Star-disk interaction simulations with PLUTO code

Miljenko Čemeljić, 席門傑

CEA/SAp/LDEE, Saclay, Paris, France

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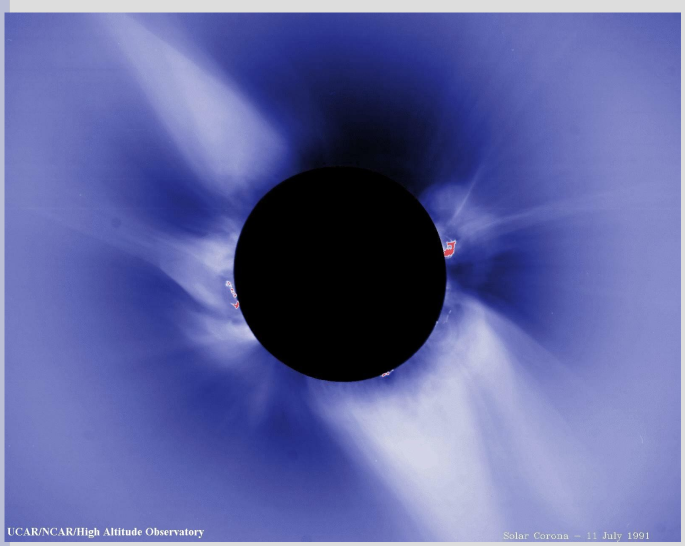
Introduction-1

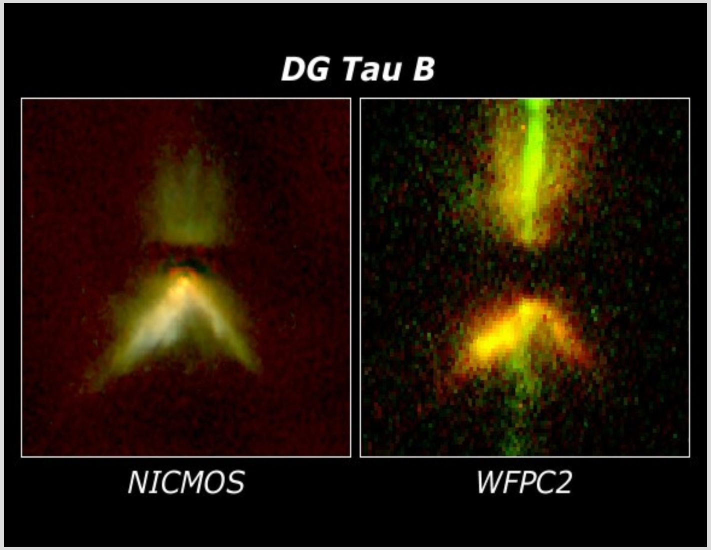
- During the evolution from a pre-stellar core to protostar, the angular momentum decreases for about 4 orders of magnitude. The spin-up of a star is probably prevented by the magnetic interaction between the star and the disk.

- The angular momentum can be extracted from the system in different ways:
-stellar winds, -violent outbursts, -stable outflows/jets, -accretion column onto the star.

Solar corona



FU Ori (ESO)



Introduction-2

- The largest dispersion in rotation rates is observed in solar mass young stars. When they reach the Main Sequence, they rotate with very different rotational velocities: from less then 10 km/s to more than 200 km/s. In a later evolution, after few billion years, most of them rotates with rotational velocity of few km/s; dispersion in rotation drops to only a few percents.

- For solar mass stars, spin-down is thought to be mainly because of a braking effect of magnetically driven winds. As the wind moves away from the star, its angular velocity decreases. The magnetic field of the star interacts with the wind, which slows the stellar rotation. As a result, angular momentum is transferred from the star to the wind, and the star's rate of rotation gradually decreases. Skumanich's Law (1972) states that, for a Main Sequence star on time scale of several hundred Myrs, angular velocity of a star decreases as $\Omega \sim 1/\sqrt{t}$.

- To obtain a full picture about torques in the system, both wind braking and star-disk interaction have to be considered. My simulations are to give an input on star-disk interaction.

Star-disk problem in TOUPIES project

- Goal is to find scaling laws for exchange of angular momentum between the star and surrounding.

- Idea is to predict the global stellar torque, which will then be used in stellar evolution models. For this, we need to be able to determine torques of stars of different masses and at different evolutionary stages. We will focus on the early evolutionary phases.

- My task is to investigate the influence of magnetic field geometry on the transport of angular momentum between the star and the environment.
- I will perform a parameter study, determining the torque in the system:
  - 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.
  -all this with various strengths and geometry of magnetic field.

