the "cold" analytic solutions of Ferreira [5].

The strength of the magnetic field is defined by the magnetization parameter $\mu = B^2/P$. Note that this parameter is used in the analytical formalism [4-6]. We study four different cases of magnetization, below and above the limits set in the previously mentioned studies. From weak to strong field configurations, cases 1 to 4 correspond to values of μ equal to 0.2, 0.6, 2.0 and 6.0, respectively. Only the second case is within the analytical limits. The initial inclination of the magnetic field satisfies the Blandford and Payne criterion [3] and is approximately current free.

The initial configuration is that of a thin disk rotating at slightly sub-Keplerian speed with an embedded magnetic field with purely poloidal field lines exiting at some angle from the disk's surface. The field is initialized through its flux function, ensuring solenoidality. The profiles of all other primitive variables are derived starting from an equatorial radial self-similarity assumption [3] and imposing a force equilibrium in both radial and vertical directions. In pressure equilibrium with the disk's surface, we overimpose a static hot corona with a radial stratification.

Our domain is a rectangular region spanning radially from 0 to $40r_0$ and vertically from 0 to $120r_0$. The temporal integration reaches ~ 63 revolutions of the disk's inner radius. Uniform resolution of $[512 \times 1536]$ is used throughout the domain. Axisymmetry is assumed on the rotation axis whereas equatorial symmetry is supposed on the disk's midplane. At the upper and right boundaries special care has been shown in order to avoid artificial collimation. Since the origin is inside the computational domain, an appropriate sink internal boundary $[1.0r_{\text{in}} \times 0.5r_{\text{in}}]$ is imposed to cope with the singularity of the radial self-similar model there.

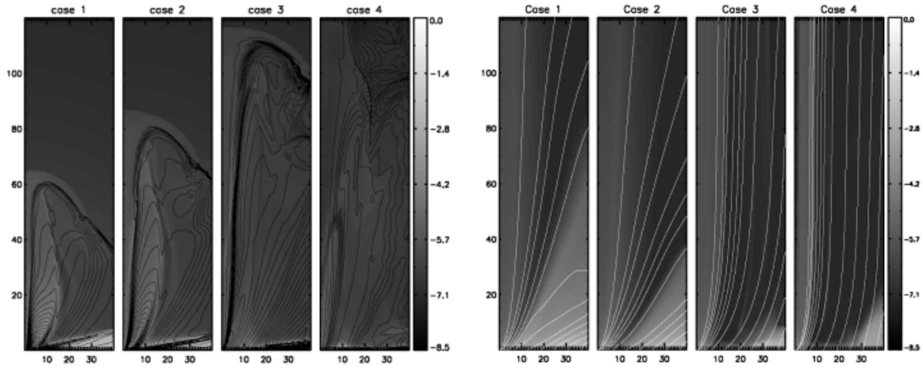

Fig. 1. – On the left: The poloidal current distribution for the four cases studied, after ~ 6 rotations of the inner radius. A butterfly topology [5] is found in sub-equipartition cases. The ejection region is identified in a range between 1 and 10 r_{in}. On the right: Sample poloidal magnetic field lines for the four cases studied after 63 rotations.

3. – Results and conclusions

In all cases a current carrying outflow is formed from the early stages of the simulations (fig. 1). The magnetic tension and the comparatevely lower magnetic Reynolds number within the disk quickly collimate the outflow in high μ configurations. The initial inclination of the magnetic field lines cannot be sustained and the angular momentum is quickly redistributed, resulting in a slower rotation of the disk. This decrease in the field's curvature has a direct impact both in the ejection efficiency of the system and its ability to accelerate the outflowing plasma. For a weak magnetic field the collimation is somewhat inefficient (fig. 1).

Monitoring the outflow/inflow rates at a control volume set in the ejection region we see that there is a clear plateu after the initial transient phase for low μ cases. The rate

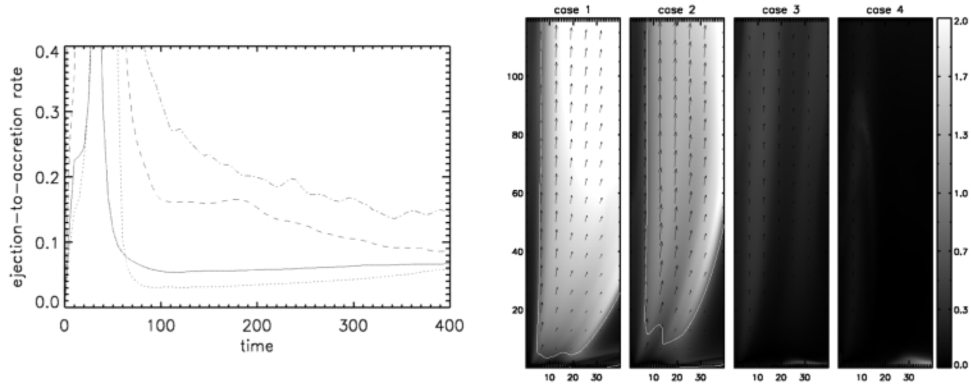

Fig. 2. – On the right: Mass ejection to accretion rates as a function of time, taking into consideration the counter jet. The notation used is: Case 1 dotted, case 2 solid, case 3 dashed and case 4 dot-dashed line. On the right: Snapshots, after ~ 35 rotations, of the poloidal velocity over the fast magnetosonic. The line indicates the Alfvénic surface and the poloidal velocity vectors are superimposed. The length of the arrows is normalized to the maximum poloidal speed reached in case 1.

is not sustained for magnetically dominant configurations (fig. 2). The ejection efficiency found for case 2 is close to the analytical results of Ferreira [5], for a set of parameters close to ours.

Only low magnetization configurations are able to cross the Alfvén and super-fast magnetosonic critical surfaces. The terminal velocities evaluated along field lines for cases 1 and 2 range between 4-5 times the Keplerian velocity of the respective footpoint. High μ cases are four to five times slower, with case 4 barely crossing the slow surface at the innermost part. This is attributed both to the field's topology and the elevated ejection rates. The Poynting flux transformation to kinetic energy for cases 1 and 2 is almost complete (magnetic to kinetic energy flux ratios $\sim 10^{-2} - 10^{-1}$ at the upper end of the domain). Magnetically dominant configurations, on the other hand, seem defficient in accelerating the outflowing plasma with ratios of 1-3.

The plateau in the ejection efficiency and the preservation of the MHD invariants (not shown here) advocate in favour of the quasi stationarity of the solutions for magnetization below equipartition. It is also clear that no such claim can be made for the strongly magnetized cases. This statement applies only to the innermost part of the magnetized disk, since the revolutions of the outer part are not enough to reach a quasi-stationary state.

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