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NUMERICAL MODELING OF MAGNETIC STAR-DISK INTERACTION

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RESUMEN

Las estrellas T Tauri clásicas (CTTS) son estrellas pre-secuencia principal magnéticamente activas, las cuales muestran evidencia de la presencia de discos de acreción circunestelares. A pesar del hecho de que todavía están contrayéndose y acretando, tienen períodos de rotación largos y constantes. En este trabajo presento simulaciones numéricas magnetohidrodinámicas (MHD) de la interacción entre un disco de acreción viscoso y resistivo y una magnetósfera estelar dipolar. El objetivo de estas simulaciones es ilustrar diferentes mecanismos que pueden contribuir a controlar el período de rotación de la protoestrella.

ABSTRACT

Classical T Tauri stars (CTTS) are known to be magnetically active pre-main sequence stars showing evidences of circumstellar accretion disks. Despite the fact that they are still actively contracting and accreting, they are characterized by long and constant periods of rotation. In this work I present numerical magnetohydrodynamic (MHD) simulations of the interaction between a viscous and resistive accretion disk with a dipolar stellar magnetosphere. The aim of these simulations is to illustrate different mechanisms which can contribute in controlling the period of rotation of the protostar.

Key Words: accretion, accretion disks — methods: numerical — MHD — stars: pre-main sequence

1. INTRODUCTION

Magnetic fields are likely to play a crucial role in the dynamics of the very central regions of the star-disk-jet system of classical T Tauri stars. Spectropolarimetric measures indicate stellar surface magnetic fields of up to a few kG (Valenti & Johns-Krull 2004), with a dipolar or even more complex topology (Jardine et al. 2008; Donati et al. 2008). Such a strong field is able to affect the dynamics of accretion: inverse P-Cygni profiles with strong redshifted absorption wings are indicative of polar accretion near free-fall velocities along magnetospheric field lines from the inner disk edge (Edwards et al. 1994). Not only accreting components are observed: evidences of the presence of hot stellar winds are starting to emerge, revealed by the broad blue-shifted absorption in high excitation lines (Edwards et al. 2003; Dupree et al. 2005).

One of the most puzzling aspects of the CTTS is that they are characterized by slow rotation periods (3–10 days, i.e. $< 10\%$ of their break-up speed, Bouvier et al. 1997): this implies a very efficient mechanism of angular momentum removal from the star during its embedded phase. Moreover these stars seem to evolve with a constant rotation speed during the T Tauri phase (Irwin et al. 2007), despite the fact that they are still actively accreting and contracting. Accretion can obviously contribute to the spin-up torque of the star. The disk truncation and the formation of accretion columns is in fact likely to occur below the corotation radius of the disk, defined as the radius where the stellar angular velocity $\Omega_\star$ is equal to the Keplerian speed of the disk, $R_{\rm co} = \left(GM_\star/\Omega_\star^2\right)^{1/3}$. In such a situation, the stellar magnetic field can in fact brake the rotation of both the disk and the material accreting in the funnel flows. This obviously implies a spin-up torque due to accretion of angular momentum of the order

$$\dot{J}_{\rm acc} = \dot{M}_{\rm acc} R_t^2 \Omega_{\rm d}\,, \qquad (1)$$

where $\dot{M}_{\rm acc}$ is the accretion rate of the disk, R_t is the truncation radius at which the disk accretion is deviated to form the accretion columns, and $\Omega_{\rm d}$ is the disk rotation rate around the truncation region.

Different solutions have been proposed to balance the spin-up torque due to accretion and contraction in order to keep the rotation period constant. A first idea is to have an *extended magnetosphere* connecting the star and the disk beyond the corotation radius: since in this region the disk is rotating slower than the star, angular momentum is transferred from the star back to the disk; if the spin-up and the spin-down torques are equal we find a so-called disk-locked condition (Ghosh & Lamb 1979; Königl 1991). Other solutions proposed are based on

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the presence of outflows, removing the excess angular momentum from the central parts of the system: along this line, it is possible to have *stellar winds* removing angular momentum directly from the star along the opened field lines of the magnetosphere (Matt & Pudritz 2005b); another possibility is to have *outflows associated with the magnetic star-disk interaction* which can remove the disk angular momentum before it falls onto the star. This is the original idea proposed in Shu et al. (1994) with the X-Wind scenario.