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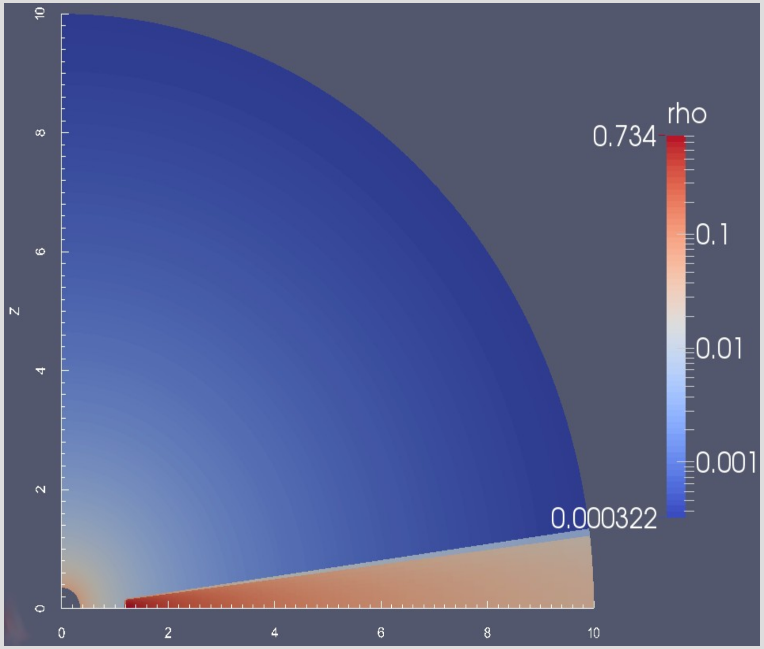
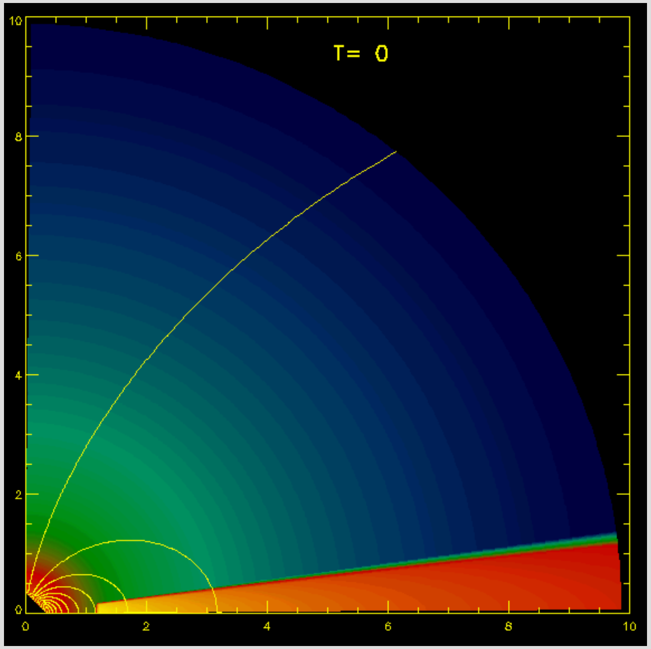
Star-disk setup-1

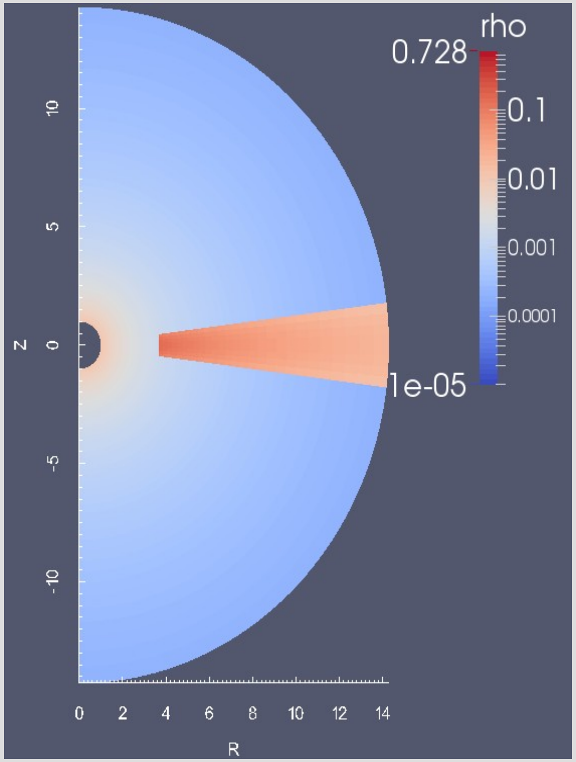
We use the PLUTO 4.1 code, with a stretched grid in spherical coordinates, to set-up a 2D-axisymmetric star-disk simulation. The disk is set by Kluzniak & Kita (2000), and viscosity and resistivity are parameterized as $\alpha c^2/\Omega$. In our initial setup, the initial magnetic field is a stellar dipole, and we use a split-field method, in which only *changes* from the initial stellar mag.field are evolved in time.





