Long-lasting resistive, viscous MHD simulations of accretion disk around neutron star

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Introduction: Star-disk problem in Neutron Stars

In the interaction of the NS with close companion star, the accretion disk around the NS is formed.

Properties of such a binary system depend on the type of companion star, the neutron star mass and the magnetic field strength and geometry.

Kluźniak & Kita (2000) gave a HD model of the accretion disk, with viscosity and resistivity parameterized by Shakura & Sunyaev (1973) as $\alpha c^2/\Omega$, where c is the sound speed, Ω is the Keplerian speed, and α is the free parameter between 0 and 1.

We extended that model to the non-ideal MHD, and included the magnetosphere in the innermost part of a star-disk system.

One example is NS in millisecond pulsars: M=1.4M_sun, R~10km, B~10^8 Gauss, P=0.01 sec (10 msec), rho_0=4.62x10^-6 g/cm^3, Mdot_0=10^-9 M_sun/yr.

Star-disk simulation setup

Tool: PLUTO, Newtonian finite volume/ difference code. We solve viscous & resistive MHD equations, with the split field method (solving only for the departure from initial magnetic field) and constrained transport for div B=0.

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

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

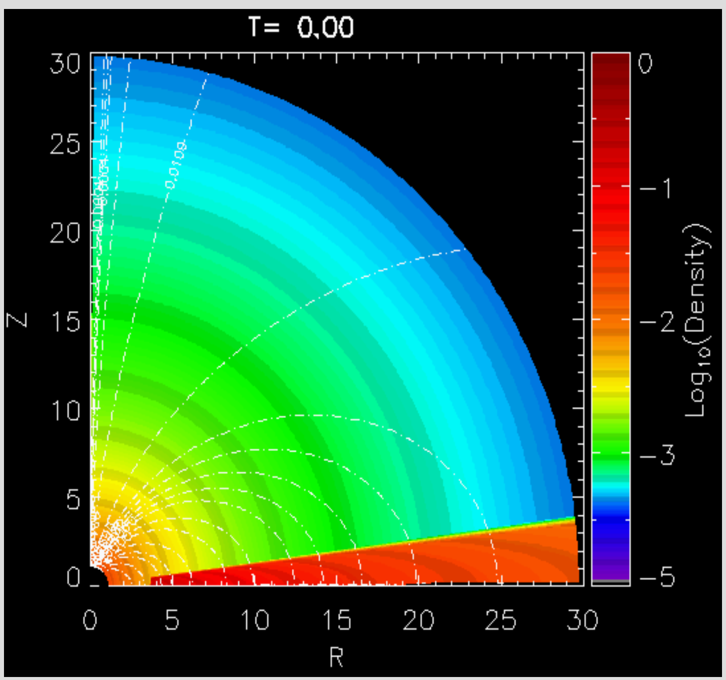
$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi} \right) \boldsymbol{u} - \frac{(\boldsymbol{u}\cdot\boldsymbol{B})\,\boldsymbol{B}}{4\pi} \right] + \nabla \cdot \left[\eta_{\mathrm{m}} \boldsymbol{J} \times \boldsymbol{B}/4\pi - \boldsymbol{u}\cdot\boldsymbol{\tau}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

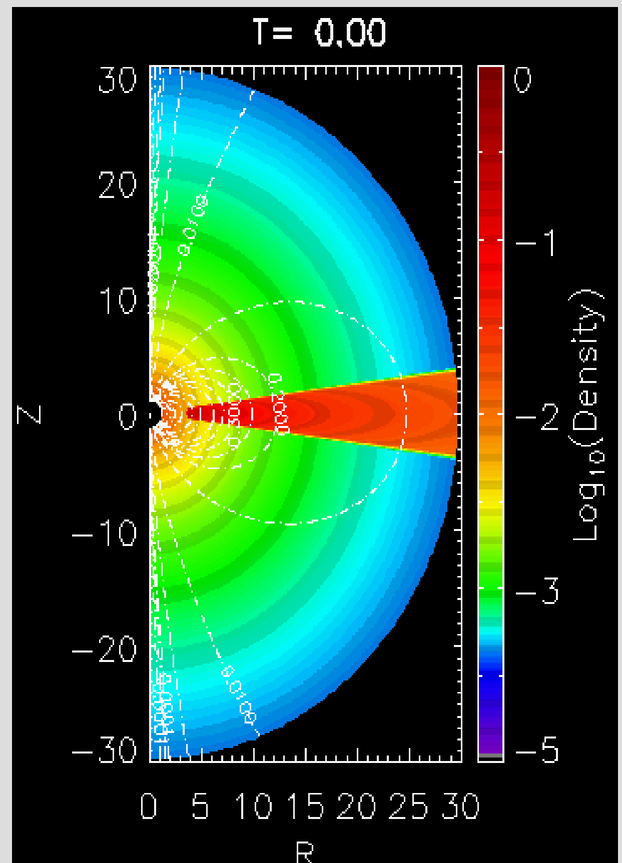
$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{u} + \eta_{\mathrm{m}} \boldsymbol{J}) = 0.$$

To avoid thermal thickening of the disk, I remove the viscous and Ohmic dissipative terms in the energy equation. Another method would be with introduction of the cooling source function, to remove the heat.

