MHD Accretion-Ejection Flows

Fabien CASSE
FOM - Institute for Plasma Physics "Rijnhuizen", P.O. Box 1207 3430 BE Nieuwegein, Netherlands, fcasse@rijnh.nl

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Abstract. In this proceeding I present recent works dealing with MHD simulations describing resistive accretion disks continuously launching large-scale, self-collimated MHD jets. In particular, I discuss the physical conditions required to produce these outflows and the related numerical issues. As an illustration I also present axisymmetric MHD numerical simulations of such accretion-ejection engines, demonstrating the mechanism controlling these flows.

Keywords: Accretion disks – Jets: YSO, X-ray binaries and AGN – MHD:numerical simulations

1. Accretion-Ejection models

Since the discovery of collimated outflows coming from various kinds of astrophysical systems as young stellar objects (YSOs), active galactic nuclei (AGN) or X-Ray binaries (XRB), several scenarios have been proposed to explain the different features exhibited by these structures. Nowadays, only one generic model has passed the test of time, this one being able to explain either energy and mass sources or collimation of the observed jets. This generic model called "accretion-ejection" model, is based on the interaction of an open large-scale magnetic field interacting with an accretion disk. In this model first proposed by (Blandford & Payne, 1982), the accretion (and the accompanying released gravitational energy) is the energy source for accelerating mass in the jet thanks to an MHD Poynting flux leaving the disk. The collimation of the jet is achieved by the action of the magnetic field that can confine the jet plasma thanks to the magnetic pinching occurring in cylindrical geometry.

Numerous studies have been performed since this first idea but because of the complexity of the problem, none of them has been able to give either complete axisymmetric analytical or numerical solutions without at some point doing any simplifying assumptions. Among the most frequent assumptions, self-similarity is very useful because it enables reduction of the 2D problem into a 1D problem. This method is based on the variable separation induced by the Newtonian gravitational potential and the most recent developments have led to self-similar disk launching stationary super-fastmagnetosonic MHD jets (see (Ferreira & Casse, 2004)). However, this method implies strong constraints on critical surfaces shapes that influence the behavior of the flow in the super Alfvénic regime. Another approach of the problem is to compute such flow using time dependent multidimensional MHD codes. A number of attempts has been done but none of them has ever been able to describe a long term evolution of an accretion disk continuously launching a super fast-magnetosonic jet (see the review by Shibata in this volume). In the next section, I am going to describe the accretion disk properties needed to obtain a stable jet and in the third section, I will illustrate such structures with numerical MHD simulations obtained with the Versatile Advection Code ((Tóth, 1996)).

2. Accretion disk and Jets

Astrophysical jets are now observed for several decades and they do not show any drastic changes in their general shape or velocity. Some variations nevertheless occur but do not influence neither collimation nor velocity. So if one wants to describe these structures, one has to perform simulations running over a large number of inner disk rotations since the rotation period ranges from a few milli-seconds in XRB to a few days in both YSO and AGN. This constraint has a direct impact on the disk structure. Indeed a disk with a bipolar topology (as suggested by the existence of observed twin jets in most of the systems) has to get a stationary magnetic structure. Since the magnetic reservoir of the accretion disk is not infinite, some resistivity η has to occur in the accretion disk in order to allow mass to cross the magnetic surfaces without dragging the magnetic field. This resistivity is probably of the same origin than the viscosity invoked in standard accretion disks and probably resulting from disk turbulence.

The other issue of accretion-ejection structure is to provide a vertical disk balance that enable a fraction of the disk mass to reach the disk surface where the magnetic field can accelerate it. This can only be consistent with a disk where vertical forces balance each other. Only three vertical forces are acting on the disk, namely the thermal pressure gradient, the magnetic force and gravity. The latter two ones can only pinch the accretion disk because of the bipolar topology of the magnetic field while thermal pressure gradient tends to lift up matter. In Keplerian disk, thermal pressure is naturally overwhelming vertical gravitational pinching so the previous equilibrium is only possible if the thermal pressure gradient is of the order of the magnetic pinching. This requirement leads to the fact that Keplerian accretion disks launching jets are in equipartition between magnetic and thermal pressure.