Star-disk setup-1b

I will also perform simulations in the full [0,PI] half-plane, to compute asymmetric flows in multipolar magnetic geometry.



Star-disk setup-2

- PLUTO code solves for the viscous & resistive MHD.
- In previous work on this problem, C. Zanni introduced a cooling term for removal of viscous and Ohmic heating-it was only to avoid thermal thickening of the disk, not actual radiative mechanism.
- In our current setup with newer version of the PLUTO code, a different tactics, also devised by C. Zanni, is used: heating terms in the viscous and resistive terms are not added in the first place in the code, so no need for the use of cooling term.

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

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

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

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

Stellar boundary condition

- It is not enough to just dump matter onto the star through the accretion column. Depending on the rotation of the portion of the disk from which the matter is lifted (with respect to the corotation radius), it will add or subtract angular momentum to the star (Zanni & Ferreira, 2009).
- Special care is needed to match stellar and rotation of the magnetic surfaces.
- Star is assumed to be a perfect, rotating conductor.

$$\boldsymbol{E}_{\Omega=\Omega_\star} = \boldsymbol{B} \times (\boldsymbol{u} - \boldsymbol{\Omega}_\star \times \boldsymbol{R}) = 0$$

$$u_\phi = r\Omega_\star + u_{\mathrm{p}} B_\phi / B_{\mathrm{p}}$$

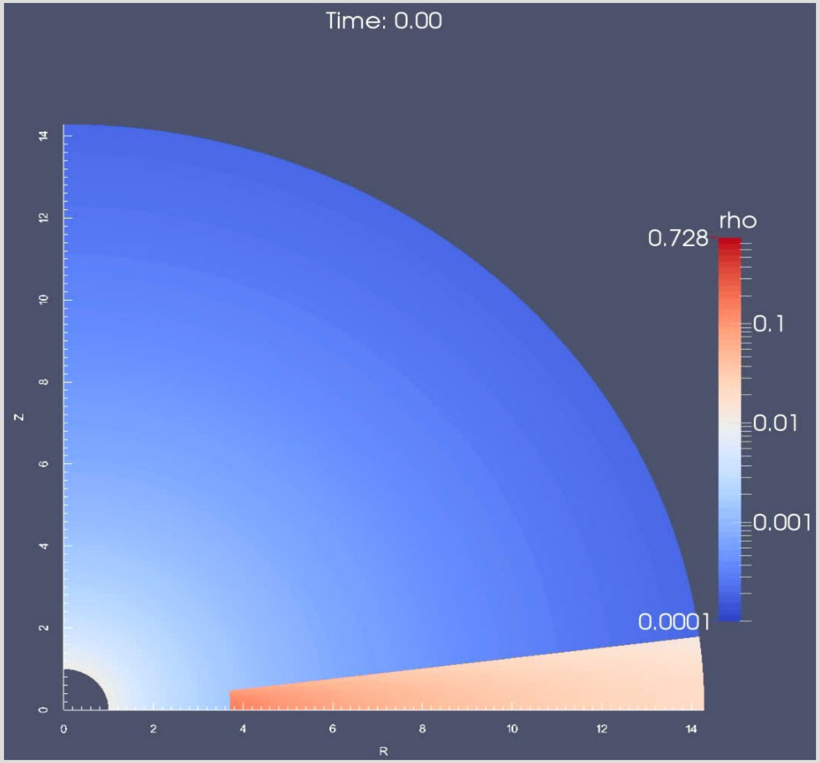
- To obtain the best match, we set simulations with different choices of inner boundary conditions, and compare the matching of stellar rotation and magnetic field surfaces.

Additional changes in the code

- Few more tweaks are needed to get PLUTO v.4.1 code to produce a stable, relaxed SDI simulation. I will list most important, some are detailed in Zanni & Ferreira (2009). My simulations are different from those, as I use the simplest setup I could find. I will work with different mag.field geometries, and there would be needed too many modifications for some more involved setup. I aim to obtain a stable, relaxed star-disk magnetosphere solution after few tens of stellar rotations.

