MHD simulations of the long-term evolution of a dipolar magnetosphere surrounded by an accretion disk

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Abstract. The evolution of an initially stellar dipole type magnetosphere interacting with an accretion disk is investigated using numerical ideal MHD simulations. The simulations follow several 1000 Keplerian periods of the inner disk (for animated movies see http://www.aip.de/~cfendt). Our model prescribes a Keplerian disk around a rotating star as a fixed boundary condition. The initial magnetic field distribution remains frozen into the star and the disk. The mass flow rate into the corona is fixed for both components.

The initial dipole type magnetic field develops into a spherically radial outflow pattern with two main components — a disk wind and a stellar wind — both evolving into a quasi-stationary final state. A neutral field line divides both components, along which small plasmoids are ejected in irregular time intervals. The half opening angle of the stellar wind cone varies from 30° to 55° depending on the ratio of the mass flow rates of disk wind and stellar wind. The maximum speed of the outflow is about the Keplerian speed at the inner disk radius.

An axial jet forms during the first decades of rotations. However, this feature does not survive on the very long time scale and a pressure driven low velocity flow along the axis evolves. Within a cone of 15° along the axis the formation of knots may be observed if the stellar wind is weak. With the chosen mass flow rates and field strength we see almost no indication for a flow self-collimation. This is due to the weak net poloidal electric current in the magnetosphere which is in difference to typical jet models.

1. Introduction

A stellar dipole magnetic field surrounded by an accretion disk is the model scenario for a variety of astrophysical sources — classical T Tauri stars, cataclysmic variables or high mass X-ray binaries. Some of them exhibit Doppler shifted emission lines indicating wind motion. Highly collimated jets are observed from young stellar objects and X-ray binaries. In general, magnetic fields are thought to play the leading role for jet acceleration and collimation (Blandford & Payne 1982; Camenzind 1990; Shu et al. 1994; Fendt et al. 1995).

Several papers numerically consider the evolution of a stellar magnetic dipole interacting with a diffusive accretion disk (Hayashi et al. 1996; Miller & Stone 1997; Goodson et al. 1997, 1999). In these papers a collapse of the inner disk is indicated. The inward accretion flow...
develops a shock near the star. The stream becomes deflected resulting in a high-speed flow in axial direction. The results of Goodson et al. are especially interesting as combining a huge spatial scale with high spatial resolution near the star. However, to our understanding, it is not clear, how the initial condition (a standard $\alpha$-viscosity disk) is actually evolving in their code without physical viscosity.

We emphasize that time-dependent simulations lasting only a short time period strongly depend on the initial condition. The simulation of jet magnetosphere over many rotational periods is essential. The observed kinematic time scale of protostellar jets can be as large as $10^4$ yrs (or $5 \times 10^5$ stellar rotations). Thus, we follow another approach for the simulation of magnetized winds from accretion disks and consider the accretion disk “only” as a boundary condition. Since the disk structure itself is not treated, such simulations may last over hundreds of Keplerian periods. For a certain initial magnetic field distribution, a stationary state self-collimating jet flow can be obtained (Ouyed & Pudritz 1997, Fendt & Cemeljic 2002).

In our project (Fendt & Elstner 1999, 2000), we are essentially interested in the evolution of the ideal magnetohydrodynamic (MHD) magnetosphere and the formation of winds and jets and not in the evolution of the disk structure itself. Therefore, we do not include magnetic diffusivity into our simulations. We follow the approach of Ouyed & Pudritz (1997) in combination with dipole magnetic field initial condition. Using the ZEUS-3D code (Stone & Norman 1992a,b) in the axisymmetry option we solve the time-dependent ideal MHD equations,

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\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) &= 0, \\
\frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{v} \times \vec{B}) &= 0, \\
\nabla \cdot \vec{B} &= 0,
\end{align*}
\]

where $\vec{B}$ is the magnetic field, $\vec{v}$ the velocity, $\rho$ the gas density, $P$ the gas pressure, $\vec{J} = \nabla \times \vec{B}/4\pi$ the electric current density, and $\Phi$ the gravitational potential. We apply a polytropic equation of state (polytropic index $\gamma = 5/3$) and do not solve the energy equation. Instead, the internal energy is defined given $e = p/(\gamma - 1)$. Similar to Ouyed & Pudritz (1997), we introduce an Alfvén wave turbulent magnetic pressure, $P_A \equiv P/\beta_T$, with constant $\beta_T$.

The main parameters of our simulation are the plasma beta just above the inner disk radius $r_i$, $\beta_i \equiv 8\pi P_i/B_i^2$, and the Mach number of the rotating gas, $\delta_i \equiv \rho_i v_{K,i}^2/P_i$, where $v_{K,i} \equiv \sqrt{GM/r_i}$. 

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2. The model – numerical realization

Our model setup represents a central star surrounded by a Keplerian disk with a gap in between.