Star-disk simulation setup

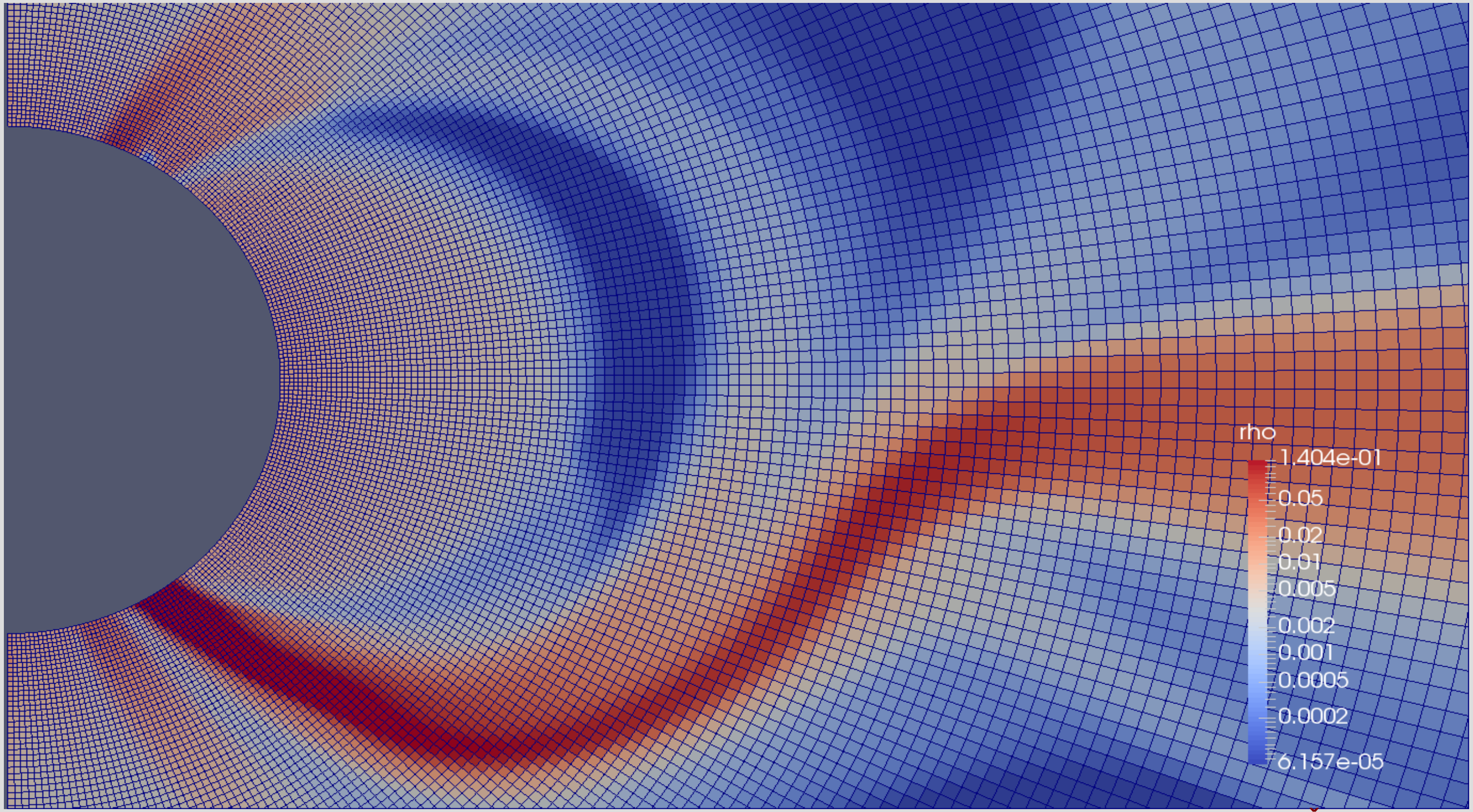
The disk is set by Kluźniak & Kita (2000) model. Initially non-rotating corona is in a hydrostatic equilibrium.
I set two kinds of 2D axi-symmetric simulations: **a)** in the half-plane ϑ=[0,π/2] and **b)** the full plane ϑ=[0,π], both to R_max=30R_*. I show the density in the logarithmic color grading.
In the case **b),** we do not prescribe the disk equatorial plane as a boundary condition, so that a more complete disk evolution is obtained.