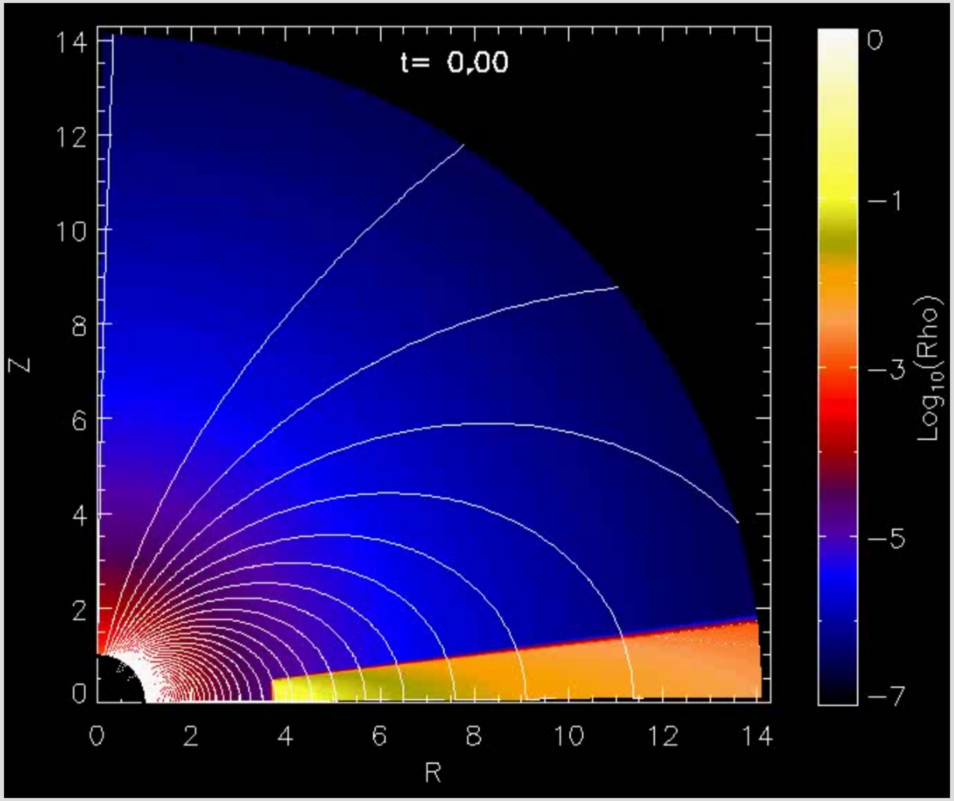
  In addition to usual init.c setup, one needs to:
- Set E_phi=0 at the stellar boundary condition in CT_Update routine (ct.c)
- Combination of limiters is also important, I follow ZF09 on this. As a “default” limiter in plm_states.c, it is better to set VL_LIMITER (instead of MC_LIMITER which is set in pluto v.4.1), it shows to be more stable.
- In ZF09, which was done with a modified version of Pluto 3, a modified Roe solver is used. We use a modified hlld solver: instead of switching to hll in the presence of shocks, flags in flag_shock.c are set to switch to hll if internal energy is less than 1% of the total energy.

Disk in HD simulations



- Without the magnetic field, I obtain a stable KK00 disk. Depending on viscosity, it will be just a disk in rotational equilibrium, or an accreting disk.

Viscous & resistive MHD simulations



- We obtain a stable, relaxed viscous & resistive-MHD disk for tens to hundreds of stellar rotations. I repeated Zanni & Ferreira 2009 result, with resistive and viscous coefficient set to unity.

Stellar boundary condition-comparison

- Now I can make a comparison of my results for matching of the stellar rotation with the rotation of the magnetic surfaces (Zanni & Ferreira, 2009).