In this work I present numerical MHD simulations of the interaction between an accretion disk and a dipolar stellar magnetosphere. In § 2 I will present the numerical setup and method. The aim of these simulations is to illustrate the mechanisms proposed to control the angular momentum of the protostar. In § 3 I will show the results of a simulation characterized by a magnetosphere extending beyond the corotation radius. In § 4 I will discuss the role played by stellar winds, while in § 5 magnetospheric ejections will be discussed. Conclusions are presented in § 6.

2. NUMERICAL SETUP

The numerical experiments presented in this work have been performed exploiting the MHD module of the PLUTO[2] code (Mignone et al. 2007). The time-dependent simulations have been carried out in 2.5 dimensions, that is in spherical coordinates (R, θ) assuming axisymmetry around the rotation axis of the disk and the star. The initial conditions are made up of three parts: the viscous and resistive accretion disk, a surrounding rarefied atmosphere and the stellar magnetic field. The viscous disk has been modeled following the three-dimensional polytropic models of α Keplerian accretion disks developed in Kluźniak & Kita (2000). The atmosphere is modeled as a polytropic hydrostatic corona characterized by a density contrast ~ 0.01 with respect to the disk density. The stellar magnetosphere is modeled initially as a purely dipolar field with the magnetic momentum aligned with the star rotation axis. The disk surface is defined by the pressure equilibrium between the star and the atmosphere, while the disk is truncated at a few stellar radii, where the magnetic pressure of the field is equal to the thermal energy of the disk.

The central rotating protostar, besides defining the gravitational potential $\Phi_g = \sqrt{GM_\star/R}$, is described by a set of boundary conditions at the inner radius of the computational domain $R_\star$. Particular attention has been devoted to perfectly absorb the infalling material, without generating shocks at the inner boundary. Moreover, the boundary condition on the toroidal component of the magnetic field B_ϕ has been carefully chosen so that the magnetic field lines anchored onto the surface of the star are corotating with an angular speed $\Omega_\star$. The stellar angular speed has been set to $\Omega_\star = 0.1\sqrt{GM_\star/R_\star^3}$, i.e. 10 % of its break-up speed. This places the corotation radius at $R_{\rm co} = 4.64R_\star$. The outer radius of the computational domain has been placed at $\sim 28.6R_\star$. The angular direction θ has been discretized with $N_\theta = 100$ points, while $N_R = 214$ points have been used in the radial direction with a stretching $\Delta R \sim R\Delta\theta$ to keep the volume of the grid cells approximatively constant. A snapshot of the initial conditions and the computational grid is presented in the left panel of Figure 1.

A "standard" normalization has been chosen to present the results: the stellar mass, radius and magnetic field have been set to $M_\star = 0.5\,M_\odot$, $R_\star = 2\,R_\odot$, $B_\star = 800$ G respectively. With this normalization the period of rotation of the star is around $P_\star \sim 4.65$ days.

I used an α (Shakura & Sunyaev 1973) parametrization for the viscosity $\nu_{\rm v}$ and the resistivity $\nu_{\rm m}$ of the disk: $\nu_{\rm v,m} = \alpha_{\rm v,m} C_s H$, where $\alpha_{\rm v}$ and $\alpha_{\rm m}$ are adimensional constants, C_s is the sound speed calculated at the midplane of the disk and H is the thermal heightscale of the disk. The simulations presented here are characterized by different $\alpha_{\rm v}$ and $\alpha_{\rm m}$ values.

3. EXTENDED MAGNETOSPHERE AND THE DISK-LOCKING PARADIGM

The evolution of a dipolar stellar magnetosphere subject to the differential rotation between a perfectly conducting star and a rotating disk has been studied by many authors, both analytically and numerically. These studies have shown that, as the twist due to the differential rotation between the star and the disk increases, more and more toroidal field is generated at the disk surface. When a critical angle $\sim \pi$ is attained, the toroidal field reaches a maximum and its pressure inflates the magnetosphere and opens up the magnetic field structure, thus disconnecting the star and the disk. Anyway it has been shown by Uzdensky et al. (2002) that, if the disk resistivity is high enough, allowing some azimuthal slippage of the field lines relative to the disk material, this critical angle is never reached and the magnetosphere stays connected with the disk even beyond the corotation.

