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Letter to the Editor

Long-term evolution of a dipolar-type magnetosphere interacting with an accretion disk

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Abstract. The evolution of a stellar dipolar-type magnetosphere interacting with a Keplerian disk is investigated numerically using the ideal MHD ZEUS-3D code in the axisymmetry option. We compute the innermost region around the stellar object using a non-smoothed gravitational potential. The disk is taken as a boundary condition prescribing the mass inflow into the corona. Depending mainly on the magnetic field strength, our simulations last several hundred Keplerian periods of the inner disk. The main result is that the dipolar structure of the magnetic field almost completely disappears. An expanding bubble of hot gas of low density forms disrupting the initial dipolar field structure. A disk wind accelerates within the time limit of the simulation to velocities of about 0.5 the Keplerian speed and potentially may develop into a stationary collimated jet. We argue that non-stationary jet phenomena should probably caused by a time-dependent disk. Simulations with a rotating and a non-rotating star show significant differences. In the case of a rotating star during the very first time steps a high speed outflow along the axis is initiated which does not exist in the case of a non-rotating star.

Key words: Magnetohydrodynamics (MHD) – accretion, accretion disks – ISM: jets and outflows – stars: magnetic fields – stars: mass-loss – stars: pre-main sequence

1. Introduction

A stellar dipolar-type magnetic field surrounded by an accretion disk is a common model scenario for various astrophysical objects. Examples are the classical T Tauri stars, magnetic white dwarfs (cataclysmic variables) and neutron stars (high mass X-ray binaries). Some of these sources show Doppler shifted emission lines and highly collimated jets are observed in young stellar objects. Magnetic fields are thought to play the leading role for the jet acceleration and collimation (Blandford & Payne 1982; Pudritz & Norman 1983; Camenzind 1990; Shu et al. 1994a,b; Fendt et al. 1995; Fendt & Camenzind 1996).

In general, two classes of papers concerning magnetohydrodynamic simulations of jet formation from accretion disks have been published recently. In one class, the evolution of dipolar-type magnetic fields in interaction with a disk is investigated including also a treatment of the disk (Hayashi et al. 1996; Goodson et al. 1997 (GWB97); Miller & Stone 1997; Kudoh et al. 1999). In these papers a collapse of the inner disk is indicated giving rise to episodic ejections of plasmoids. A two-component structure of the flow develops – a collimated axial jet and a disk wind flow. Using an adaptive grid GWB97 were able to combine a huge spatial scale (2 AU) with a high spatial resolution near the star ($0.1 R_{\odot}$)!

However, all these simulations could be performed only for a few Keplerian periods of the inner disk! Further, the applied disk initial condition is not compatible with a magnetized disk. It is not surprising that the disk immediately becomes unstable giving rise to ejections. Clearly, it is not yet numerically feasible to include the disk structure self-consistently. The second class of papers deals with the evolution of a magnetized disk wind taking the disk only as a boundary condition for the inflow, an idea first proposed by Ustyugova et al. (1995) (see also Ouyed & Pudritz 1997 (OP97); Romanova et al. 1997, Ustyugova et al. 1999 (U99)). A monotonous flux distribution across the field is assumed. For a certain initial magnetic field a final stationary collimating jet flow could be found (OP97; U99).

We are essentially interested in the evolution of the ideal MHD magnetosphere and the formation of winds and jets and not in the evolution of the disk itself. Therefore, we do not include magnetic diffusivity into our simulations. The disk acts only as a boundary condition for the corona/jet region. In this sense we will follow the ideas developed by OP97. The winding-up process of magnetic field due to differential rotation between the star and the disk would be present even if diffusivity in a disk is taken into account. A treatment of the long-term evolution of such systems is essential for their interpretation, since it is then when they are being observed.

Here, we present first results of our simulations. We give a more detailed discussion in a forthcoming publication. A movie will be provided under *http://kosmos.aip.de/∼cfendt*.