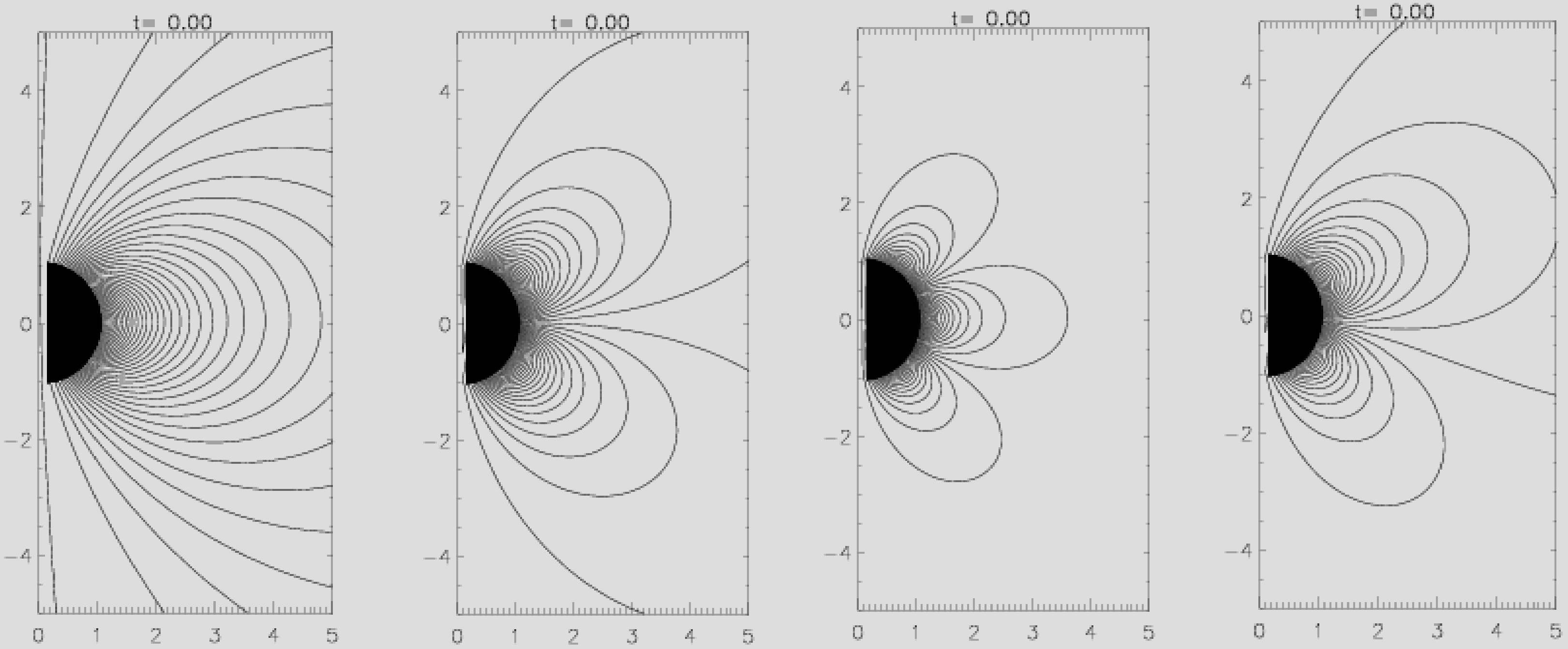
Star-disk simulation setup

Resolution is Rxϑ=[217x200] grid cells in ϑ=[0,π], with a logarithmic grid spacing in the radial direction. In a zoom close to the star after T=25 stellar rotations, for the dipole magnetic field case, I show that the accretion column is well resolved.
Star in my simulations typically rotates at about 1/10 of the breakup rotational velocity.



Star-disk simulation setup

I am investigating solutions with the different geometries of a stellar magnetic field: dipole, quadrupole, octupole and combinations of those (multipole).

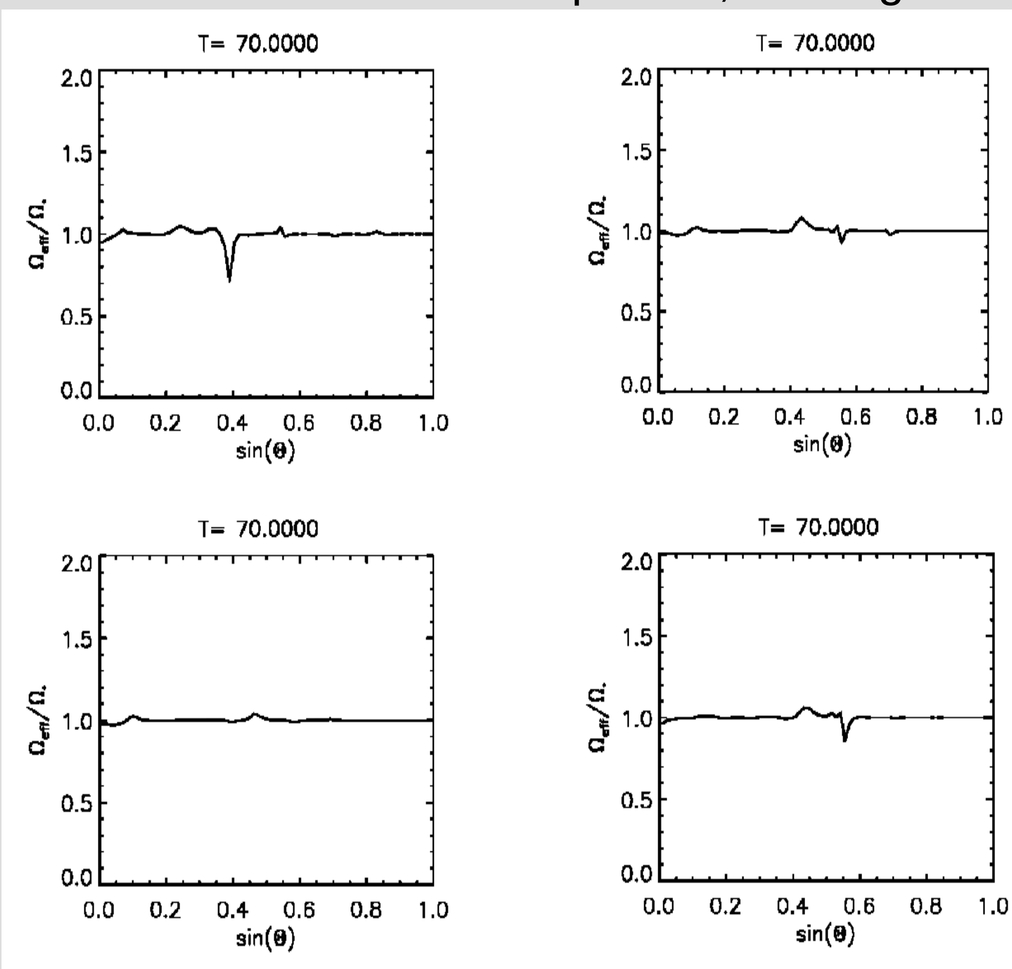


Stellar surface as a boundary condition

Special care is needed for matching of rotation of the star and magnetic field lines.
Star is assumed to be a perfect, rotating conductor:

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

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



Omega_eff in YSO's cases.

