Angular momentum transfer in star-disk interaction with complex stellar magnetic field

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Abstract: **In a star-disk magnetospheric interaction, transfer of angular momentum determines the evolution and stability of a system. We investigate the influence of complex magnetic fields on the transport of angular momentum between a magnetized protostar and an accretion disk. For the first time we compare results of axisymmetric resistive and viscous MHD simulations of a star-disk system in the full [0,PI] half-plane, with the increasing complexity of the stellar magnetic field, lasting for more than hundred stellar rotations. We vary the stellar field from the pure dipole to quadrupole, octupole and mixed, multipole magnetic fields.**

Introduction:

Angular momentum transport in the early phase of evolution of sun-like stars is still an unsolved problem in stellar astrophysics. There is a general consensus that spin-up of the young star because of gain of angular momentum from disk accretion, is prevented by the magnetic interaction between the star and the disk. We study the angular momentum transfer of the star with an extended magnetosphere beyond the disk corotation radius with dedicated star-disk interaction (SDI) simulations.

Numerical setup:

We use the PLUTO v.4.1 code (Mignone et al. 2007, 2012), with logarithmic stretched grid in spherical coordinates, to perform a 2D-axisymmetric star-disk simulation in the full [0,PI] half-plane, in the resolution RxZ = [109x100] grid cells with the maximal radius of 30 stellar radii. Following Zanni & Ferreira (2009), the disk is set following Kluzniak & Kita (2000), as shown in Fig.1. The viscosity and resistivity are parameterized by the Shakura-Sunyaev prescription as $\alpha c^2/\Omega$, so that the magnetic Prandtl number $P_m=3\alpha_v/2\alpha_m$. We use a split-field method, in which only changes from the initial stellar magnetic field are evolved in time. The equations solved by the PLUTO code are:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=0$$

$$\frac{\partial\rho\boldsymbol{u}}{\partial t}+\nabla\cdot\left[\rho\boldsymbol{u}\boldsymbol{u}+\left(P+\frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi}\right)\boldsymbol{I}-\frac{\boldsymbol{B}\boldsymbol{B}}{4\pi}-\boldsymbol{\tau}\right]=\rho\boldsymbol{g}$$

$$\frac{\partial E}{\partial t}+\nabla\cdot\left[\left(E+P+\frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi}\right)\boldsymbol{u}-\frac{(\boldsymbol{u}\cdot\boldsymbol{B})\boldsymbol{B}}{4\pi}\right]$$
$$+\nabla\cdot[\eta_{\rm m}\boldsymbol{J}\times\boldsymbol{B}/4\pi-\boldsymbol{u}\cdot\boldsymbol{\tau}]=\rho\boldsymbol{g}\cdot\boldsymbol{u}-\Lambda_{\rm cool}$$

$$\frac{\partial\boldsymbol{B}}{\partial t}+\nabla\times(\boldsymbol{B}\times\boldsymbol{u}+\eta_{\rm m}\boldsymbol{J})=0.$$

In our SDI setup, the Ohmic and viscous heating terms are removed from the PLUTO energy equation, to prevent the thermal thickening of the accretion disk.

In the boundary conditions, we set the stellar surface as a rotating perfect conductor, so that in the stellar reference frame the electric field is zero, and the flow speed is parallel to the magnetic field. This prescribes the rotation of the matter atop the star, and the effective rotation rate of the field lines:

$$\Omega_{\rm eff}=\Omega-u_{\rm p}B_\phi/rB_{\rm p}$$

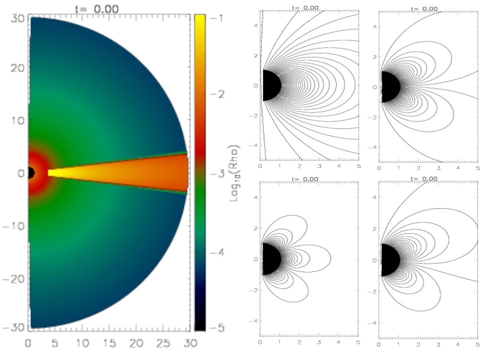

Figure 1: *Left panel: the initial matter density distribution in our simulations, shown in logarithmic color grading. Right panels: zooms into our initial magnetic field setups for the dipole, quadrupole, octupole and mixed multipole stellar field, respectively.*