The initial coronal density distribution is in hydrostatic equilibrium. The gravitational potential is not smoothed. We choose the initial field distribution of a force-free, current-free stellar magnetic dipole, deformed by the effect of “dragging” in the disk. Therefore the poloidal field is inclined towards the disk surface. Since the boundary condition for the poloidal magnetic field along the inflow boundary is fixed, the magnetic flux from the star and disk is conserved. The disk toroidal magnetic field is also force-free, \( B_\phi = \mu_i / r \) for \( r \geq r_i \) with \( \mu_i = B_{\phi,i} / B_i \).

Hydrodynamic boundary conditions are 'inflow' along the \( r \)-axis, 'reflecting' along the symmetry axis and 'outflow' along the outer boundaries. The inflow parameters into the corona are defined with respect to the three different boundary regions – star, gap and disk. The stellar wind boundary condition is motivated by the fact that stellar winds are indeed observed. The ratio of mass flow rates in the two outflow components also governs the structure of the flow.

3. Results and discussion

In the following we discuss the results of our simulations. For details see Fendt & Elstner (1999, 2000). As a general behavior, the initial dipole type structure of the magnetic field disappears on spatial scales larger than the inner disk radius and a two component wind structure – a disk wind and a stellar wind – evolves. On the very long time scale we find a quasi-stationary final state of a spherically radial mass outflow.

The stellar rotational period is chosen as \( \Omega_\star = (v_{K,i} / r_i) = 1 \). Thus, the magnetospheric co-rotation radius is at \( r_i \). Other parameters are \( \beta_i = 1.0, \delta_i = 100, \mu = -1.0 \), and a stellar radius \( r_\star = 0.5 \). A numerical grid of 250\(^2\) elements is used for a box of physical size \( 20 \times 20 r_i \). The stellar wind mass flow rate is rather large, \( M_\star / M_D = 2 \).

3.1. The first evolutionary stages

During the first evolutionary stages the magnetospheric structure is characterized by the following features. The winding-up of the dipolar poloidal field, the formation of a neutral field line, a transient axial jet feature, a two component outflow consisting of a stellar wind and a disk wind.

The winding-up process of poloidal magnetic field due to differential rotation between star and disk and the static initial corona induces a
toroidal field with a positive (negative) sign along the field lines outside (inside) the slowly emerging neutral field line.

During the first 50 rotations a jet feature evolves along the rotational axis with a pattern velocity of about $0.2 v_K$. Such an axial jet is known as a characteristic result of MHD simulations performed in the recent literature (Hayashi et al. 1997; Goodson et al. 1997, 1999; Kudoh et al. 1998). However, we find that the formation of this feature results from the adjustment of the initially hydrostatic state to a new dynamic equilibrium and disappears on the long time scale.

The disk wind accelerates rapidly from the low injection speed to fractions of the Keplerian speed. The flow starts already super Alfvénic due to the weak dipolar field in the disk. Thus, magneto-centrifugal
acceleration along the inclined dipole type field lines of the initial magnetic field is not the acceleration mechanism. The acceleration mechanism is mainly due to the centrifugal force on the disk matter reaching the non-rotating corona. Higher above the disk also the Lorentz force contributes to the acceleration.

The rotating stellar magnetosphere generates a stellar wind. Due to the strong stellar field, the flow starts sub-Alfvénic. It is initially magneto-centrifugally driven with a roughly spherical Alfvén surface.

3.2. The Long-term Evolution

The total mass flow rate into the corona determines how fast the flow will establish a (quasi-)stationary state. First, the outflow evolution is highly time-variable and turbulent. After relaxation of the MHD configuration from the initial magnetohydrostatic state into a new
dynamical equilibrium, we finally observe a two-component outflow from disk and star distributed smoothly over the whole hemisphere and moving in spherically radial direction. After about 2000 rotations a quasi-stationary outflow is established over the whole grid (Fig. 1). However, small scale instabilities can be observed along the neutral field line separating stellar and disk wind and along the symmetry axis.

Figure 2 shows the poloidal velocity vectors. High velocities (> $v_{K,i}$) are only observed far from the axis. The asymptotic speed is about 1.5 $v_{K,i}$ for both components. The initial axial jet feature disappears. The axial flow moves with 0.2 $v_{K,i}$.

The axial blobs (or rather tori) generated in this simulation run move with pattern speed of about 0.1 the Keplerian speed at $r_i$. We emphasize that the knot size and time scale of knot formation in our simulation is far from the jet knots observed in protostellar jets.

The quasi-stationary two-component outflow obtained in our simulations show almost no indication for collimation. This is in agreement with the analysis of Heyvaerts & Norman (1989) who have shown that only jets carrying a net poloidal current will collimate to a cylindrical shape. In our case we have an initially dipolar magnetosphere and the final state of a spherically radial outflow enclosing a neutral line with a poloidal magnetic field reversal. The toroidal field reversal implies a reversal also of the electric current and, thus, only a weak net poloidal current. Thus, the flow self-collimation naturally obtained in a monotonous magnetic flux distribution (Ouyed & Pudritz 1997, Fendt & Cemeljic 2002) cannot be achieved.

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