In addition to this, we need to set the correct magnetic torque to drive the plasma rotation atop the star. We measure the matching by the comparison of the stellar angular velocity and the effective rotation rate of the field lines:

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

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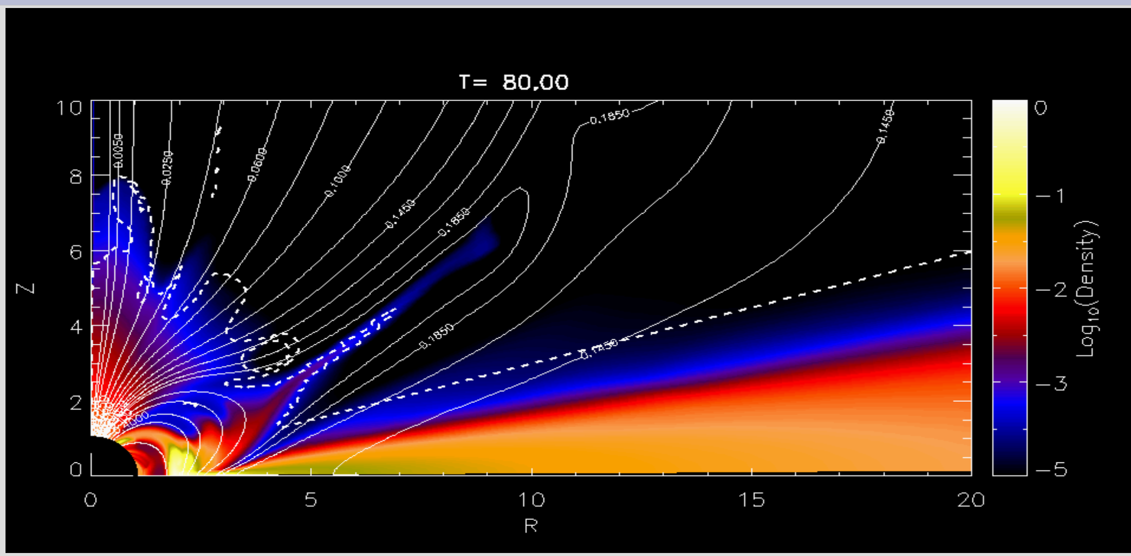
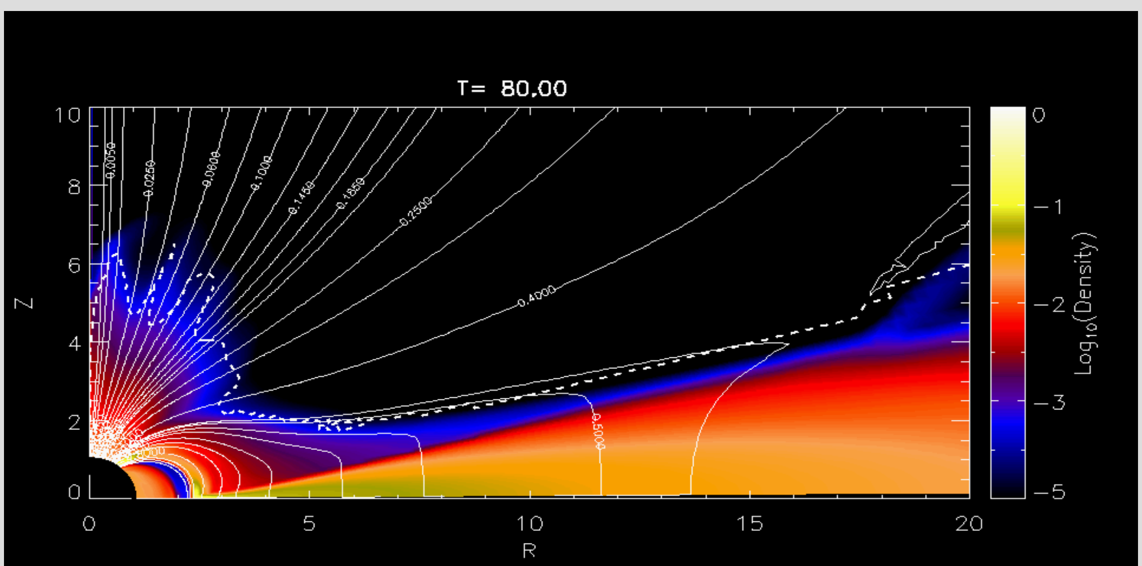
Preliminary results: YSO in ϑ=[0,π/2]





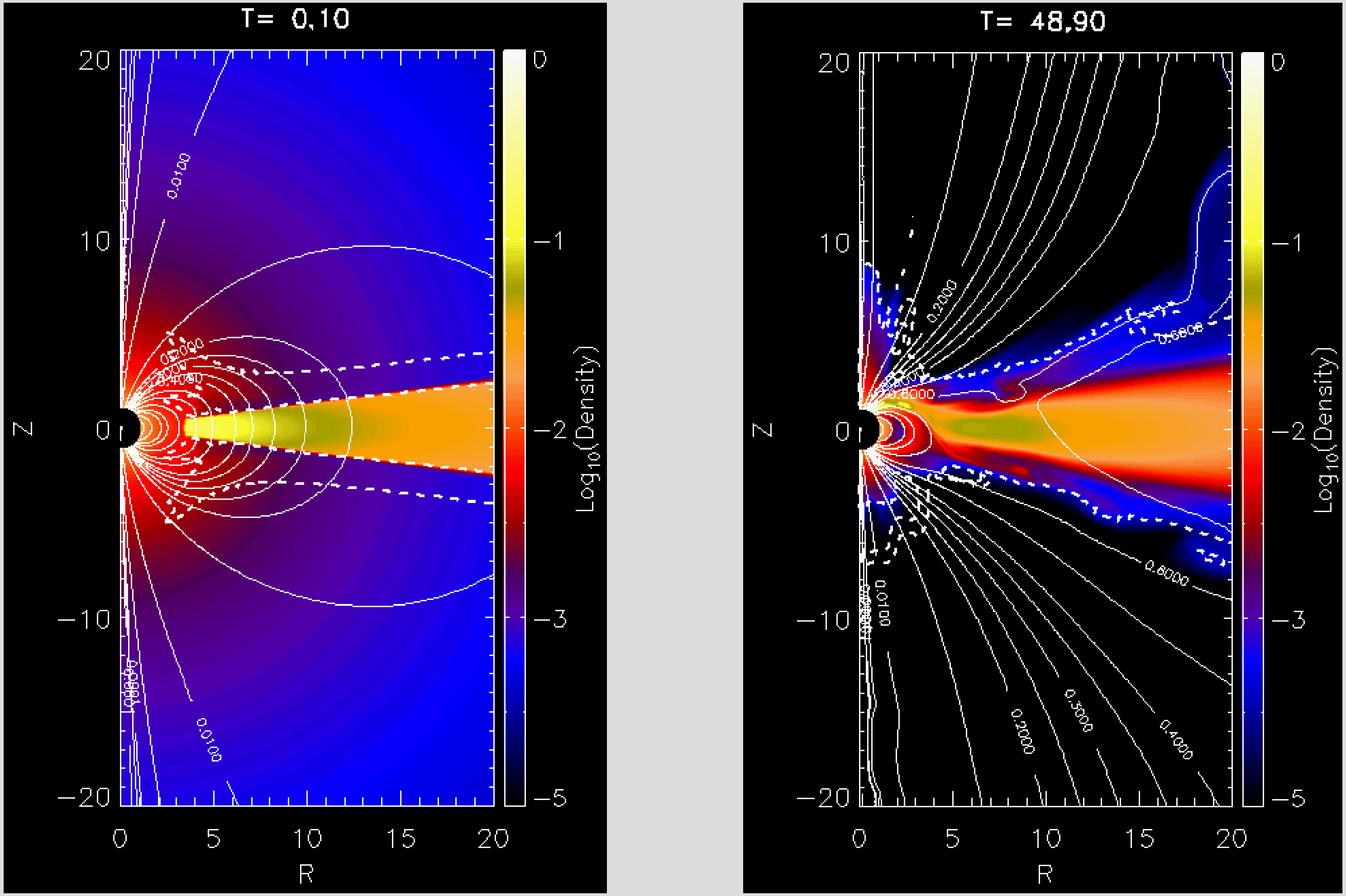
In the more resistive simulations, magnetic field lines connecting the star and the disk, extend well beyond the corotation radius, which is R_cor=4.65 R_* in our YSO's setup.