[2]PLUTO is freely available at http://plutocode.to.astro.it.

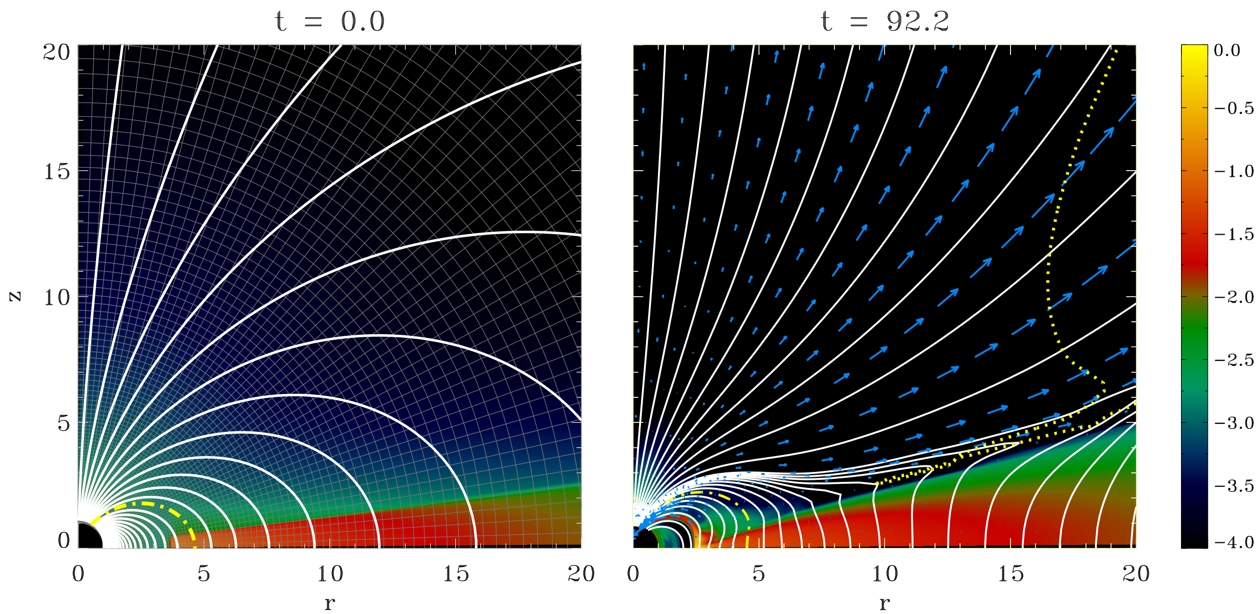

Fig. 1. *Left panel*: initial conditions of an axisymmetric simulation of the interaction of an accretion disk with a dipolar stellar magnetosphere. The disk includes resistive and viscous effects, in order to ensure a continuous accretion of the disk. The magnetospheric field lines are co-rotating with the central star which is modeled as a perfect conductor rotating at 10% of its break-up speed. The dot-dashed line marks the magnetic surface anchored at the corotation radius. *Right panel*: outcome of a simulation characterized by a stellar field $B_\star = 800$ G and the viscous and resistive α coefficients $\alpha_{\rm v} = \alpha_{\rm m} = 1$. The snapshot is taken after ~ 92 periods of rotation of the protostar. The dot-dashed line marks the magnetic surface anchored at the corotation radius, arrows indicate the velocity vectors and the Alfvènic surface of the stellar wind is marked by a dotted line.