Results:

We obtained long-lasting solutions for the four chosen geometries of magnetic field, as shown in Fig. 2. In the pure dipole and octupole case, after the initial symmetric formation of two columns, an asymmetric solution with the accretion column attached to northern or southern half of the star is formed. In the quadrupole and mixed multipole case with a quadrupole leading term, the solution is more symmetric, with the accretion column attached around the stellar equatorial region. In Fig.3 we show matching of the matter rotation with the stellar surface, by computing the effective rotation rate of the magnetic field lines.

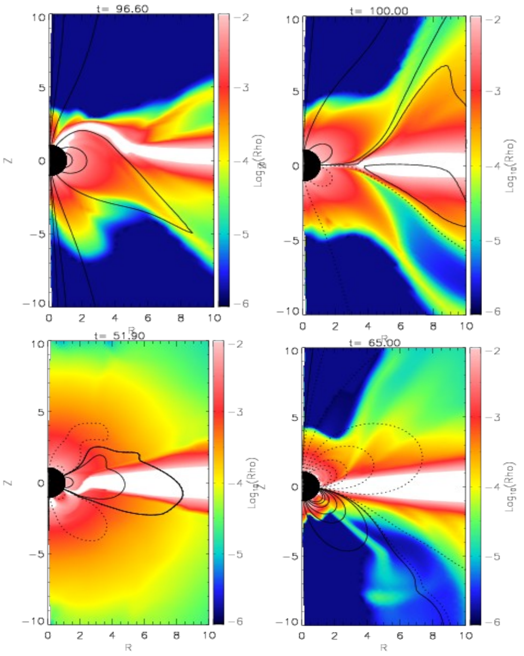

Figure 2: *Stable solutions in our SDI simulations, for the different geometries of the magnetic field, with time t given in stellar rotations. The matter density distribution is shown in logarithmic color grading, with the poloidal magnetic field shown in solid and dashed lines, depending on the direction of the field. We sampled the magnetic field lines to leave out the density distribution close to the star visible. The results for dipole, quadrupole, octupole and mixed multipole cases are shown from left to right, top to bottom, respectively.*

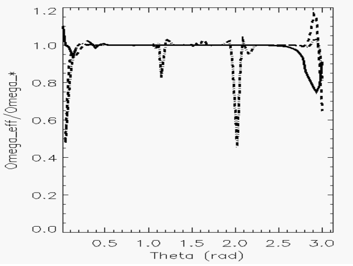

Figure 3: *The effective rotation rate of the magnetic surfaces, measured along the surface of the star. The dipole, quadrupole and octupole solutions are shown in solid, dashed and dot-dashed line. In the dipole solution matching is good, and in quadrupole and octupole solutions peaks occur where the current sheet approaches closer to the star. The mixed multipole solution is varying too much to be shown here.*

We note that except near current sheet, te field lines do rotate at the stellar spin rate. Torques in our dipole SDI simulation, computed at the stellar surface, are shown in Fig.4.

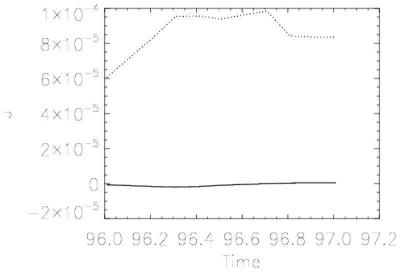

Figure 4: *Preliminary result for the average torque acting on the stellar surface in the dipole field case. In solid line is shown the magnetic, and in dotted line the kinetic torque. Time is given is stellar rotations.*

Conclusions and future work:

We presented preliminary results of the long-lasting numerical simulations of a star-disk system with complex magnetic field. It will be followed by a parameter study, determining the torque in the system, for various strength and topology of magnetic field. We will be changing the rotation rates from 2-10 days, accretion rates from 10^-9 to 10^-6 solar mass/year, with mass outflow of about 1/10 of the accretion rate, and different magnetic Prandtl numbers.

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