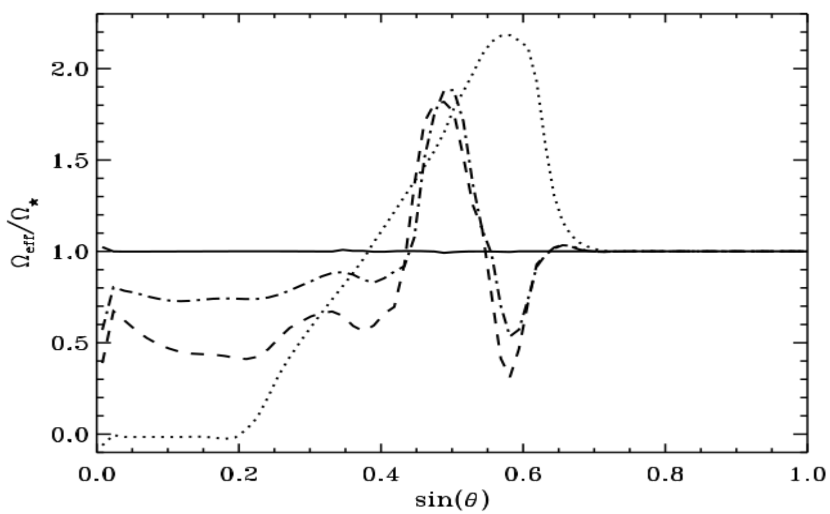
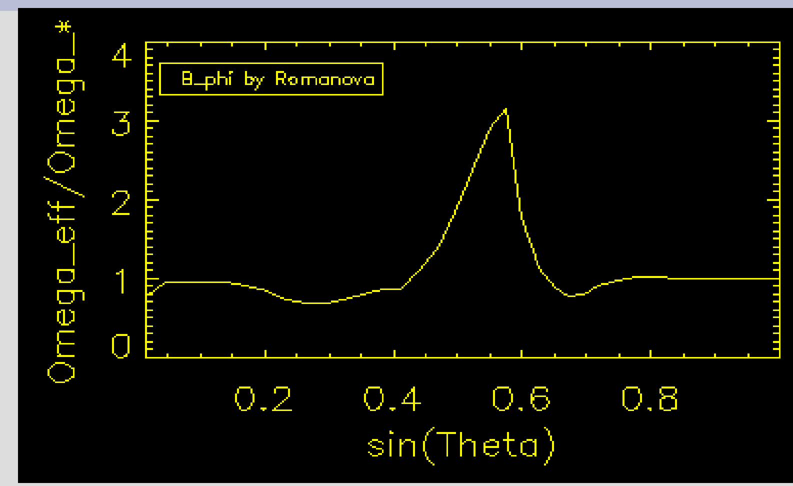
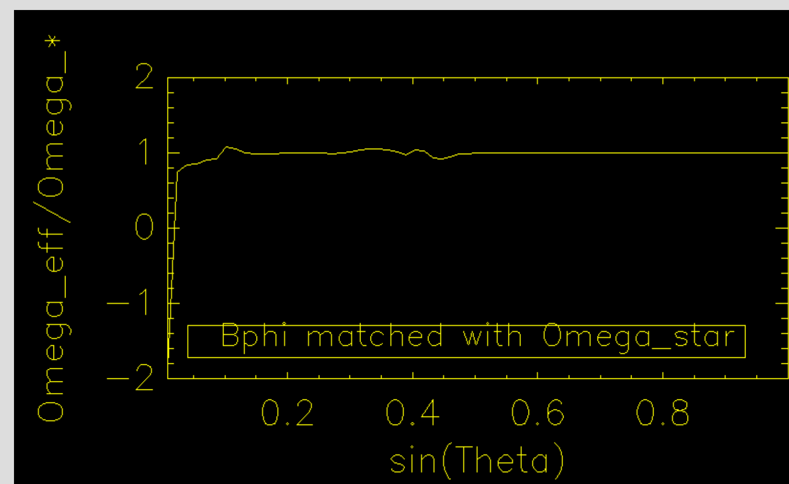
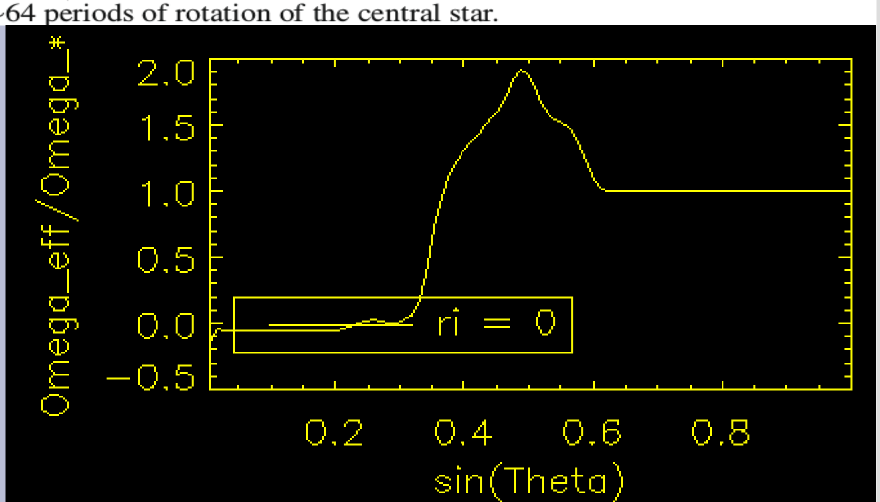


