SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

MHD SIMULATIONS OF THE MAGNETIC COUPLING BETWEEN A YOUNG STAR AND ITS ACCRETION DISK

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Abstract.
The magnetic star-disk interaction is important in the context of the dynamic evolution of low mass protostars. In particular, Classical T-Tauri Stars (CTTS) have a puzzling low rotation rate despite accretion. In such a complex star-disk system, we need to take into account the stellar and disk magnetic fields with a realistic accretion disk structure. Magnetohydrodynamic (MHD) simulations are necessary to support and extend analytical work. First, we briefly review theoretical models and past numerical work. We discuss the difficulties to set up initial conditions with a realistic accretion disk structure, as well as the choice of the boundary conditions at the star surface to correctly handle angular momentum transport. Then, we present our 2.5D MHD simulations done with the Versatile Advection Code (VAC), modified here to handle strong dipole stellar fields by a splitting strategy for the magnetic field. In this paper, we only consider the stellar magnetic field and its interaction with the disk. We confirm the process of poloidal magnetic field expansion when the disk resistivity is negligible, and identify physical conditions needed for the formation of accretion columns.

1 Introduction

Pre-main sequence Classical T-Tauri Stars (CTTS) are slow rotators (observed rotation periods are $P \approx 3 - 8$ days) although they are still in a contracting stage and accrete rotating mass from their environment. Compared with similar young stars without disk signature such as Weak-line T-Tauri Stars which are fast rotators, this dynamic evolution is clearly controlled by the disk (Bouvier et al. 1995, Herbst et al. 2002). Moreover, CTTS are magnetically active, with mean magnetic field magnitudes commonly around 1kG, enough to disrupt the accretion disk (e.g. Johns-Krulls et al. 1999). In their spectra, we can observe inverse P-Cygni profiles with strong redshift absorption wings, indicative of accretion near free-fall velocities along magnetospheric field lines (Edwards et al. 1993). The large range in timescales in photometric and spectroscopic variations is also an important characteristic for this kind of objects (Herbst et al. 1994, Bouvier et al. 1999, 2003). Here, we present current models and MHD simulations of the star-disk interaction. Then, we discuss our own preliminary simulations results focusing on the conditions needed for formation of accretion columns.

2 The star-disk paradigm and MHD simulations

Although recent polarimetric measurements show evidence for strong multipolar components (Valenti & Johns-Krull 2004), models fo simplicity reasons usually assume a dipolar topology for the stellar magnetic field. Two main kinds of models can be found in the literature, which differ mainly in the magnetic topology of the star-disk coupling zone: the extended magnetosphere model, initially introduced by Gosh & Lamb (1979), versus the X wind (Shu et al. 1994) and ReX wind (Ferreira et al. 2000) models with a localized extraction of angular momentum. In the first one, the stellar magnetic field is anchored over a large range in the accretion disk. By defining the corotation radius $R_{co} = (\frac{GM_*}{\Omega_*^2})^{\frac{1}{3}}$, we easily conclude that assuming Keplerian disk rotation and pure dipole stellar fields, all magnetic field lines rooted in the disk below R_{co} tend to accelerate the star, while all

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others beyond R_{co} can brake it. It is however not trivial to quantify the global magnetic torque, which is needed to address the question of angular momentum transport (Konigl 1991). This is because we need to know the magnetic topology of the entire star-disk system, which depends above all on the poorly known disk resistivity. Because of differential rotation along a magnetic field line connecting the star to the disk, there is generation of a strong toroidal magnetic field in an ideal MHD limit which leads to a strong poloidal field expansion and tends to evolve to an open magnetic topology. Eventually, one gets open field lines partly rooted in the star and partly in the outer parts of the disk. These open field regions can then support a stellar and a disk wind, respectively. However, if the disk resistivity is comparable to the turbulent viscosity (Bardou & Heyvaerts 1996) radial diffusion of the magnetic field is dominant and this expels the magnetic field from the disk, which effectively cancels the star-disk magnetic coupling. Thus, this extended scenario has been disregarded in favor of a more localized interaction. Otherwise, we always have a closed magnetosphere as the magnetic field dominates near the star. When the magnetic field becomes strong enough, matter from the disk is then diverted from the disk midplane as it accretes, and accretion occurs along the magnetic field lines forming accretion columns. This radius may be defined as the truncation radius R_t.

In the case of the ReX wind model, the disk has its own magnetic field and if it is parallel to the stellar magnetic moment, we have an X point where the magnetic field cancels. At this reconnection point, the accreted matter is lifted upwards by the Lorentz force. Contrary to disk wind models, the ejection efficiency could be much higher. Matter is then dragged outwards and accelerated away along the newly reconnected field lines. Since these lines are now anchored to the star, this wind leads to efficient braking.

