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Funnel flows from protoplanetary disks

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Abstract. We study the accretion flow from a protoplanetary disk onto a T Tauri star using numerical simulations assuming axisymmetry. Starting from a configuration consisting of an accretion disk, a halo of low density, and a dipolar magnetic field rooted in the star and threading the disk, we evolve the system in time. We find an outflow in the halo at intermediate latitudes and a funnel flow from the truncated disk to the star. The torque on the stellar surface is variable. The star is spun up on average but there are episodes of torqueless accretion and spin-down.

Key words. stars: magnetic fields – T Tauri stars – accretion, accretion disks

1. Introduction

In the Ghosh & Lamb (1978) scenario of braking the rotation of neutron stars a dipolar magnetic field rooted in the star threads the surrounding disk and is wound up by the rotational shear between star and disk. For a Keplerian disk, the parts closest to the star rotate faster than the stellar surface while at greater distance the rotation period is longer than the stellar rotation period. Magnetic coupling of star and disk will therefore lead to an angular momentum transport from the star to the outer parts of the disk as well as from the inner parts of the disk to the star. For an effective braking of the stellar rotation the contribution of the outer part must dominate, which for a dipolar field is only possible when the innermost part of the disk is disrupted by the stellar magnetic field. At the truncation radius the accretion flow is lifted out of the disk plane and forced to move parallel to the magnetic field until it hits the stellar surface at high latitudes.

So far such funnel flows have not been directly observed. However, recent Doppler images of the T Tauri star MN Lupi show a ring of bright spots around the star's polar cap (Strassmeier et al. 2005) which can be interpreted as signature of magnetospheric accretion. Figure 1 shows a composite image of a MN Lupi and a funnel flow from a numerical simulation. In this paper we show results from a numerical simulations of a star-disk system with a dipolar magnetic field rooted in the star.

2. Model

We solve the conservation equations for mass, momentum, and gas energy together with the induction equation in spherical polar coordinates assuming axisymmetry using the code described in Küker et al. (2003). The force term in the momentum equation contains gravity, Lorentz force, and (turbulent) viscous stress, the gas energy equation includes viscous and magnetic heating. The equation of state is that for a perfect gas. We start with a disk with an accretion rate $\dot{M} = 10^{-8} M_\odot/\mathrm{yr}$

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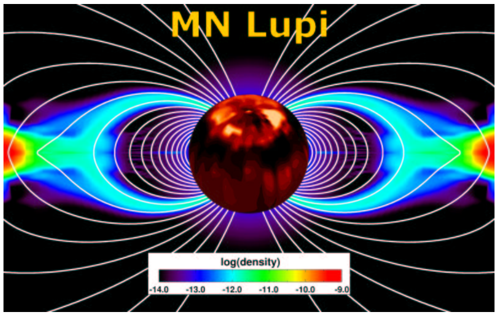

Fig. 1. Colour contour plot of the initial disk/halo configuration from the RHD model. Left: $t = 0$ (start of the simulation. Right: $t = 80$

that is interpolated from 1D models computed at the inner and outer radius, respectively, with the RHD code of Kley (1989).

The simulation box extends in radius from the stellar surface to a distance of 20 stellar radii from the center of the star and in latitude from the equatorial plane to the axis of rotation. Symmetry (anti-symmetry, where applicable) is assumed with respect to the equatorial plane. The disk is initially truncated at the co-rotation radius. The left part of Figure 2 shows the initial density distribution as a color contour plot. The white lines mark the magnetic field. The star and the surrounding disk (truncated at the co-rotation radius) are embedded in a halo. The star itself is excluded from the domain. Its surface constitutes the inner boundary.

The inner boundary condition allows gas to leave the computation box but prevents a gas flow from the star into the disk or halo. For the magnetic field we require that the radial derivatives of toroidal components of both the magnetic and the electric field vanish. At the outer boundary we distinguish two regions. At low latitudes the density and (negative) radial velocity of the start solution are maintained and a keplerian $R^{-3/2}$ variation is assumed for the angular velocity. Above the disk the same conditions as at the inner boundary apply to the radial and latitudinal velocity components and the magnetic field. The angular velocity is assumed constant with radius (no viscous stress). The system is fed mass through the outer boundary at low latitudes. At higher latitude it can lose gas through the boundary but is prevented from accreting. The initial gas density in the halo is $\rho = \rho_0 x^{-3}$ with $x = r/R_*$ and $\rho_0 = 10^{-11}\mathrm{gcm}^{-1}$. The initial temperature is constant. With the exception of the immediate vicinity of the star, which is in co-rotation, the gas rotates with an angular velocity $\Omega = \Omega_0 x^{-3/2}$, where Ω_0 is the stellar breakup angular velocity. The magnetic field is a dipole rooted in the star with a polar field strength of 5 kG at the stellar surface.