2. Basic equations

Using the ZEUS-3D MHD code (Stone & Norman 1992a,b; Hawley & Stone 1995) in the axisymmetry option we solve the system of time-dependent ideal MHD equations,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,\ \frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,\ \nabla \cdot \boldsymbol{B} = 0, \quad (1)$$

$$\rho \left[\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\, \boldsymbol{v} \right] + \nabla (P + P_{\rm A}) + \rho \nabla \Phi - \boldsymbol{j} \times \boldsymbol{B} = 0, \quad (2)$$

$$\rho \left[\frac{e}{\partial t} + (\boldsymbol{v} \cdot \nabla)\, e \right] + P (\nabla \cdot \boldsymbol{v}) = 0, \quad (3)$$

with the magnetic field $\boldsymbol{B}$, velocity $\boldsymbol{v}$, gas density ρ, gas pressure P, internal energy e, electric current density $\boldsymbol{j} = \nabla \times \boldsymbol{B}/4\pi$, and gravitational potential Φ. We assume a polytropic gas, $P = K\rho^{5/3}$ and do not solve the energy equation (3). Additionally, we have introduced a turbulent magnetic pressure due to Alfvén waves, $P_{\rm A} \equiv P/\beta_T$, with a constant β_T (OP97)

Using dimensionless variables, $r' \equiv r/r_i$, $z' \equiv z/z_i$, $v' \equiv v/v_{K,i}$, $t' \equiv t r_i / v_{K,i}$, $\rho' \equiv \rho/\rho_i$, $P' \equiv P/P_i$, $B' \equiv B/B_i$, $\Phi' = -1/\sqrt{(r'^2 + z'^2}$', where the index i refers to parameter values at the inner disk radius r_i, the normalized equation of motion eventually being solved with the code is

$$\frac{\partial \boldsymbol{v}'}{\partial t'} + (\boldsymbol{v}' \cdot \nabla')\, \boldsymbol{v}' = \frac{2\, \boldsymbol{j}' \times \boldsymbol{B}'}{\delta_i\, \beta_i\, \rho'} - \frac{\nabla'(P' + P'_{\rm A})}{\delta_i\, \rho'} - \nabla' \Phi' \,. \quad (4)$$

Here is $\beta_i \equiv 8\pi P_i / B_i^2$ and $\delta_i \equiv \rho_i v_{K,i}^2 / P_i$ with the Keplerian speed $v_{K,i}^2 \equiv \sqrt{GM/r_i}$. For a 'cold' corona ($P'_{\rm A} > 0$) it follows $\beta_T = 1/(\delta_i(\gamma - 1)/\gamma - 1)$. In the following we will omit the primes and will discuss only normalized variables.

3. The model, initial and boundary conditions

We apply the same boundary and initial conditions as developed by OP97 with the exception of a initial *dipolar-type* magnetic field from a stellar surface. Due to our choice of cylindrical coordinates we cannot treat the star as a sphere. The field distribution along our *straight* lower boundary, $z = 0$, corresponds to that along a surface with $z = z_{\rm D}$ across a dipolar-type field with a point-like star. This boundary is divided into a 'star', $r = 0, ...r_\star$, a gap from $r_\star$ to $r_i = 1.0$, and the disk from r_i to $r_{\rm out}$. Hydrodynamic inflow boundary conditions (b.c.) are set along this axis. Matter is injected from the disk into the corona with $\boldsymbol{v}_{\rm P} = v_{\rm inj} v_{\rm K} \boldsymbol{B}_{\rm P}/B_{\rm P}$, and $\rho_{\rm inj}(r) = \eta_i\, \rho(r, 0)$. The stellar rotational period can be chosen arbitrarily.

The initial density distribution is in hydrostatic equilibrium, $\rho = (r^2 + z^2)^{-3/4}$. The initial magnetic field structure is that of a force-free deformed dipole calculated with a finite element code described elsewhere (Fendt et al. 1995). There, the vector potential A_ϕ is computed using the double grid resolution. Then, the initial field distribution for the ZEUS code is derived with respect to the staggered mesh. In the undisturbed regions the initial field remains force-free on a level of $0.01\,\%$. A *force-free* initial field is essential in order to apply a hydro*static* corona as initial condition. The maximum $|\nabla \cdot \boldsymbol{B}|$ is 10^{-15}.