However, these semi-analytical models are steady-state configurations and time-dependent MHD simulations must be used to better understand the dynamical trends seen in the observations. First attempts to tackle the problem of star-disk interaction were done in the nineties. These firstly tried to understand the funnel flow formation conditions. Ideal MHD simulations, like those by Romanova et al. (2002) and Miller & Stone (1997), showed that polar accretion occurs only when strong magnetic fields are present, i.e. when it is in equipartition with the disk rotation energy ($\frac{B^2}{2} = \rho\Omega^2 r^2$). Resistive MHD simulations like in Kuker et al. (2003) have too weak fields ($\frac{B^2}{\rho v_\Phi^2} \approx 10^{-4}$), to avoid direct accretion from happening. A second topic of study is the angular momentum balance to see if the star can spin down. This is only possible in long term evolutions of the system, so the initial conditions must not be far from an equilibrium state, such as those in Romanova et al. 2002 or Kuker et al. 2003. Recently, Long & Romanova (2005) found a disk-locking state where the star spins at around a tenth of the breakup rotation. However, in the endstate the position where the angular momentum flux changes sign is well below the initial corotation radius. This then in effect corresponds to a faster rotator, and it is important to see how this varies with the detailed treatment of the inner boundary condition on the star. In Kuker et al. (2003), the disk resistivity is not sufficient to prevent the poloidal field from opening and we have a final situation where the disk and the star are no longer connected. Thus, star braking can only come from the opened field lines connected to the star, but the accretion torque still dominates and the star is therefore spun up.

3 Ideal and resistive MHD simulations with VAC

3.1 Numerical setup

To compute star-disk interactions, we use the VAC [1] code (Tóth 1996) . We solve the full set of resistive MHD equations using cylindrical coordinates in the poloidal plane (r,z) and assume axisymmetry. The initial conditions described below are time-advanced using the conservative second order accurate Lax Friedrich scheme with minmod limiters applied on primitive variables. To ensure the divergence free property of the magnetic field, we use the projection scheme method at each time step. The code is modified for our purposes, to compute only the deviations from the dipolar component in order to properly represent an initial force-free configuration numerically (Powell et al. 1999).

We choose a basic initial condition with a cold adiabatic disk with $\gamma = \frac{5}{3}$ and an aspect ratio of 0.1 truncated analytically by an isothermal corona. The dimensionless disk truncation radius is at R=1 corresponding to 3 R_* where we have pressure balance between the disk and the corona. The temperature in the corona is 2.10^5 K. We consider a 0.8 $M_\odot$ young star with a radius of 2 $R_\odot$. We use a polar grid stretched in the radial direction to

[1] http://www.phys.uu.nl/ toth/

have finer resolution near the star. This stretching allows to use a fairly modest resolution of (N_r,N_θ)=(200,50). We have $\Delta R = [0.35, 5.35]$, which corresponds to a radial extension up to 0.15 AU. As far as the boundary conditions are concerned, we take symmetric and asymmetric ones for the axis and the disk midplane. At the inner edge corresponding to the stellar surface, we maintain the density and pressure stratification, and force the poloidal velocity to be parallel to the poloidal magnetic field (which is fixed at the star surface) to have ideal MHD conditions. We let the matter rotate with the star angular velocity and put the toroidal field equal to zero, such that the magnetic surfaces locally rotate at the stellar rotation rate. At the outer edge, we use continuous outflow type boundary conditions.

3.2 Results

First, we present ideal MHD results. We then always observe expansion of the poloidal magnetic field due to the differential rotation between the star and the disk. This leads to ejection of several plasmoids, as also demonstrated by Hayashi et al. 1996, but we follow the evolution for longer times. With a magnetic field of 100 G at the star surface, see Fig. 1, we find a strong compression of the magnetosphere caused by accretion. The poloidal field anchored in the disk is bent outwards preventing matter from being lifted up along the magnetic field lines. Thus, we have direct accretion onto the star without an accretion column and an open configuration in the outer parts of the disk coming from the opening of the poloidal field by the differential rotation. No super-alfvenic wind is however produced because the magnetic field strength is too low. At the disk inner edge, the magnetic field is in equipartition with the disk thermal pressure. Thus, the Alfvén velocity at the disk surface is always much lower than the escape speed and we have a breeze-like ejection.