Zoom into the preliminary results with the **dipole** stellar magnetic field of 500 G (my simulations S2), in simulations with different resistivity. In the top panel, alpha_m=0.1, in the bottom, it is alpha_m=1.0.

Torque exerted on the star by the infalling material is different in both amount and sign in the two cases.

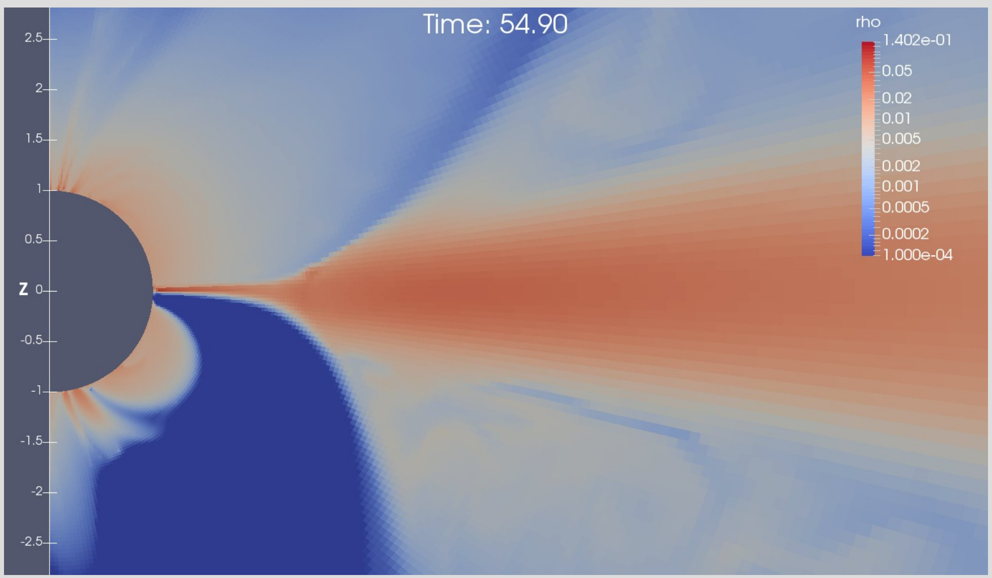
Preliminary results: YSO in ϑ=[0,π]

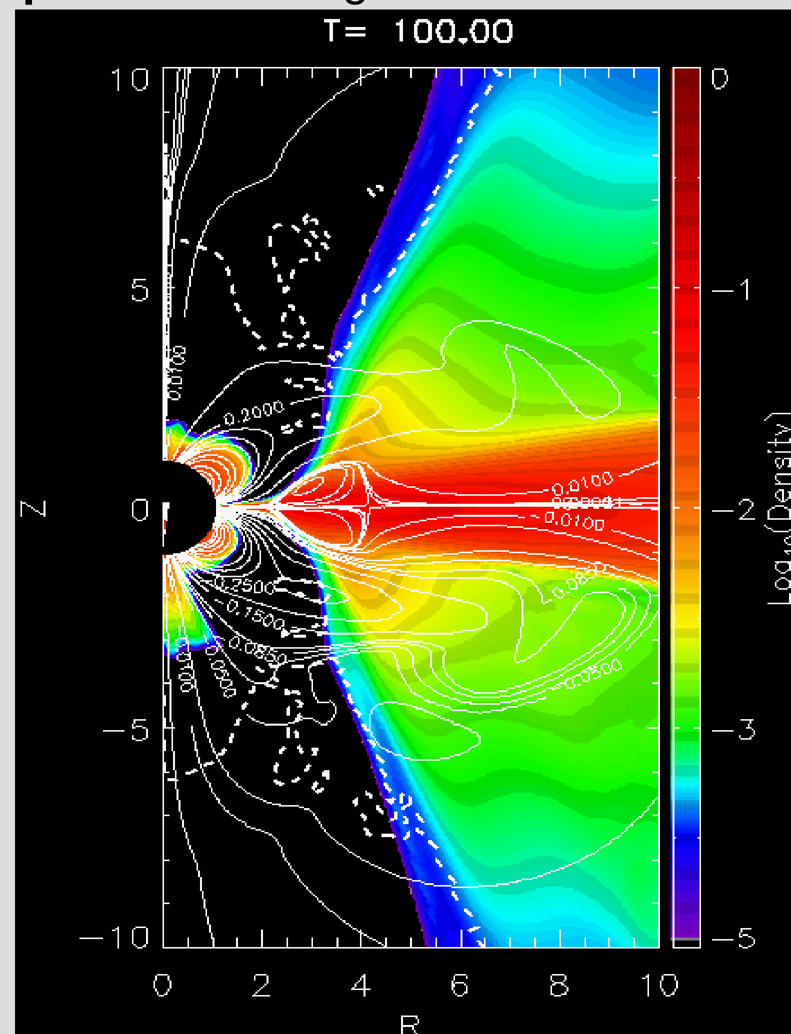
Stills from the animation of results with the **dipole** magnetic field.