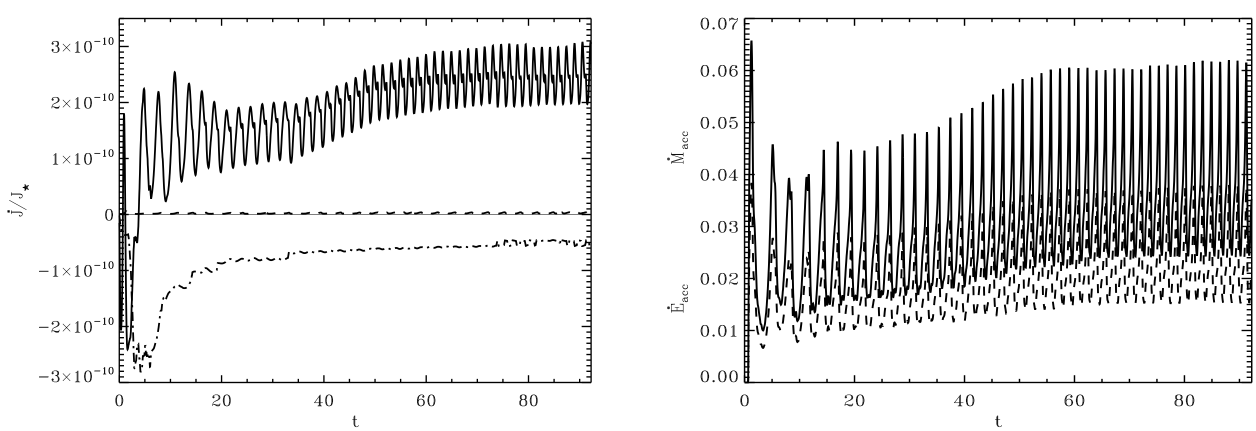

Fig. 2. *Left panel*: Time evolution of torques acting on the surface of the star, normalized over the star angular momentum. This defines the inverse of the braking time. Plotted are the torque acting along the opened field lines (dot-dashed line) and on the magnetosphere connected to the disk (solid line). Conventionally a positive value spins up the stellar rotation. A value 2×10^{-10} corresponds approximatively to 10^{-6} Myr^{-1}. Time is given in units of the rotation period of the central star. *Right panel*: Time evolution of the mass accretion rate (solid line) and the energy flux (dashed line) measured on the surface of the star. For our standard normalization, an accretion rate 0.03 corresponds approximatively to $1.2 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$.

An example of a highly resistive ($\alpha_{\rm m} = 1$) and viscous ($\alpha_{\rm v} = 1$) disk interacting with a dipolar stellar magnetosphere is shown in Figure 1. Several features can be noticed: the formation of accretion funnel flows emerging from the accretion disk truncated at $R_{\rm t} \sim 2.8\, R_\star$; an extended magnetosphere connecting the star and the disk up to $R_{\rm out} \sim 12\, R_\star$, well beyond the corotation radius located at $R_{\rm co} = 4.64\, R_\star$; a stellar wind flowing along the opened magnetic field lines anchored onto the surface of the star. This in an ideal case to test the disk-locking scenario: the temporal behavior of the torques acting on the surface of the star for this simulation are shown in the left panel of Figure 2: unfortunately the torque calculated along the magnetosphere closing onto the disk, which includes both the accretion and the extended magnetosphere torques, is still spinning up the star rotation. As argued by Matt & Pudritz (2005a) it is really hard to extend the magnetosphere far enough beyond the corotation radius to balance the torque coming from accretion. The quasi-periodic oscillations showed by the magnetospheric torque reflect the oscillations of the accretion rate (right panel of Figure 2) with a period around $\sim$ 2 periods of the star: this is a consequence of an unbalance between the viscous torque, controlling the accretion rate on the large scale of the disk and the magnetic torque associated with the star rotation, regulating accretion in the central regions of the disk.

In the left panel of Figure 2 we can also see that the torque calculated along the opened field lines of the magnetosphere is efficiently spinning down the star rotation, even if it is not strong enough to balance the accretion spin-up torque: this reflects the presence of a stellar wind flowing along these magnetic surfaces, as clearly visible in Figure 1. This outflowing component is discussed and described in the following section.

4. STELLAR WINDS

The characteristics of the stellar wind visible in Figure 1 are summarized in Figure 3, where I show the temporal evolution of its mass outflow rate $\dot{M}_{\rm wind}$ and its average magnetic lever arm $r_{\rm A}/R_\star$, i.e. the average position of the Alfvèn characteristic surface normalized over the stellar radius. These two quantities define the torque exerted by the wind onto the surface of the star

$$\dot{J}_{\rm wind} = \dot{M}_{\rm wind} r_{\rm A}^2 \Omega_\star \,. \qquad (2)$$