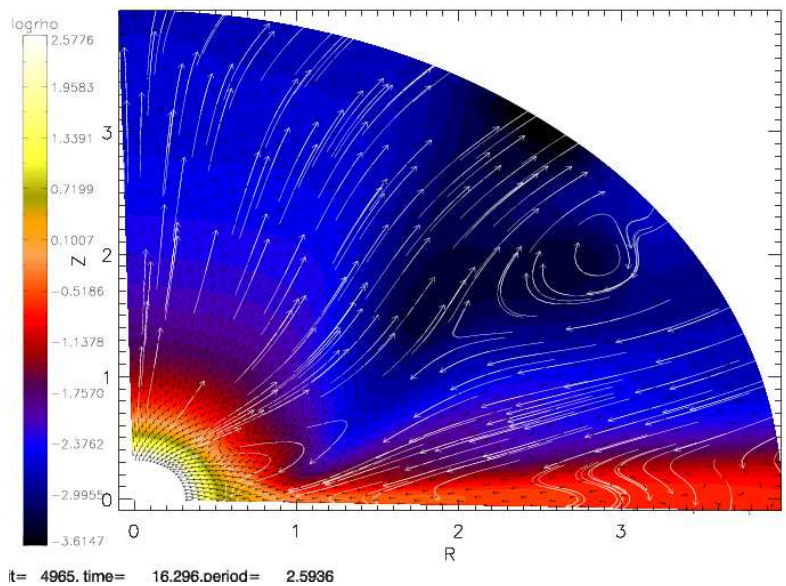

Fig. 1. Ideal MHD simulation with $B_* = 100G$ after 14 keplerian rotations at the star surface. We show the density distribution in the computational domain. The white lines draw the magnetic field lines and the black arrows represent the velocity field. We observe the expansion of the poloidal magnetic field, plasmoid ejection and transient disk ejecta. We have direct accretion onto the star.

With a stronger field ($B_* = 1$ kG), a (transient) accretion column appears. In this case, the magnetic pressure of the star balances the rotational energy of the disk and we have a "magnetic wall", like those found in previous ideal MHD simulations by Romanova et al. (2002) and Miller & Stone (1997). The problem with the initial condition chosen here is a lack of a realistic density contrast between the corona above the star (which is $\rho_c \approx 700$) and a possible accretion column forming from the disk inner edge ($\rho_d \approx 1$). This is why we choose to revisit these simulations, this time with an adiabatic corona with $\gamma = \frac{5}{3}$, allowing us to take a more realistic coronal density $\rho_c \approx 0.1$.

Next, we included an alpha prescription for the disk magnetic resistivity ν_m. We take $\nu_m = \alpha_m \Omega_k h^2$ where $h = \frac{c_s}{\Omega_k}$ is the disk scale height. In this resistive MHD case (Fig. 2), we obtain funnel flows even for weak

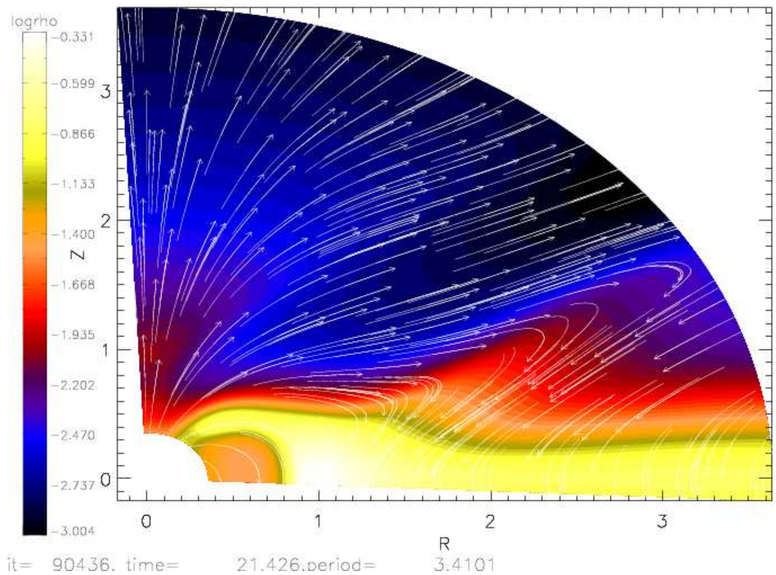

Fig. 2. Resistive MHD simulation with $B_* = 100G$ and $\alpha_m = 1$ after 17 keplerian rotations at the star surface. We observe the accretion column, the opening of the magnetic field lines and transient disk ejecta.

magnetic field ($B_* = 100$ G), because the magnetic braking in the toroidal direction is weaker with resistivity. We found that the magnetospheric radius corresponds to the position where the magnetic pressure is balanced by the disk thermal pressure ($\frac{B^2}{2} = \rho\Omega^2 h^2$), i.e. where the plasma beta parameter takes on values near 1.

3.3 Further developments

Current investigations take into account the stellar rotation. In that situation, disk material beyond the corotation radius tends to be accelerated outwards by the stellar magnetosphere. Thus, in order to achieve accretion, another torque must balance this one. This is done by using an alpha prescription for the turbulent viscous disk. This work is in progress.

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