Numerical simulations of star-disk magnetospheric interaction

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Outline

- Introduction
- Star-disk simulations setup
- Stellar surface as a boundary condition
- Preliminary results YSO
- Preliminary results NS, WD
- Summary & Prospects

Introduction- Star-disk problem in protostars- TOUPIES project

- 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, but the exact mechanism of this decrease is still not known. The angular momentum can be extracted from the system by violent outbursts, stable outflows & jets, or by an accretion column from the disk onto the star.
- As a part of the French ANR-TOUPIES (TOwards Understanding the sPIn Evolution of Stars) project on rotational history of solar-like stars, rotational velocities of several hundreds of stars in open clusters, at various evolutionary stages, will be measured. Goal is to find scaling laws for exchange of angular momentum between the star and surrounding. Then we would use the predicted stellar torques in stellar evolution models

- My task is to investigate the influence of geometry of magnetic field on the transport of angular momentum between the star and the environment. I am performing a parameter study, determining the torque in the system. I am to change 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 should be done with various strengths and topology of magnetic field.

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Introduction- Star-disk problem in protostars- TOUPIES project

mu (B[kG])	α_v	α_m	P_m	θ=[0,pi/2] Tempf t (P_*)	θ= [0,pi] Tempf t (P_*)		
1.4 (1.0)	1.0	0.1	6.7	D 800 74	Simulation **S1**, test run for comparison with ZF09		
0.7 (0.5)	Runs for our parameter study. Quadrupole and octupole runs only in θ= [0,pi] case.						
	1.0	0.1	6.7	D 800 100	D 800	Q 200 100	O
	1.0	0.4	1.67	D 800 100 **S2**	D 800 32.1 **S3**	Q 800 74.4 **S4**	O **S5**
	1.0	0.7	0.95	D 800 86.9	D 800 48.9	Q 800 55.	O
	1.0	1.0	0.67	D 800 85.2	D 800 20.	Q 800 43	O
0.7 (0.5)	Initial runs for wider parameter study.						
	0.7	0.1	4.67	D **S6**	D **S7**	Q 800 **S8**	O **S9**
	0.7	0.4	1.17	D	D	Q 800	O 400 62

Table 1: Parameter space explored in my simulations.

Parameters of a typical protostar:
M=0.5M_sun, R=2R_sun, P_*=4.63 days, v_K,0=218km/s,rho_0=8.5x10^(-11) g/cm^3, B_0=500 G, 1kG

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.
- We observe various configurations of binary systems. Properties depend on the type of the companion star and the neutron star 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 $\alpha c^2/\Omega$.
- We wish to extend that model to the non-ideal MHD, and to consider the radiative transfer in the disk and the magnetosphere.
- Typical parameters for NS: M=1.4M_sun, R~10km, B~10^8 Gauss, P=0.01 sec (1 msec), rho_0=4.62x10^-6 g/cm^3

Introduction: star-disk problem in White Dwarfs

- White dwarfs are Earth-radius stars of Solar mass.
- In the WD case I set M_*=M_sun, R_*=5000km, P_*=61s, B_*=10kG/100kG, rho_0=9.4e-9 g/cm^3
- Mdot_0=1.9e-8 M_sun/yr, V_K,*=5.15e8 cm/s

Star-disk simulations setups

- There exist only two sets of long-lasting star-disk MHD simulations- both before 2010, and no-one except their authors could repeat them. My goal is to obtain long-lasting quasi-stationary solutions, which could eventually be repeated by other researchers.
- Tool: PLUTO, a finite volume/ difference code. We solve viscous & resistive MHD equations, with split field method and constrained transport for div B=0.
- To avoid thermal thickening of the disk, I remove the viscous and Ohmic dissipative terms in the energy equation. Another method is to introduce the cooling source function. Best: do radiative transfer.

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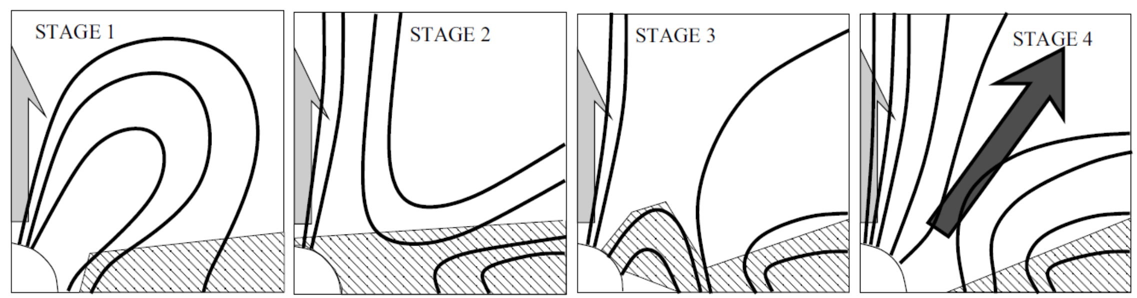
Čemeljić, Shang, & Chiang



