Launching mechanisms of astrophysical jets

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Abstract The combination of accretion disks and supersonic jets is used to model many active astrophysical objects, viz., young stars, relativistic stars, and active galactic nuclei. However, existing theories on the physical processes by which these structures transfer angular momentum and energy from disks to jets through viscous or magnetic torques are still relatively approximate. Global stationary solutions do not permit understanding the formation and stability of these structures; and global numerical simulations that include both the disk and jet physics are often limited to relatively short time scales and astrophysically out-of-range values of viscosity and resistivity parameters that are instead crucial to defining the coupling of the inflow/outflow dynamics. Along these lines we discuss self-consistent time-dependent simulations of the launching of supersonic jets by magnetized accretion disks, using high resolution numerical techniques. We shall concentrate on the effects of the disk physical parameters, and discuss under which conditions steady state solutions of the type proposed in the self-similar models of Blandford and Payne can be reached and maintained in a self-consistent nonlinear stationary state.

Keywords Jets · Accretion disks · Magnetohydrodynamics · Numerical simulations

1 Introduction

Supersonic outflows and collimated jets have been detected in many astrophysical objects: young stellar objects (YSO), microquasars, X-ray binaries, gamma-ray bursts (GRB), extended radio galaxies and active galactic nuclei (AGN). In all these scenarios the production of outflows is correlated with the presence of inflows in the form of disks accreting onto a central compact object. The outflow velocities appear to be of the order of the escape velocity from the central attractors; therefore in the most active environments, where the central attractors are most likely black holes, the outflow velocities are relativistic. Although supersonic velocities can be reached by purely hydrodynamic mechanisms or by radiation pressure, outflows with Lorentz factors substantially large can only be explained by the intervention of electromagnetic effects. Therefore, the most acknowledged models for interpreting the origin of astrophysical supersonic and relativistic jets are based on the interaction of large scale magnetic fields with an accreting quasi-Keplerian disk.

In seminal works Lovelace (1976) and Blandford (1976) showed that starting from a force-free poloidal field anchored in a Keplerian disk it is possible to extract energy and angular momentum creating a Poynting flux jet that accelerates a plasma current along the disk funnel up to relativistic speeds. This model has been adapted to the MHD regime, including the matter’s inertia, by Blandford and Payne (1982), who showed how the Poynting jet can transfer its energy and momentum to the kinetics of a matter outflow through a magneto-centrifugal mechanism capable of reaching superfast-magnetosonic speeds. In these works the disk was considered as a fixed boundary and no self-consistent treatment of the whole inflow/outflow dynamics was attempted.

While the Poynting flux solutions may apply to the extended radio sources and AGN jets whose densities appear
much lower than in the ambient medium, the MHD case with relatively dense jets carrying inertia is in fact of more general application for all types of jets. In fact most of the works in the last 20 years make reference to the Blandford and Payne model aiming to include the dynamics of the accretion disk to show for which parameters the MHD launching of the jet may occur. Ferreira and Pelletier (1995) and Casse and Ferreira (2000) have derived analytic “cold” steady state outflow solutions linked to accreting slim disks including viscous and resistive effects in the disks and allowing for anisotropic magnetic diffusivity between poloidal and toroidal fields; their conclusion is that superfast-magnetosonic outflows can be obtained with magnetic fields around equipartition, for a limited range of Prandtl numbers and larger toroidal diffusivity.

Ogilvie and Livio (2001) investigated the effect of the vertical structure of a cold disk in equilibrium with an isothermal corona considering also different topologies of the poloidal field; they showed that substantial outflow rates are allowed only for magnetic fields around equipartition values and poloidal components exiting at angles around 35–45° from the disk.

Supercomputer simulations have been used to investigate time-dependent solutions, often still limited to the study of the origin of the outflow and treating the disk as a boundary condition (Ustyugova et al. 1999; Ouyed and Pudritz 1997a, 1997b; Krasnopolsky et al. 1999), or treating the entire disk-jet system but for very short timescales (Uchida and Shibata 1985; Kato et al. 2002). Casse and Keppens (2002) have followed the evolution of an accretion-ejection system for longer timescales but replacing the energy equation by a simple polytropic equation of state; more recently they updated their work to include non-adiabatic effects (Casse and Keppens 2004).

At present the stability of configurations of jet-driving magnetized disks is still under discussion. An interesting approach on this issue has been proposed by Königl (2004) working out a stability criterion that show the existence of a class of stable solutions of the self-similar Blandford and Payne model.