We have chosen an initial field distribution of a current-free magnetic dipole, artificially deformed by 'dragging' of an accretion disk, and an 'opening' of the field close to the outflow boundaries. This implies a poloidal field inclined to the disk surface supporting the launching of a disk wind. The amount of 'dragging' can be chosen by the b.c. in the finite element code. The stability of our initial condition is demonstrated in Fig. 1: density and field in the yet undisturbed regions perfectly match during the first decades of evolution ($t < 75$).

The b.c. for the poloidal magnetic field is set by the initial field distribution and the divergence-free condition (2). The b.c. for the toroidal component of the magnetic field is $B_\phi = \mu_i / r$ for $r \geq r_{\rm i}$, consistent with a Keplerian disk without any magnetic force. The emf b.c. along the r-axis is calculated directly from the velocity and field distribution prescribed, $\boldsymbol{\mathcal{E}}(\boldsymbol{r}) = \boldsymbol{v}(r) \times \boldsymbol{B}(r)$. For a rotating star $\boldsymbol{\mathcal{E}} \neq 0$.

We have carefully tested the application of the ZEUS-3D code to our model assumptions by recalculating the results of OP97 (obtained with the ZEUS-2D code) and found very good agreement (Fendt & Elstner 1999, in preparation). Another signature of the quality of our simulations is the stability of the hydrostatic initial condition and force-freeness over several decades of the computation.

4. Results and discussion

We have investigated numerically the evolution of a stellar dipolar-type magnetosphere in interaction with a Keplerian accretion disk using the ideal MHD ZEUS-3D code in the axisymmetry option. We are able to follow the evolution over more than 200 Keplerian periods of the inner disk (or 2.2 periods at the outer disk at $20\, r_i$)! The stellar radius is $r_\star = 0.5\, r_i$ The other parameters applied are $\delta_i = 100$, $\beta_i = 0.2$, $\mu_i = -1.0$, $\eta_i = 100$, $v_{\rm inj} = 0.001$, similar to OP97. For a typical protostar this corresponds to a disk density at r_i of

$$\rho_D = 10^{-11} \eta_i \beta_i \delta_i \left(\frac{B_i}{10\,{\rm G}} \right)^2 \left(\frac{r_i}{10\,{\rm R}_\odot} \right) \left(\frac{M}{{\rm M}_\odot} \right)^{-1} {\rm g\,cm^{-3}}. \quad (5)$$

Our main result is that the initial dipolar-type field structure disappears on spatial scales larger than the inner disk radius and a slowly collimating disk wind evolves (Fig. 1). An expanding low density 'bubble' forms disrupting the field and moving with an axial speed of $v_{\rm z} \simeq 0.4 v_{K,i}$ (at $t = 100$). A weak back-flow of material exists close to the axis.

The general behavior of the system is independent from a variation of the field strength. For strong fields, the bubble is moving faster, however, the numerical life time of the simulation is accordingly shorter. This is a major difference to OP97, resulting from the inner 'stellar' b.c. and differential rotation between star and disk. After $t = 75$, torsional Alfvén waves reach the outer region and the whole initial field distribution is distorted. A flow along the field develops close to the disk. Its inclination angle *slowly* increases with time. We interpret this as indication for a possible stationary final state. We hypothesize that such a solution will look similar to the jet solutions of OP97, since the disk inflow condition is the same. OP97 have shown that for a certain initial magnetic field distribution the evolving jet flow becomes stationary after about 400 Keplerian periods. Also, Romanova et al. (1997) find a stationary collimating disk wind, however, applying a monopole-type initial field structure. Further extending this approach, U99 have generally proven the