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

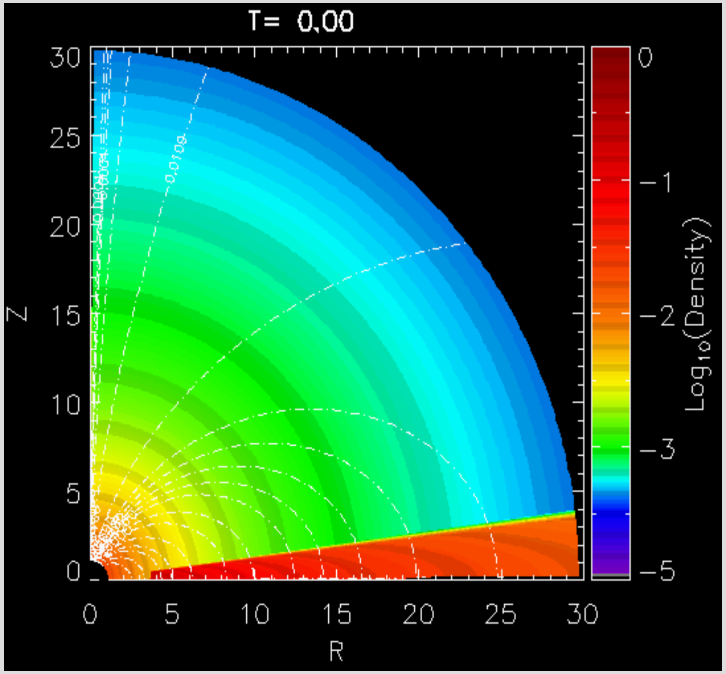
$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{u}\boldsymbol{u} + \left(P + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi} \right) \boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} - \boldsymbol{\tau} \right] = \rho \boldsymbol{g}$$

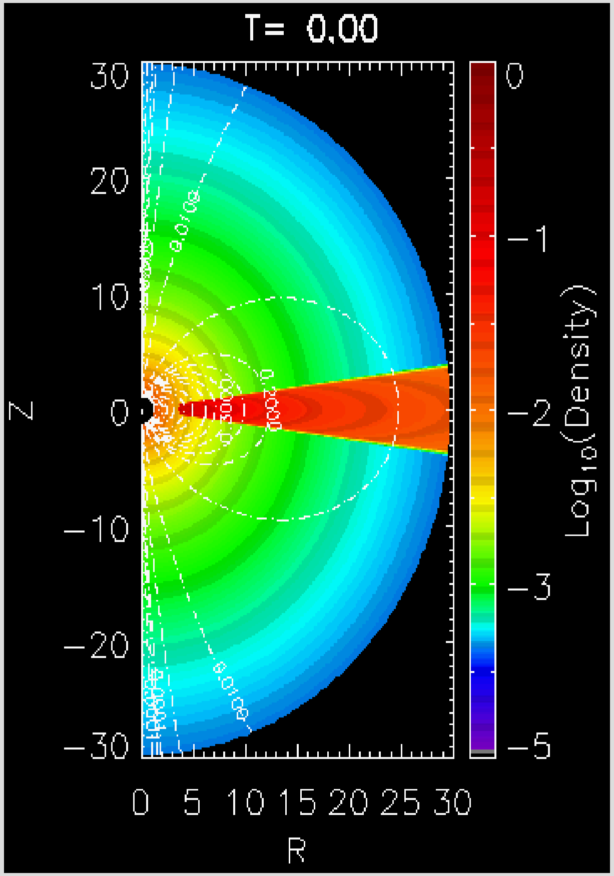
$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi} \right) \boldsymbol{u} - \frac{(\boldsymbol{u}\cdot\boldsymbol{B})\,\boldsymbol{B}}{4\pi} \right] + \nabla \cdot [\eta_{\mathrm{m}} \boldsymbol{J} \times \boldsymbol{B}/4\pi - \boldsymbol{u}\cdot\boldsymbol{\tau}]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