In this review we address the same inflow/outflow dynamics problem based on compressible MHD numerical simulations and analyze the effects of the physical parameters with respect to the possibility of reaching steady state solutions over long time scales of integration. Simulations have been performed making use of two different numerical codes, the FLASH (Fryxell et al. 2000) and the PLUTO (Mignone et al. 2007) codes. We shall concentrate our discussion on the non-relativistic dynamics of a jet-driving disk. The interaction with the central object and the outflows which could possibly emerge from this part of the system will be neglected.

2 The MHD simulation setup

The dynamics of MHD accretion/ejection is solved numerically in terms of the MHD equations; we shall neglect the physical viscosity but include resistivity: in fact for Prandtl numbers close to unity and magnetic fields not too far from equipartition the effect of viscosity is negligible (Meliani et al. 2006). For reference we report here the equations used, with the standard meaning of the physical quantities.

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \left[ \rho \mathbf{u} \mathbf{u} + \left( P + \frac{\mathbf{B} \cdot \mathbf{B}}{2} \right) \mathbf{I} - \mathbf{B} \mathbf{B} \right] \\
&\quad + \rho \nabla \Phi_\mathrm{g} = \mathbf{0}, \\
\frac{\partial e}{\partial t} + \nabla \cdot \left[ \left( e + \frac{\mathbf{B} \cdot \mathbf{B}}{2} \right) \mathbf{u} - (\mathbf{u} \cdot \mathbf{B}) \mathbf{B} + \bar{\eta} \mathbf{J} \times \mathbf{B} \right] \\
&\quad = -\Lambda_{\mathrm{cool}}, \\
\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times \mathbf{E}, \quad \mathbf{E} = -\mathbf{u} \times \mathbf{B} + \bar{\eta} \mathbf{J}, \quad \mathbf{J} = \nabla \times \mathbf{B}.
\end{align*}
\]

Here \( \Phi_\mathrm{g} = -GM/\sqrt{r^2 + z^2} \) is the gravitational potential, \( \Lambda_{\mathrm{cool}} \) is a cooling function and \( e = P/(\gamma - 1) + \rho \mathbf{u} \cdot \mathbf{u}/2 + \mathbf{B} \cdot \mathbf{B}/2 + \rho \Phi_\mathrm{g} \) is the total energy density. The system was closed by the equation of state for ideal gas \( P = n K T \) with polytropic index \( \gamma = 5/3 \). The magnetic resistivity is a diagonal tensor \( \eta_{ij} \) whose non zero components are \( \eta_{\phi \phi} = \eta_m \) and \( \eta_{rr} = \eta_{zz} = \eta_m' \); the anisotropy between \( \eta_m \) and \( \eta_m' \) will be henceforth denoted by the free parameter \( \chi_m \) defined as \( \eta_m' = \chi_m \eta_m \). The cooling function \( \Lambda_{\mathrm{cool}} \) will be taken equal to the Ohmic heating term \( \Lambda_{\mathrm{Ohm}} = \bar{\eta} \mathbf{J} \cdot \mathbf{J} \); i.e. the Ohmic heating is radiated away instead of being dissipated locally inside the disk.

The simulations started from a thin disk rotating at slightly sub-Keplerian speed and threaded by a purely poloidal magnetic field defined by its flux function ensuring \( \nabla \cdot \mathbf{B} = 0 \):

\[
\psi = \frac{4}{3} B_{\mathrm{c0}} r^2 \left( \frac{r}{r_0} \right)^{3/4} \frac{m^{5/4}}{(m^2 + z'^2)^{5/8}},
\]

where the parameter \( m \) determines the initial bending of the field at the disk surface and the coefficients \( B_{\mathrm{c0}}, r_0 \) can be derived by normalization at the disk’s midplane; in particular \( B_{\mathrm{c0}} \) is used to define the magnetization parameter \( \mu = B_{\mathrm{c0}}^2 / 2 P \), i.e. the strength of the magnetic field at the midplane. While the radial behavior of the flux function has been chosen in order to have a constant magnetization \( \mu \) along the midplane of the disk, its bending and curvature have been imposed by testing that with such a radial gradient the magnetic field naturally tends to open and bend to balance its radial pressure gradient with its curvature and tension. Pressure, density and rotation velocity of the disk have