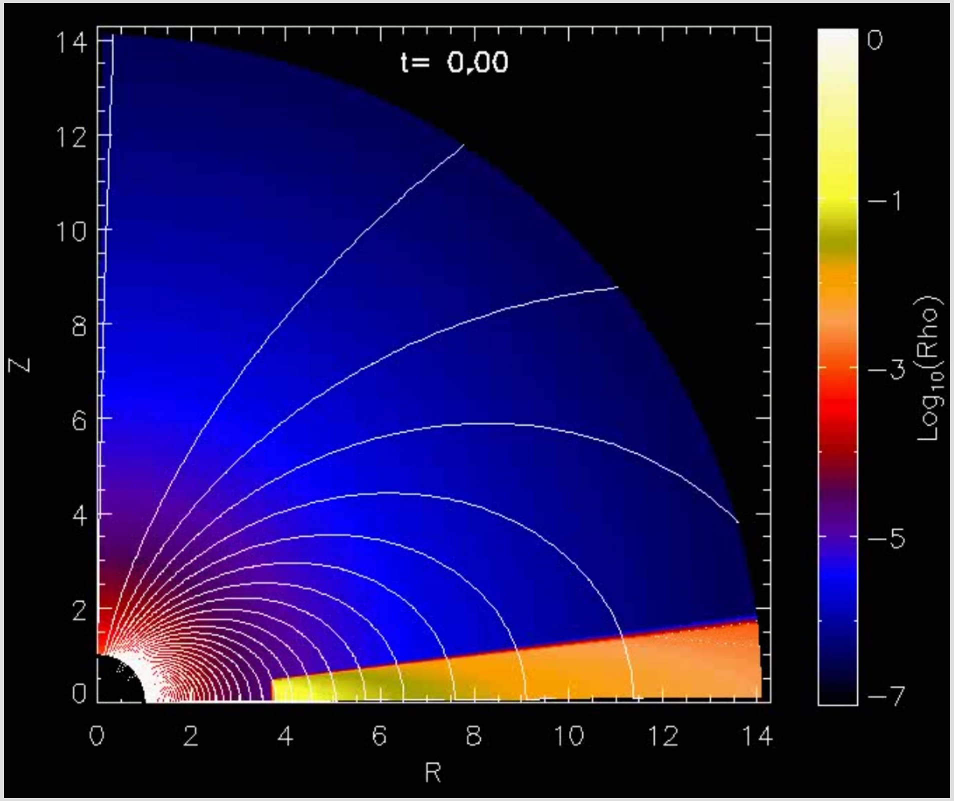
Fig. A.1. Effective rotation rate of the magnetic surfaces measured on the surface of the star as a function of the polar angle θ. The curves correspond to different boundary conditions on the toroidal field: the boundary condition used in this paper (solid line), $\partial\left(RB_\phi\right)/\partial R = 0$ condition (dot-dashed line), "outflow" boundary condition (dashed line), and $B_\phi = 0$ condition (dotted line). The snapshots are taken after ~64 periods of rotation of the central star.