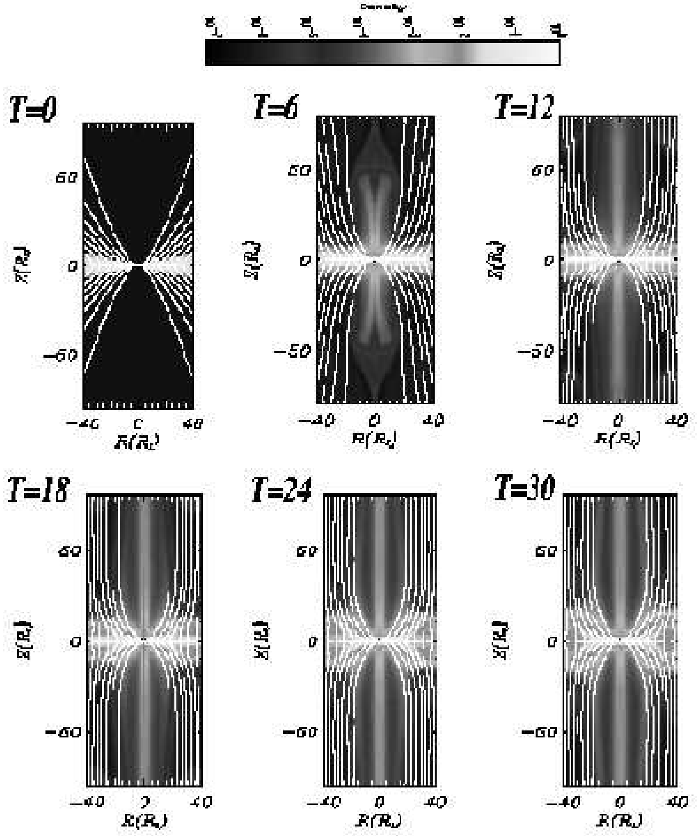

Figure 1. Temporal evolution of a resistive accretion disk threaded by a poloidal magnetic field. Color levels represent density level while solid lines stand for poloidal magnetic field lines. The time unit labeling each snapshot is the number of rotations of the inner radius. After a few rotations, outflows are escaping from the disk and remain focused despite an initial bent poloidal magnetic configuration. Once jets are launched, the structure varies little during the remainder of the whole computation.

3. MHD equations and Initial conditions

One has to solve the whole set of MHD equations in order to describe the dynamics and energetics of the flow. This includes mass ρ,