The wind torque is strongly enhanced by the huge lever arm $r_{\rm A}/R_\star \sim 16$, which is also a consequence of the widely opened geometry of the magnetic surfaces. This lever arm is basically the same required in Matt & Pudritz (2005b) to model an "accretion powered" stellar wind capable to balance the spin-up

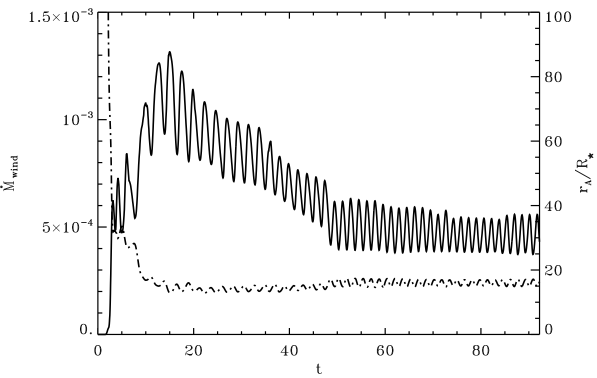

Fig. 3. Time evolution of the mass flux of the stellar wind observed in the simulation shown in Figure 1. The outflow rate is measured on the opened filed lines emerging from the star surface (solid line, left scale). The average magnetic lever arm of the wind is also plotted (dot-dashed line, right scale).

torque coming from accretion and contraction. On the other hand the authors required also an ejection efficiency $\dot{M}_{\rm wind}/\dot{M}_{\rm acc} \sim 0.1$, i.e. ten times higher than the one characterizing this simulation, which therefore displays a ten times less efficient torque. A systematic numerical study of "accretion powered" stellar winds has been presented recently by the same authors (Matt & Pudritz 2008).

One major complication in the modeling of stellar winds in the case of slowly rotating young stars, such as T Tauri stars, is that the rotational energy is not enough to thrust the stellar wind. An additional energy input at the base of the flow comparable to the gravitational potential energy of the star is needed to give the initial drive to the outflow. In Matt & Pudritz (2005b) it has been suggested that this extra input of energy can be linked to the energy deposited by the accretion. In the simulation presented here the initial thrust comes from a thermal pressure gradient: the temperatures required to launch this type of outflow pose a serious cooling problem. An alternative energy source could come from turbulent Alfvèn waves (DeCampli 1981). Notice that even if the initial thrust comes from a thermal driving, the outflow is magnetically dominated: the transport of energy and angular momentum is in fact mainly given by the Poynting flux. The magnetic energy could be possibly transferred to the outflowing material beyond the Alfvèn surface. The effect of these magnetically dominated stellar winds is similar to the "magnetic towers" propagating along the axis of rotation of the star proposed by Long et al. (2005) to explain the braking torques spinning down the star rotation.