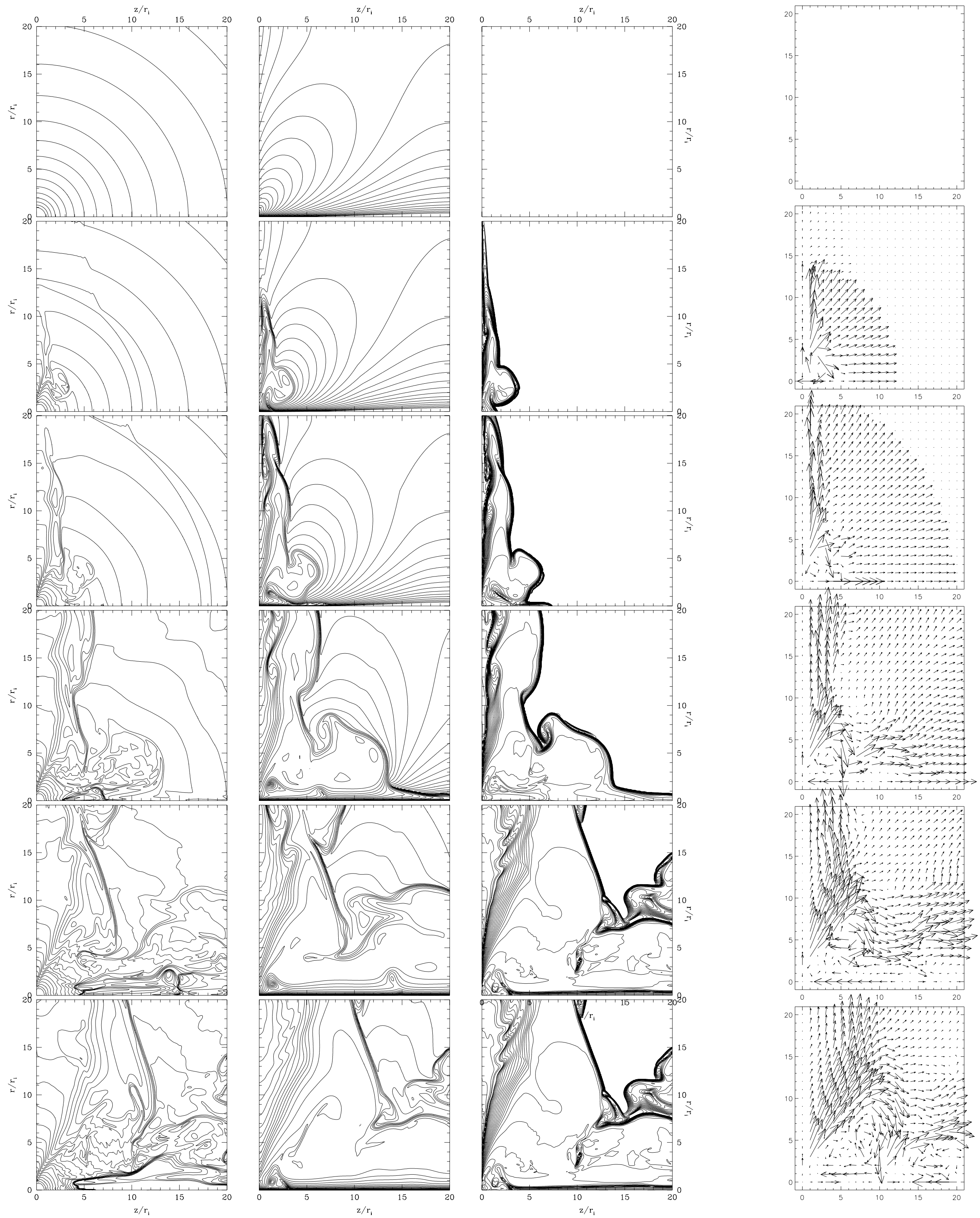

Fig. 1. Evolution of a dipolar-type magnetosphere in interaction with a Keplerian disk. Shown is (from *left* to *right*) the density ρ, magnetic field distribution ($B_{\rm P}$-lines and B_ϕ contours) and velocity vectors (on scale only within each frame) for $t = 0, 25, 50, 100, 150, 200$ (from *top* to *bottom*). The inflow from the disk along the r-axis is parallel to the initial poloidal field. The innermost density contour ($\rho = 1.0$) indicates the inner disk radius $r_{\rm i} = 1.0$. The stellar radius along the r-axis is $r_\star = 0.5\, r_{\rm i}$. The numerical resolution is 250×250 grid elements.