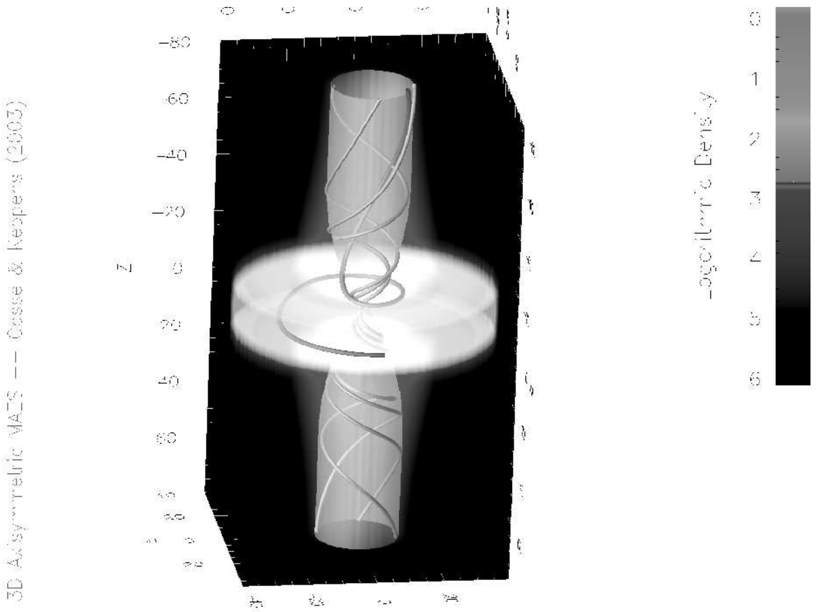

Figure 2. Three-dimensional impression of the final near-stationary end-state reached in our simulations. Grey scale levels represent a volume rendering of plasma density and translucent surface stands for a magnetic surface anchored at $R = 3$ in the disk. Light and dark lines stand for magnetic field lines and flow streamline respectively. As can be seen, magnetic field lines are twisted by disk rotation which provokes mass acceleration as shown by the flow streamline that is initially accreting toward the central object and then turns into the jet.

momentum $\rho\mathbf{v}$ and energy conservation e, namely

$$\begin{aligned}
\frac{\partial\rho}{\partial t} &= -\nabla\cdot(\rho\mathbf{v}) \\
\frac{\partial\rho\mathbf{v}}{\partial t} &+ \nabla\cdot(\mathbf{v}\rho\mathbf{v}-\mathbf{B}\mathbf{B})+\nabla\left(\frac{\mathbf{B}^2}{2}+P\right)+\rho\nabla\Phi_G = 0 \\
e &= \frac{\mathbf{B}^2}{2}+\frac{\rho\mathbf{v}^2}{2}+\frac{P}{\gamma-1}+\rho\Phi_G \\
\frac{\partial e}{\partial t} &+ \nabla\cdot\left[\mathbf{v}\left(e+P+\frac{B^2}{2}\right)-\mathbf{B}\mathbf{B}\cdot\mathbf{v}\right] = \eta\mathbf{J}^2-\mathbf{B}\cdot(\nabla\times\eta\mathbf{J}). \quad (1)
\end{aligned}$$

where $\mathbf{J} = \nabla\times\mathbf{B}$ is the current density, Φ_G is the Newtonian gravitational potential, η the resistivity and $\gamma = 5/3$ the specific heat ratio. Note that we do not consider radiative losses in the energy equation. The following simulations will then only stand for non-radiative accretion disks as for instance in M87 AGN.

Compiling previous necessary conditions for jet launching, one naturally ends up with initial conditions close to the one I am presenting here. Indeed if one assumes a Keplerian accretion disk in the "standard" accretion disk framework (Shakura & Sunyaev, 1973) neglecting radiative pressure, one has the sound speed scaling as $\Omega_K H$ where Ω_K is the Keplerian angular velocity and $H = \epsilon R$ is the disk scale height ($\epsilon \ll 1$ for thin accretion disk). Scaling all velocities to the sound speed enables us to obtain a natural Keplerian-like disk configuration where quantities are described as the product of a radial power-law and a vertical profile (Casse & Keppens, 2004).

The initial magnetic field configuration is really crucial because the final collimation of the jet has to be confirmed without the action of any numerical effect that may occur. In order to avoid any initially induced collimation we have to design a bent poloidal magnetic field taking into account several constraints: plane symmetry at the disk mid-plane ($Z = 0$), axial symmetry at $R = 0$, $\nabla \cdot \mathbf{B} = 0$ and coming from previous sub-section, equipartition with thermal pressure. This led us to employ an initial prescription as

$$\begin{aligned}
F(R,Z) &= \sqrt{\beta_P}\frac{R_o^{5/4}R^2}{(R_o^2+R^2)^{5/8}}\frac{1}{1+\zeta Z^2/H^2}, \\
B_R(R,Z) = -\frac{1}{R}\frac{\partial F}{\partial Z} &\quad , \quad B_\theta(R,Z) = 0 \\
B_Z(R,Z) &= \frac{1}{R}\frac{\partial F}{\partial R} + \frac{\sqrt{\beta_P}}{(1+R^2)} \ . \qquad (2)
\end{aligned}$$

An illustration of this magnetic field topology is shown on figure 1 in the first snapshot. It is noteworthy that the computational domain used to describe these flows requires a sink region at the origin to avoid both gravitational singularity and mass accumulation. The sink we have designed enables mass to fall into the sink but does not permit any outflow to originate from this region. Thus the outflow observed in the simulation can only come from the accretion disk itself.