Preliminary results: YSO in ϑ=[0,π]

Zoom into the preliminary results with the **quadrupole** stellar magnetic field.





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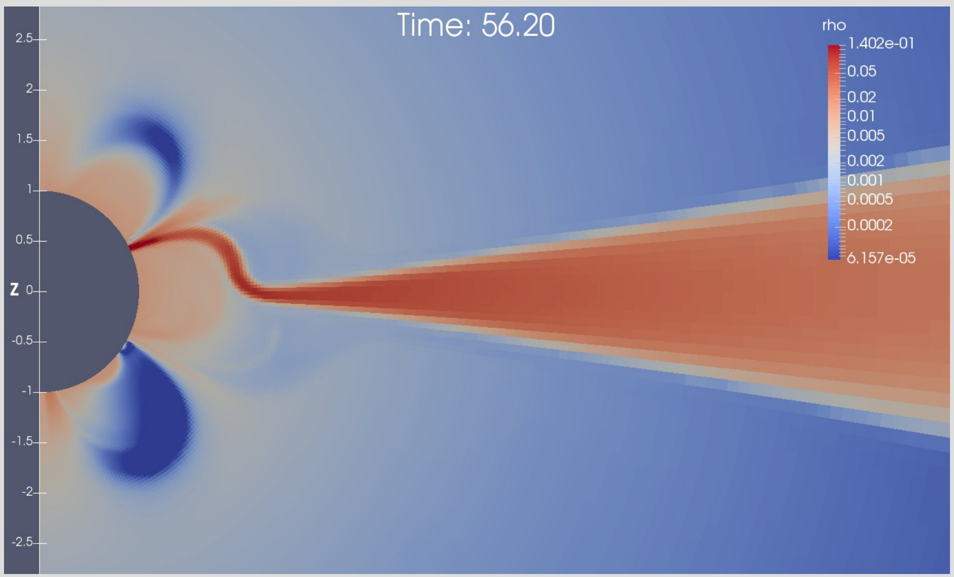
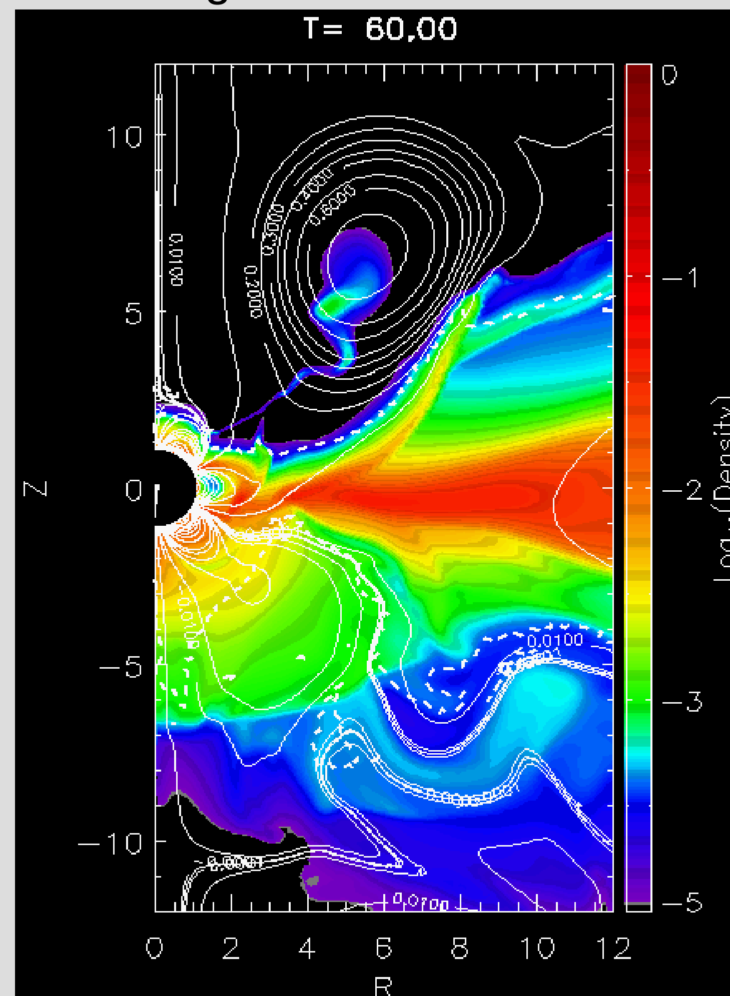
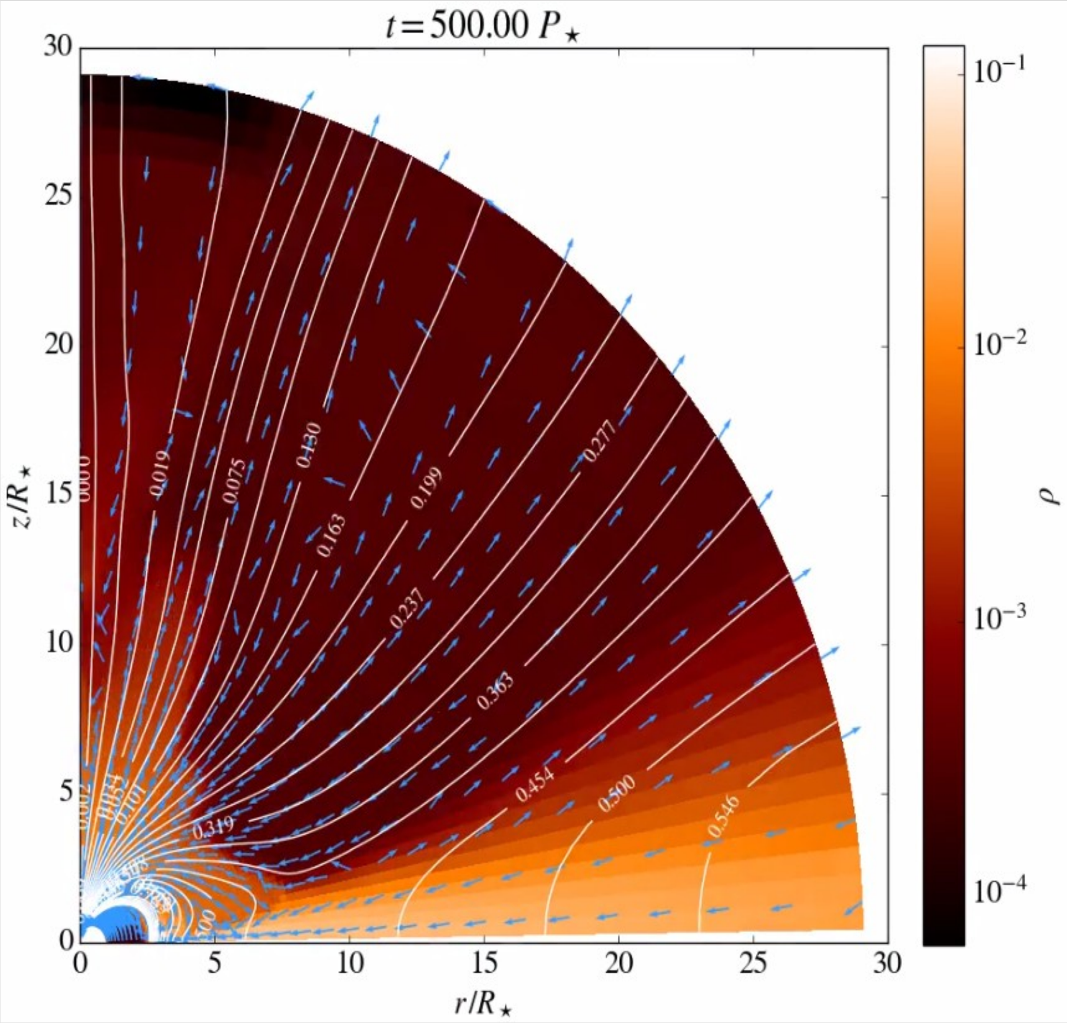
Preliminary results: YSO in ϑ=[0,π]