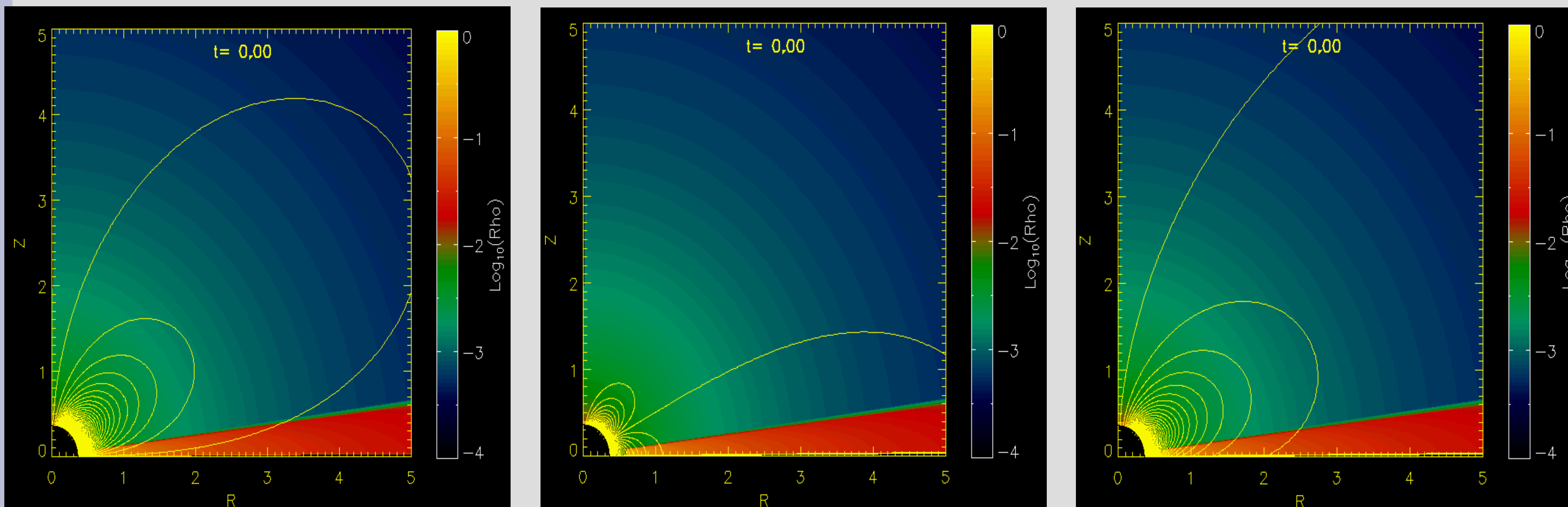


Viscous & resistive MHD simulations 2



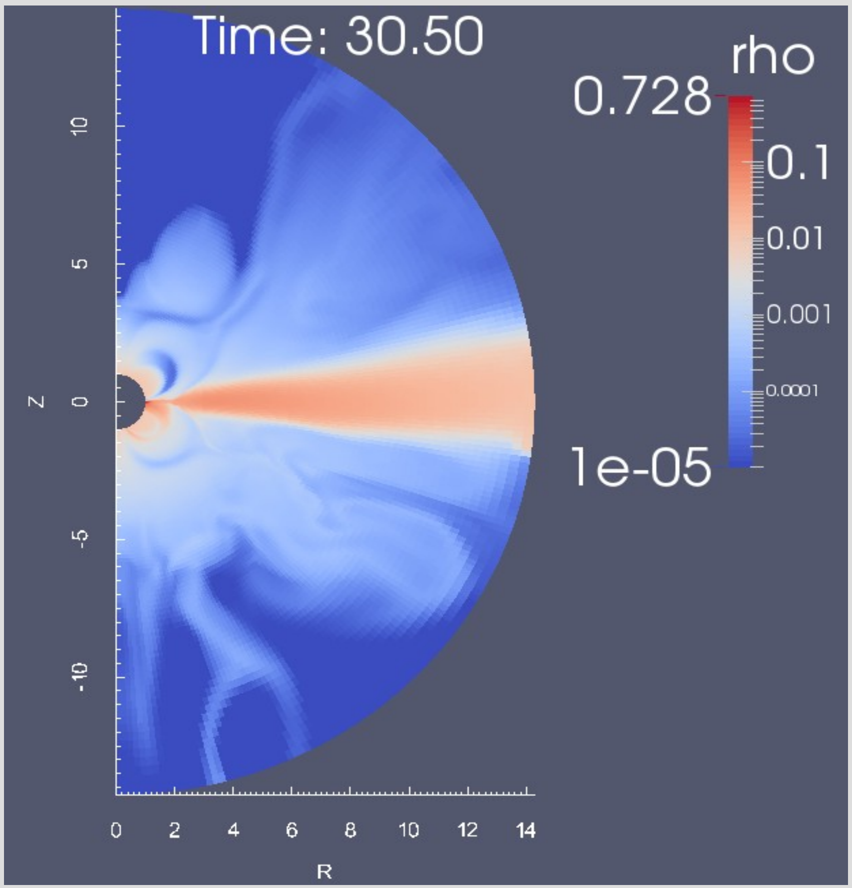
- I also repeated Zanni & Ferreira 2013 results, with conical outflows. Those are outcome of varying coefficient of viscosity, for the resistive coefficient alpha=0.1