4. Non-radiative MHD accretion-ejection flows

The result of numerically simulating the full MHD dynamics of the resistive magnetized accretion disk is displayed in Figure 1. The six snapshots represent six poloidal cross-sections of the structure at different stages of its temporal evolution. The rotation of matter twists the initially purely poloidal magnetic field lines such that outflows appear at the surface of the disk. The outflow is continuously emitted during the further evolution of the system. The evolution of both the mass outflow and the magnetic field topology gets closer to an equilibrium

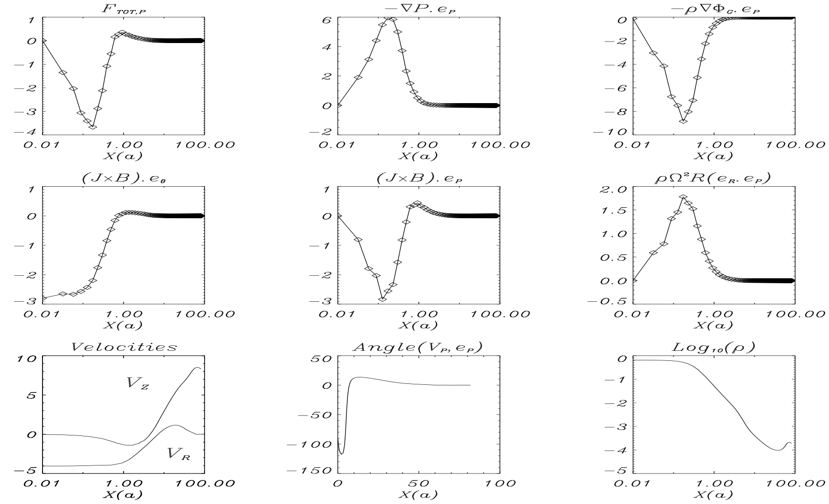

Figure 3. Plots of forces projected along a given magnetic surface as a function of the curvilinear abscissa along this magnetic surface $X(a)$ at T=30. The foot-point of this surface is at $R = 3$. From left to right and from top to bottom: total force, thermal pressure gradient, gravity, magnetic torque, poloidal magnetic force, centrifugal force, radial and vertical velocities, angle between poloidal velocity and poloidal magnetic field and density. The key to achieve an accretion-ejection configuration is to have a magnetic configuration where the Lorentz force pinches the disk and accelerates matter in the jet.

as time increases since the poloidal velocity component of the outflow becomes parallel to the poloidal magnetic field. Moreover, the outflow is radially collimated and crosses the Alfvén and fast magnetosonic speeds, to become superfastmagnetosonic well before it reaches the top boundary of the computational domain. In Figure 2, we present a three-dimensional representation of the final stationary end-state reached. We visualized a magnetic surface which is anchored at $R = 3$ which nicely shows its initial fanning out as well as its eventual collimation. Selected field lines are light lines, revealing their helical character. We also plot a streamline (dark line) which shows the path of a plasma parcel that is initially accreting within the disk in a spiral fashion, until it reaches the jet launch area where it gets propelled into the jet.

The accretion-ejection zone is the most crucial area when simulating the launching of jets. A subtle balance between different forces must be obtained in order to achieve a continuous emission of matter, as well as the collimation of the resulting outflow. As an example, we display in Figure 3 the different forces in the disk equilibrium at the final time of the simulation from Figure 1. In this figure, the poloidal forces are represented along a given magnetic surface already repre-