3. Results

The initial phase is mainly characterized by the buildup of the toroidal field caused by the rotational shear between star and disk. While the original dipole field is force-free, the combination of dipole and toroidal field exerts a Lorentz force on the gas. After about 100 stellar breakup periods the back-reaction of the Lorentz force on the gas motion reduces the shear between gas and disk and the toroidal field energy saturates.

The middle part of Figure 2 shows a snapshot from that saturated regime. The poloidal field is mostly contained in a magnetosphere with a radius of 2.5 stellar radii. This magnetosphere is in co-rotation with the star and has no toroidal field. It is supported by the magnetic pressure, $p_{\mathrm{mag}} = B_p^2/4\pi$, against the infalling gas. The field configuration shown in Figure 2 is a "compressed dipole." Compared to the pure dipole we started with the field lines lie closer together and the magnetic pressure is higher. The stellar dipole has been squeezed by the accretion flow, which in turn has been deflected out of the equatorial plane and turned into a funnel flow that hits the stellar surface at high latitudes.

The right part of Fig. 2 shows the angular momentum flux in the immediate vicinity of the star at t=200. Two effects contribute to the angular momentum transport, namely advection by the gas flow (accretion stress), which is always directed inwards, and the Maxwell stress, which can be directed outwards or inwards. The accretion stress is naturally tied to the gas flow. The Maxwell stress, which dominates the total stress in Fig. 2, is maximal at the

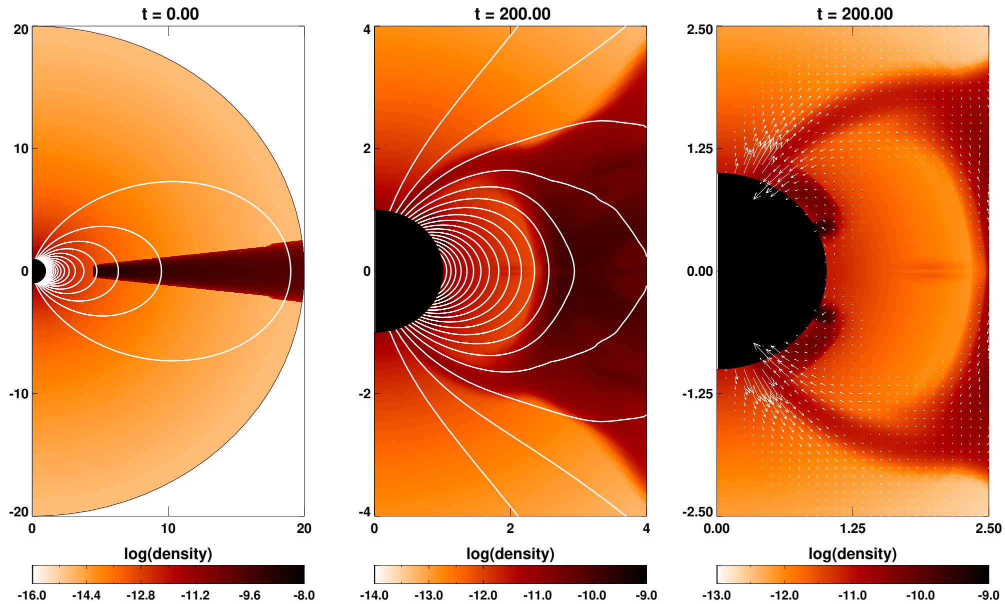

Fig. 2. Left: Colour contour plot of the density distribution at the start of the run. The white lines indicate the magnetic field. Middle: Zoom into the neighborhood of the star. The colour contours show the density, the white lines the magnetic field. Right: flux of angular momentum (white arrows) vs. gas density (colour contours).

boundaries of the funnel flow. In the polar cap it is directed outwards while at the interface between the funnel and the magnetosphere it is directed towards the star. The integral over the stellar surface can be either positive or negative but is negative most of the time, indicating an inward flow of angular momentum, i.e. spin-up. At the time of the snapshot the two torques are roughly balanced and the total torque on the star vanishes.

The model shows a breakup of the field lines that initially connect the polar cap of the star with the outer parts of the disk. As the field lines leaving the star at lower and mid-latitudes are confined to the magnetosphere only a small part of the disk remains magnetically connected to the star. The magnetic field drives an outflow that leaves the simulation box at mid-latitudes. Compared to the start model the density in the halo is substantially higher up to about 45 deg latitude. Our simulations show that both braking and spin-up are possible, depending on the stellar rotation rate, mass accretion rate, and magnetic field strength. A similar result has been found by Romanova et al. (2002) for a more generic setup. So far the simulation times have been too short to reach true equilibrium or stellar spin-down over a prolonged period. Longer simulation times and solving for the stellar rotation rate together with the MHD equations will bring us closer to a comprehensive model of stellar braking.

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