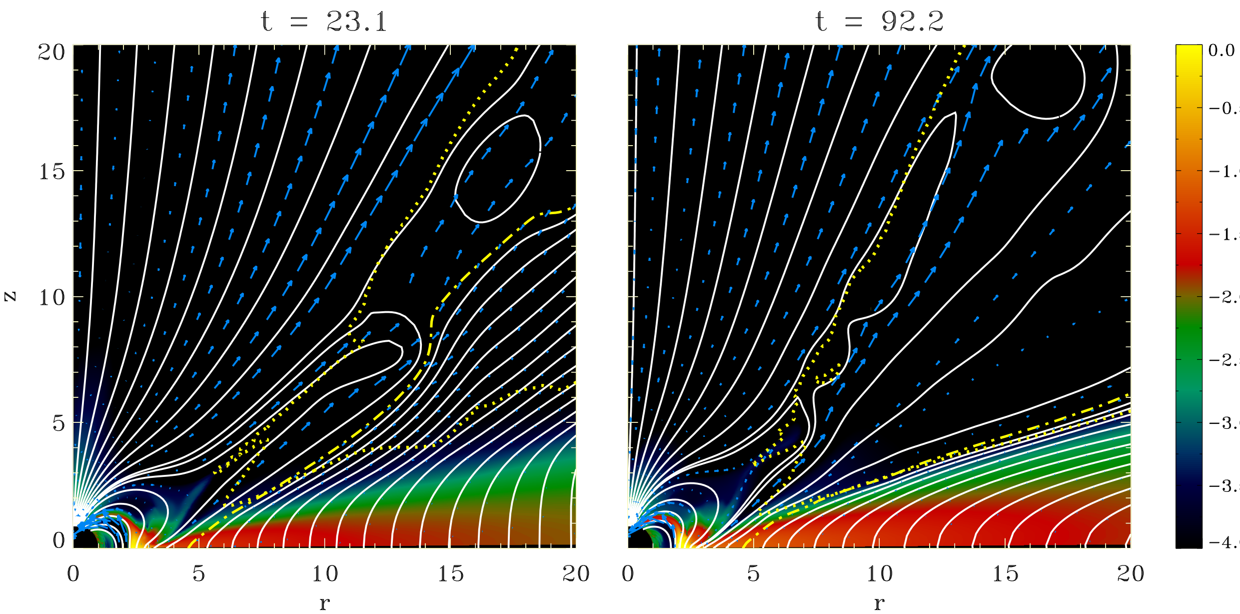

Fig. 4. Time evolution of density maps for a simulation characterized by $\alpha_{\rm v} = 1$, $\alpha_{\rm m} = 0.1$, $B_\star = 800$ G, $\Omega_\star = 0.1\sqrt{GM_\star/R_\star^3}$. Time is given in units of the stellar rotation period. The ejection of plasmoids due to the inflation and opening of the magnetosphere is visible.

It is therefore clear that, even if stellar winds cannot explain all the dynamical features of T Tauri jets, they can play a crucial role to regulate the rotation period of the star.

5. MAGNETOSPHERIC EJECTIONS

Many numerical models show that the evolution of a closed magnetosphere connecting a rotating star with a surrounding Keplerian accretion disk leads to the inflation and opening of the magnetospheric field lines (see e.g. Goodson et al. 1997; Bessolaz et al. 2008). As discussed in § 3 this is the natural outcome of the differential rotation between the star and the disk, and the effect becomes more evident when the magnetic coupling between the disk and the magnetic field is strong, i.e. when its resistivity is low. The opening of the magnetospheric field lines is accompanied by magnetic reconnection events with plasmoids launched along the current sheet separating the opened field lines anchored inside the disk and the opened field lines anchored onto the star surface (see Figure 4). Due to the episodic and unsteady character of these ejection events an analytical analysis of these outflows is not feasible; on the other hand in the simulations published the magnetic reconnection is controlled by numerical dissipation, thus arising issues on the timescales and the dynamics associated with these phenomena. Moreover, moving ballistically at 45° and not being confined by any external agent, these episodic ejections are not a good candidate to explain the dynamical features of T Tauri jets. The inflation and opening of the magnetosphere produces also opened magnetic surfaces anchored onto the disk surface: a disk-wind component can in principle be present.

The unsteady magnetospheric ejections can represent an efficient mechanism to remove angular momentum from the central parts of the system, thus helping the spin-down of the star. The initial acceleration happens along field lines which are still connecting the star with the disk: the angular momentum is extracted therefore both from the star and the disk, accumulated on the tip of the highly deformed magnetospheric lines and then released in the reconnection event, as in a huge magnetic sling.

To quantify the angular momentum and the mass extracted from the system by these episodic events is not an easy task. As it is shown in Figure 5, even when these outflows are characterized by a small mass ejection efficiency, the torque exerted on the accretion disk is stronger than a Keplerian torque, i.e. the torque needed to accrete from one Keplerian orbit to another. The disk rotation determined by the presence of these magnetospheric ejections can be therefore strongly sub-Keplerian. This type of outflows can be therefore an efficient mechanism to remove angular momentum from the disk *before* it is accreted onto the star. This effect goes back to the original idea of the X-Wind: anyway, as already