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

Star-disk simulation setups

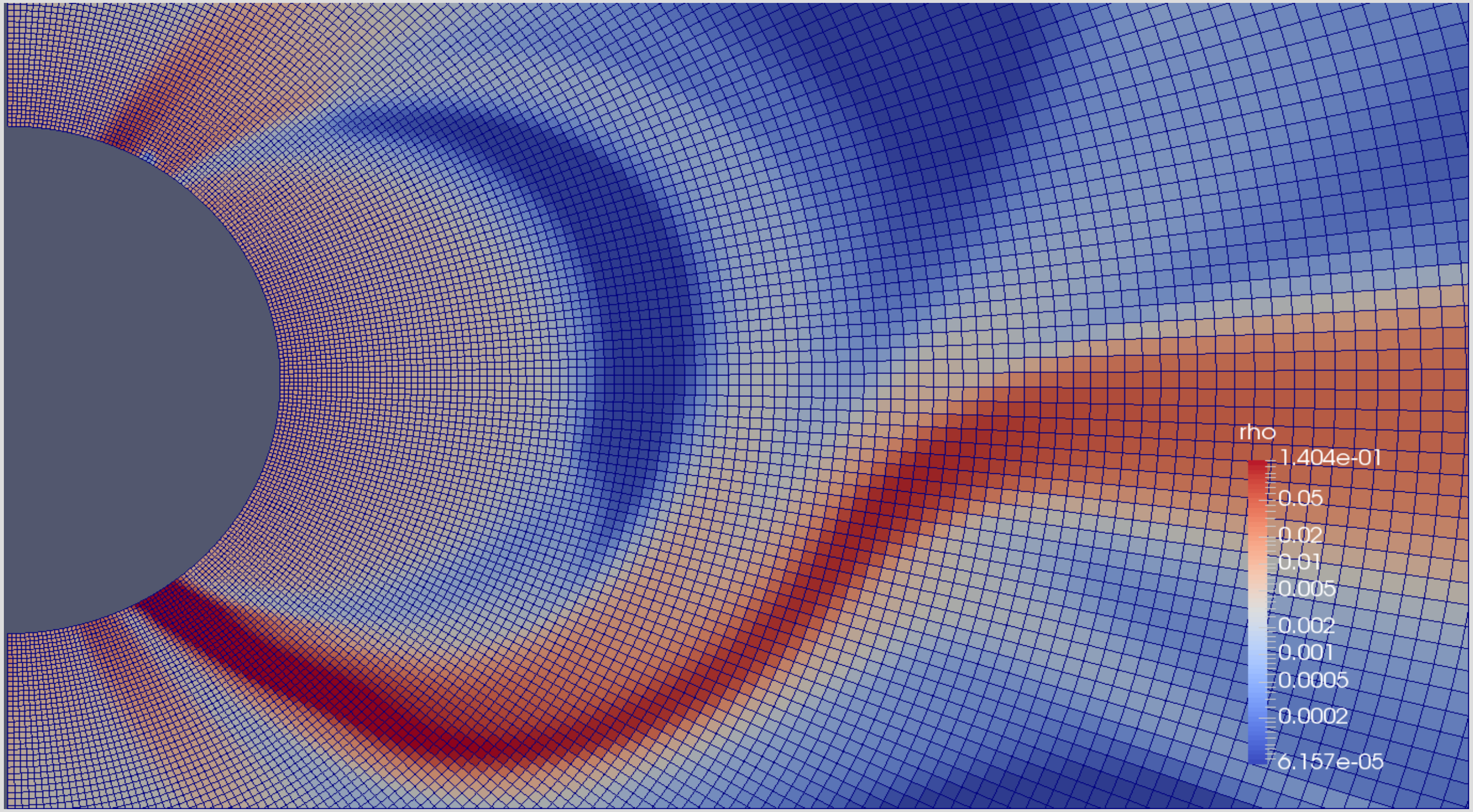
- The disk is set by Kluźniak & Kita (2000) model.
- We set two kinds of 2D axi-symmetric simulations: **a)** in the half-plane ϑ=[0,π/2] and **b)** the full plane ϑ=[0,π], both to R_max=30R_*. I show the density in the logarithmic color grading.
- In the case **b),** we do not prescribe the disk equatorial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