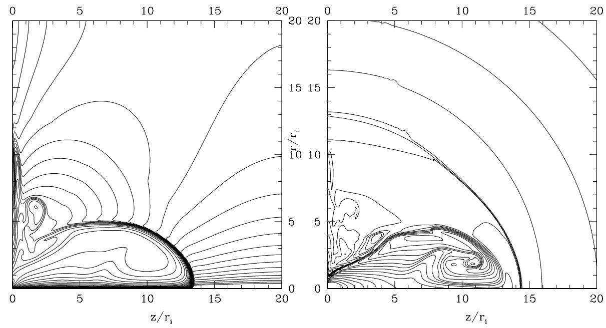

Fig. 2. Example solution of the magnetosphere for stellar rotation for the time step $t = 25$, corresponding also to 25 stellar rotational periods. Density distribution (*left*) and poloidal magnetic field lines (*right*). Same contour levels as in Fig. 1.

existence of stationary disk jets in agreement with predictions of the stationary MHD theory. In our simulations the disk wind accelerates to poloidal velocities of $v_{\rm p} > 0.5 v_{K,i}$. The wind is launched predominantly from the inner disk, due to the fact that the poloidal field strength drops very fast! In difference to OP97 the magnetic field (with the initial dipole) does not evolve into a *monotonous* flux distribution across the field, but into a *reversed* field structure with a neutral line of vanishing field strength! The dipole survives close to the star with a density distribution similar to the initial one.

Simulations with a rotating and a non-rotating star show significant differences (Fig. 2), although differential rotation between star and disk is present in both scenarios. For a rotating star a collimated high-speed outflow is generated close to the axis during the first periods, in agreement with the GWB97 results. However, this axial jet does not survive very long, if not an additional inflow of a *stellar wind* is prescribed.

Hayashi et al. (1996) and GWB97 already demonstrated that a stellar magnetic dipole connected to a disk is deformed within some Keplerian periods. However, the fate of such a field geometry over many rotational periods has not been investigated. One may suppose that the X-ray flares found by Hayashi et al. might be a phenomenon occurring only during the very first decades of rotation until the star-field-disk system has substantially developed from its initial state. Although we find the same general structure of the flow evolution – jet and disk wind – our study gives strong indication that episodic outbursts do not appear on longer time-scales. However, as GWB97 discuss, outbursts are initiated from the time-dependent behavior of the accretion disk, the structure of which we do *not* treat. Our conclusion is that a *stationary* disk most probably will produce a stationary outflow on large scales!

We now compare our results with stationary jet models in the literature. (Note that protostellar jet formation observed on dimensions of $\lesssim 1000\, r_i$ cannot yet be studied on a *global* spatial scale with the numerical codes presently available due to the lack of numerical resolution). Camenzind (1990) developed a basic model of jet formation from a magnetized young star - accretion disk system. Stationary model calculations based on such a scenario did not find jet solutions if a large-scale dipolar stellar field is applied as b.c., whereas a dipole concentrated only to the star permitted an asymptotic jet with monotonous field distribution across the jet (Fendt et al. 1995, Fendt & Camenzind 1996). Our simulations shows that this innermost dipole is not destroyed. In the Shu et al. (1994a,b) model the jet flow emerges centrifugally accelerated from a so-called X-point at the inner disk radius. A critical field line divides the closed dipolar loops from the open wind/jet field. At a quick look our simulations seem to favor the hypothesis of Shu et al., their critical surface corresponding to our dominant flow channel emanating from the inner disk radius. However, in our simulation, the strong acceleration at this location is due to the strong differential rotation at this point and the subsequent induction of toroidal magnetic fields, while in Shu et al.'s theory centrifugal forces play the dominant role.

In summary, our long-term simulations show that (1) short-term simulations should be interpreted with care, being probably biased by the initial condition. Further, (2) the long-term evolution indicates on a possible final *stationary* state of a collimating high speed disk wind, in difference to papers on this topic published previously. Direct comparison of the simulations with a rotating and a non-rotating star shows that (3) the first steps of the evolution differ greatly. In the long-term evolution, however, both systems may evolve quite similar. This would imply that (4) jet formation depends mainly on the disk and not on the stellar rotation. Such a 'prediction' may be tested by observing jet sources with different rotational periods.

Further studies are needed to understand the complex behavior of the flow and field evolution. We will present a more detailed analysis of our results in a subsequent paper.

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