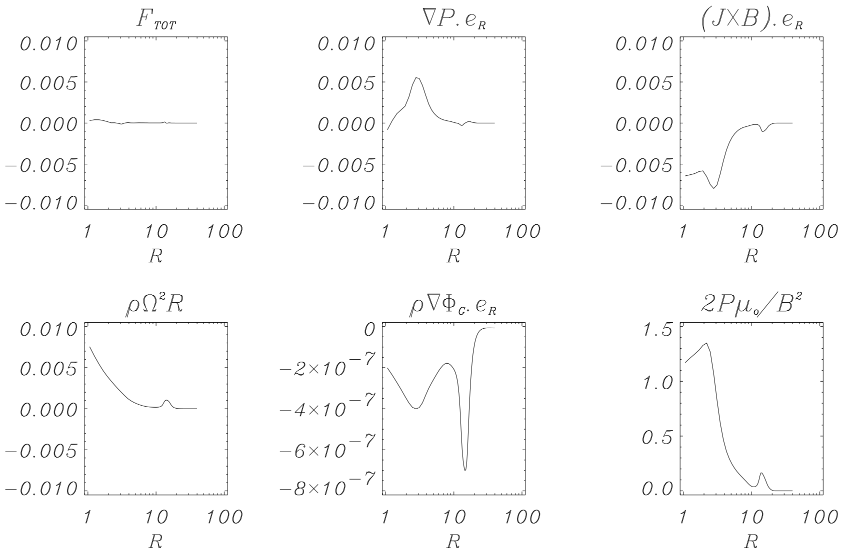

Figure 4. Plots of radial forces acting on the jet at Z=60 and at T=30. The total force is very small and ensures a good collimation for the jet. The radial equilibrium of the jet is achieved thanks to a thermal pressure gradient and centrifugal force balancing the radial magnetic force. This equilibrium where thermal pressure is of the same order than magnetic pressure is the signature of a "hot" jet.

sented in Figure 2 as well as the magnetic torque, poloidal velocity and temperature. The vector $\hat{\mathbf{e}}_P$ occurring in Figure 3 is defined as $\mathbf{B}_P/|\mathbf{B}_P|$. The upper-left plot represents the total force applied on the plasma which is negative in the disk and becomes positive near the disk surface. This configuration enables the matter below the disk surface to be pinched and to remain in an accretion regime while beyond the disk surface, matter is accelerated along magnetic field lines, leading to a jet. This balance is obtained from competing forces where thermal pressure gradient and centrifugal force counteract magnetic and gravitational pinching. The crucial point of the accretion-ejection connection is to accurately capture the sign change of the sum of all forces in the numerical stationary state. This change of sign can only be achieved if the poloidal magnetic force along the magnetic surface changes its sign near the disk surface, as shown on Figure 3. Since this force is directly related to the magnetic torque, $(\mathbf{J} \times \mathbf{B}) \cdot \mathbf{B}_P = -(\mathbf{J} \times \mathbf{B}) \cdot \mathbf{B}_\theta$, this also implies that the magnetic torque changes its sign there, as also shown in Figure 3. This configuration is at the core of magneto-centrifugal acceleration since toroidal acceleration (or braking) determines poloidal acceleration (or braking) of matter. The poloidal velocity field shown in Figure 3 confirms the above statements, since this field is consistent with an accretion motion in the disk (dominant negative radial velocity) while the vertical velocity becomes dominant beyond the disk surface. The angle between the poloidal velocity and poloidal magnetic field is displayed on the bottom middle panel and again confirms the required accretion-ejection configuration where flow is perpendicular to the magnetic field in the disk and becomes essentially parallel to it in the jet region.

In the present work, we purposely choose an initial magnetic configuration where the poloidal surfaces are strongly bent at $T = 0$ as shown in Fig. 1. The resulting jet is well collimated, which is a direct proof that the collimation of this flow is arising self-consistently. We display in Fig. 4 the radial balance of the jet for the same snapshot than in Fig. 2 at $Z = 60$. Clearly, the total force is vanishingly small, proving that there is equilibrium in the jet. The thermal pressure gradient as well as the centrifugal force are balancing the total radial magnetic force. This kind of force balance between thermal pressure and magnetic force is another clue to the occurrence of a “hot” jet where thermal energy is of the same order than the magnetic energy. In order to rule out any artificial collimation of the jet, we have performed the same simulation with different box size and boundary conditions for the magnetic field. We have followed exactly the same approach than (Ustyugova et al., 1999) and obtained a solution very close to the one presented in Fig.1.

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