Stellar quadrupole, octupole and multipole field



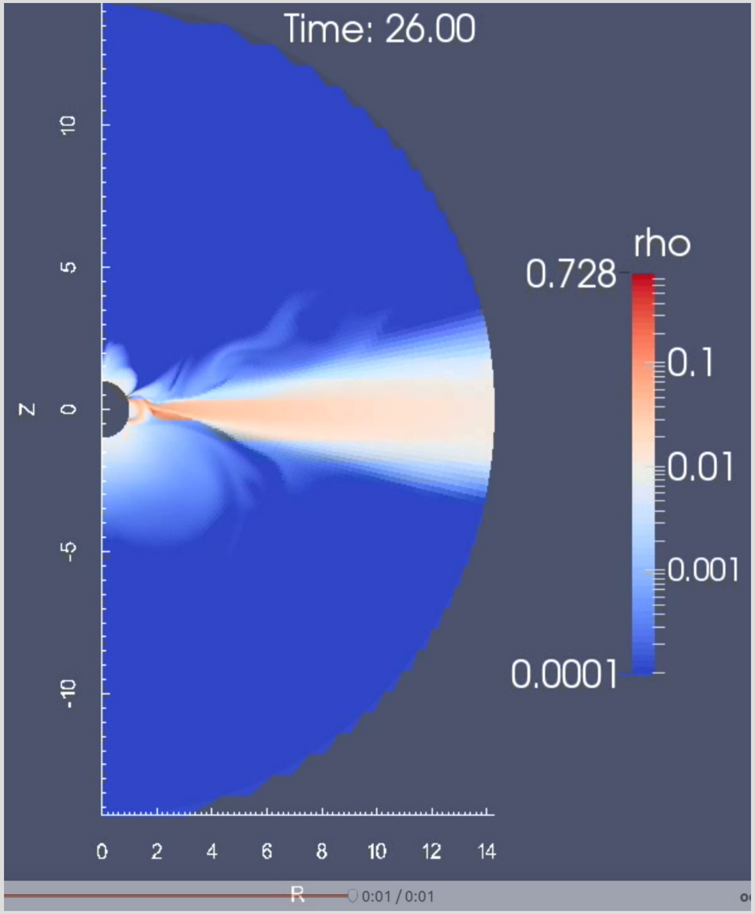
- We will set more complicated stellar field than only a dipole: quadrupole and octupole, and various combinations of those. It will be needed to work in full [0,PI] half-plane, to include asymmetry of the magnetic field.
- After 2D parameter study to find the best torque formulation, work on the same problem should be continued in 3D-it is interesting also because of different properties of reconnection in 2D and 3D.

Stellar quadrupole field



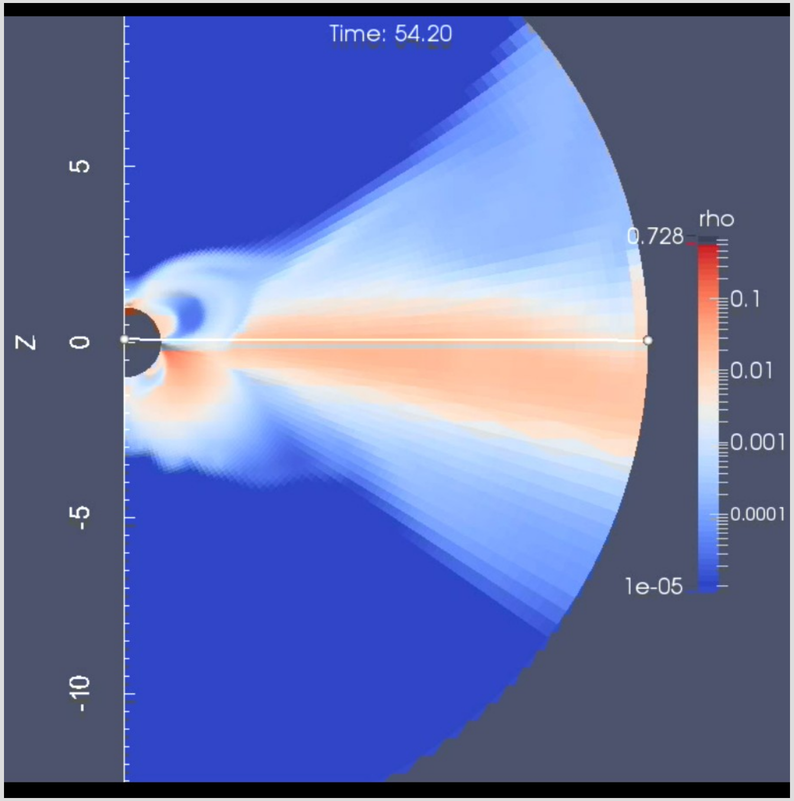
- Accretion column is not present in this case, and the disk innermost part is pressed towards the midplane of the disk.

Stellar octupole field



- Accretion column is still present in this case, at a different height from the disk mid-plane.

Mixed stellar field: dipole+quadrupole+octupole



- In this case it turns to be similar to quadrupole.

Summary

- Our simulations are to provide scaling laws for exchange of angular momentum between the star and surrounding, in dependence of the geometry and strength of the magnetic field.

- I will perform a parameter study, first for dipole, then quadrupole and octupole, and then mixed field, multipole. Goal is to find the best torque formulation from 2D simulations.

- For more complicated mag.field geometry I will also perform simulations in a complete [0,Pi] half-plane in Theta, and then in full 3D simulations.

- In my next post from October 2015, in Copernicus Center (CAMK) in Warsaw, Poland, I will add radiative transfer to the star-disk simulations. Modification for the radiative module published and made available online by Stute & Kolb is already in preparation (modifications for Pluto v.4.1) by a PhD student in Warsaw, V. Parathasarathy.