Zoom into the preliminary results with the **octupole** stellar magnetic field.

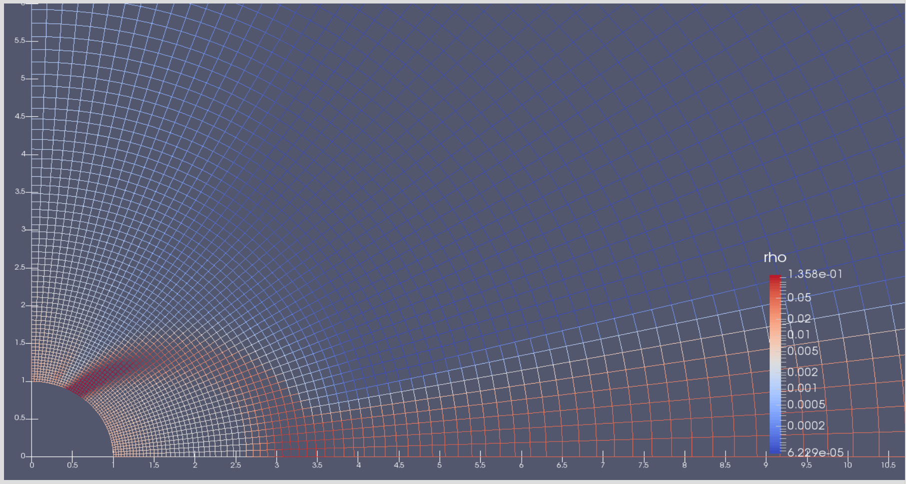




Preliminary results: NS

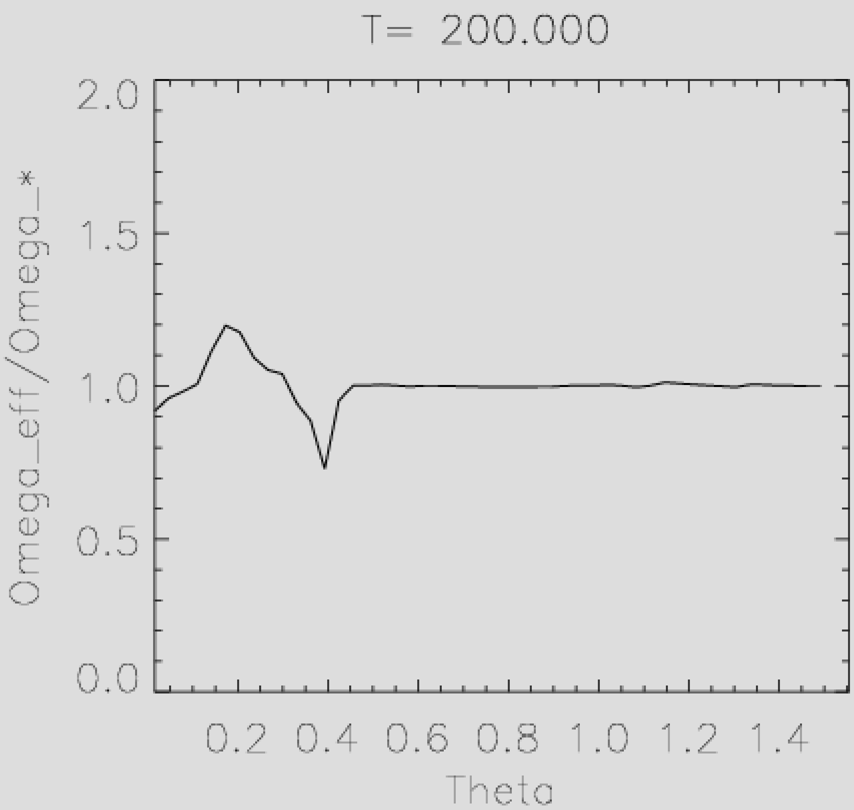


By comparison of different resolution simulations I investigated which is the lowest resolution for the reliable MHD simulations. For the [0,π/2] case it is enough to have Rxϑ=109x50 grid cells. Then I run the simulation for a long time in this resolution.



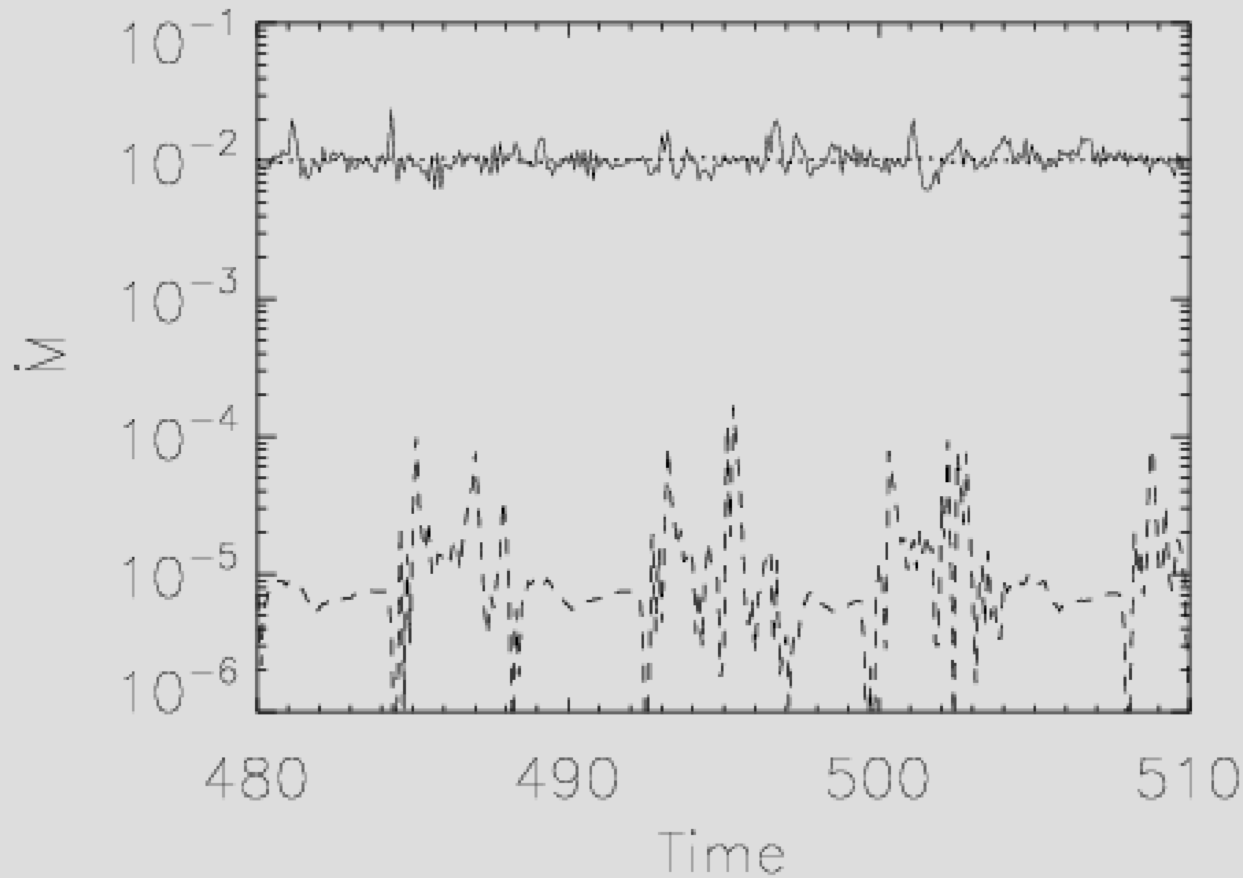
Solution for the NS case with millisecond pulsar parameters, up to T=500 stellar rotations=5s.

Preliminary results: NS, Omega_eff



Omega_eff in NS case at T=200 P_*.

Preliminary results: NS, mass flux



Time evolution of the mass flux in the system in the quasi-stationary state, during the 30 rotations. In the dotted line is shown the mass flux through the disk at R=12R_*. This mass flux is then distributed onto the star (solid line) and into the stellar wind (thin dashed line). Note the logarithmic Mdot scale. Most of the mass from the disk is accreted onto the star, and about 1/1000 goes into the stellar wind.

Summary

I obtained long lasting star-disk simulations in 2D axi-symmetric case with PLUTO code, with viscous & resistive MHD, in both [0,π/2] and [0,π] domains of the ϑ-plane.

Simulations have been performed with dipole, quadrupole, octupole and multipole magnetic field configurations.

I obtained relaxed, quasi-stationary results for the setup with parameters of YSOs, WDs and NSs.

We are currently working on the resistive magnetic extension to Kluźniak-Kita HD disk equations, in the asymptotic expansions approach. The results of such analytical solutions will then be compared with the simulations results.