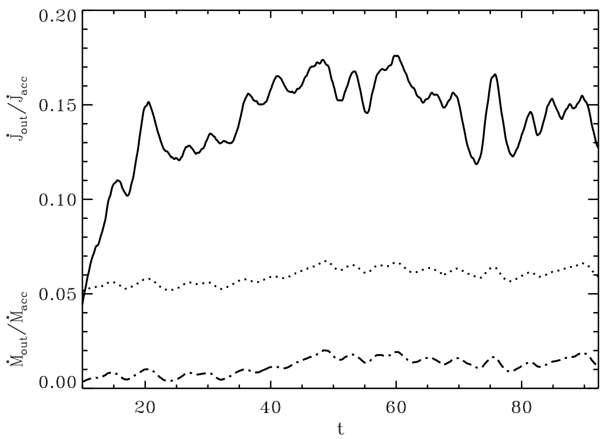

Fig. 5. Time evolution of quantities characterizing the episodic magnetospheric ejections visible in the simulation shown in Figure 4. Plotted are the mass ejection efficiency (dot-dashed line) and the ratio between the ejection torque and the accretion torque (solid line). The "Keplerian" torque necessary to accrete from one Keplerian orbit to another is plotted with a dotted line.

pointed out, these magnetospheric ejections cannot be characterized as disk-winds and cannot reproduce the dynamical characteristics of observed T Tauri jets, in terms of poloidal speed, collimation and angular momentum. Moreover, despite the fact that some mass is outflowing also along the opened field lines anchored on the disk surface, the low ejection efficiency and the small torque do not characterize the disk-wind component observed in this particular simulation as an X-Wind.

This is not the unique magnetic configuration which leads to reconnection and episodic outflows. If a vertical magnetic field is present inside the disk with a polarity which is parallel to the protostellar magnetic moment, a reconnection X-point and a neutral line form at the disk midplane. According to this scenario, accreted mass is lifted vertically above the X-point by the strong Lorentz force and is loaded onto newly opened field lines anchored onto the star surface. If the X-point is located farther than the corotation radius the matter loaded onto the opened field lines is accelerated by the star rotation and produces a so-called "reconnection X-Wind" (Ferreira et al. 2000). No numerical experiments exist of such a magnetic configuration: this would require the simultaneous modeling of the disk magnetic field, and therefore of disk-winds, and of the star-disk magnetospheric interaction.

6. SUMMARY AND CONCLUSIONS

I presented models based on numerical MHD simulations of the interaction between the accretion disk and the dipolar magnetosphere of a protostar. Recurring to simulations characterized by different disk resistivities I illustrated different mechanisms proposed to explain the spin-down of accreting T Tauri stars.

I confirmed that, in order to maintain an extended magnetic connection between the disk and the star, a large disk resistivity is required. This is necessary to allow some azimuthal slippage of the field lines relative to the disk material and prevent the toroidal field to grow too much at the surface of the disk. Adopting an $\alpha_{\rm m} = 1$, which is basically the maximum value allowed by an α parametrization, the magnetosphere can extend up to 12 $R_\star$, where the corotation radius of the simulations was placed at 4.64 $R_\star$. Despite the magnetosphere extends well beyond the corotation radius, the spin-down torque transferring angular momentum from the star back to the disk is not sufficient to balance the accretion spin-up torque.

I therefore suggested that the spin-down torque must be linked to ejection phenomena. Stellar winds can provide a viable mechanism to extract angular momentum along the opened magnetic surfaces anchored onto the stellar surface. On the other hand, since T Tauri stars are slow rotators, the initial thrust cannot be given by the centrifugal acceleration, as it happens in disk-winds (Blandford & Payne 1982). An additional source of energy, comparable to the gravitational potential energy, must provide the initial drive: this initial energy input, which can be of thermal or turbulent magnetic origin, can in principle be linked to the energy deposited by accretion onto the star (Matt & Pudritz 2005b). Anyway these outflows can be magnetically dominated, providing huge lever arms which help braking the stellar rotation.

Another type of ejection capable of extracting the excess angular momentum from the central region of the star-disk system is given by the episodic magnetospheric ejections due to the inflation-reconnection-opening of the magnetospheric field lines connecting the star with the disk. This kind of ejection can extract angular momentum both from the star and the disk: in particular the simulations show that the torque exerted by these outflows on the disk is able to produce a sub-Keplerian rotation, thus reducing the angular momentum deposited onto the star by the accretion disk. This type of ejection becomes more important when the coupling between the field and the disk is stronger, i.e. for smaller $\alpha_{\rm m}$. On the other hand, since this phenomenon strictly depends on the strength of the magnetic coupling and, most important, determines reconnection events, an exhaustive study of the parameter space and of the physics involved in the process is still required.

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