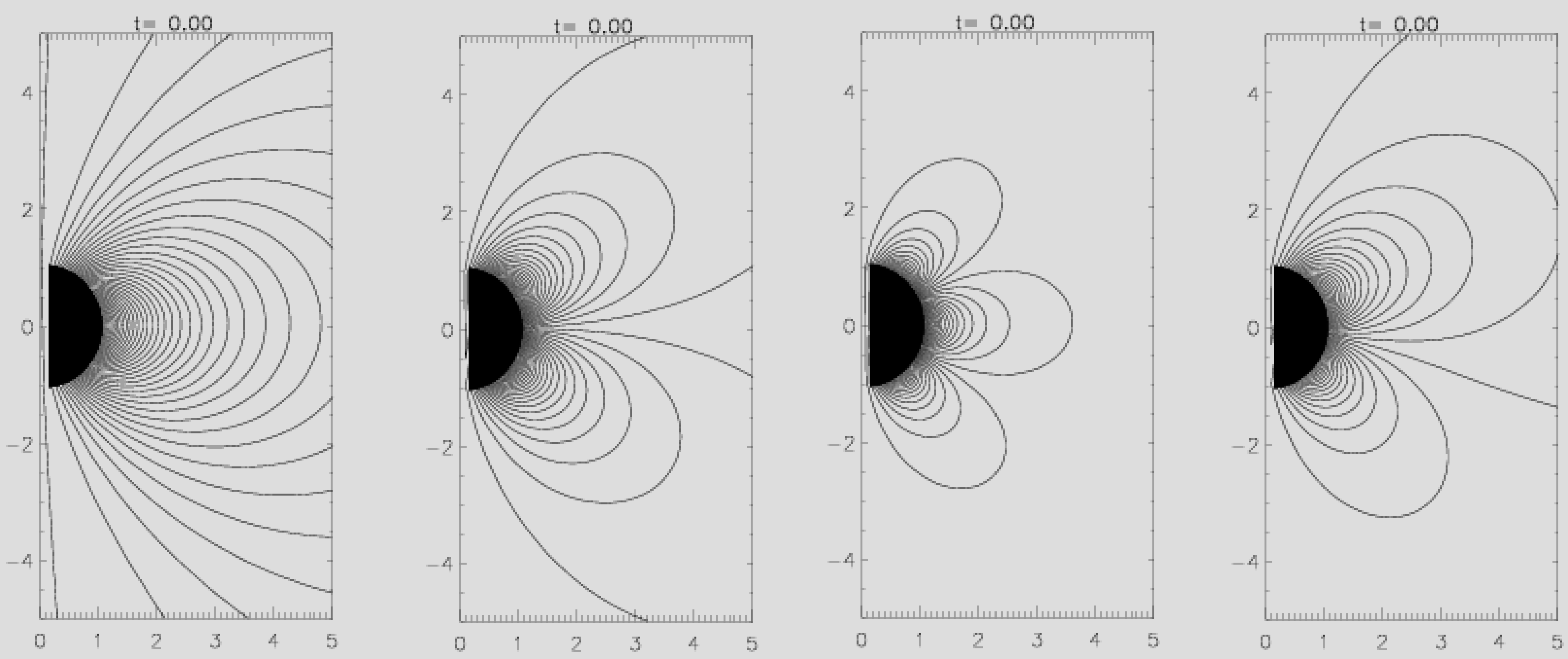
Star-disk simulation setups

- 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 setups

- I am investigating solutions with the different geometries of a stellar magnetic field: dipole, quadrupole, octupole and combinations of those (multipole).
- V.Parthsarathy is focusing on radiative transfer in the accretion disk around a neutron star. He is adapting the existing radiative module for PLUTO, which he will first test on the HD setup. Then we will add the radiative transfer to the viscous, resistive MHD solutions.



Stellar surface as a boundary condition

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

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

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

1132 C. Zanni and J. Ferreira: MHD simulations

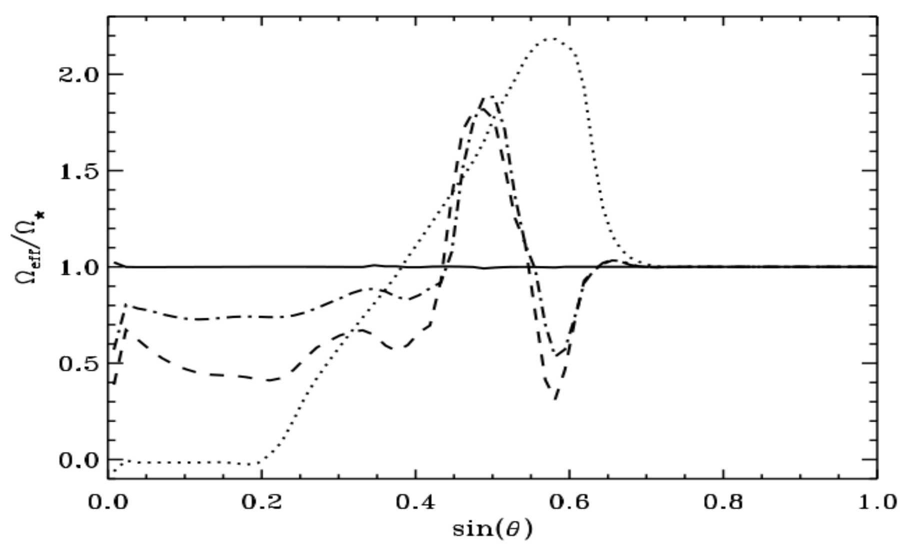


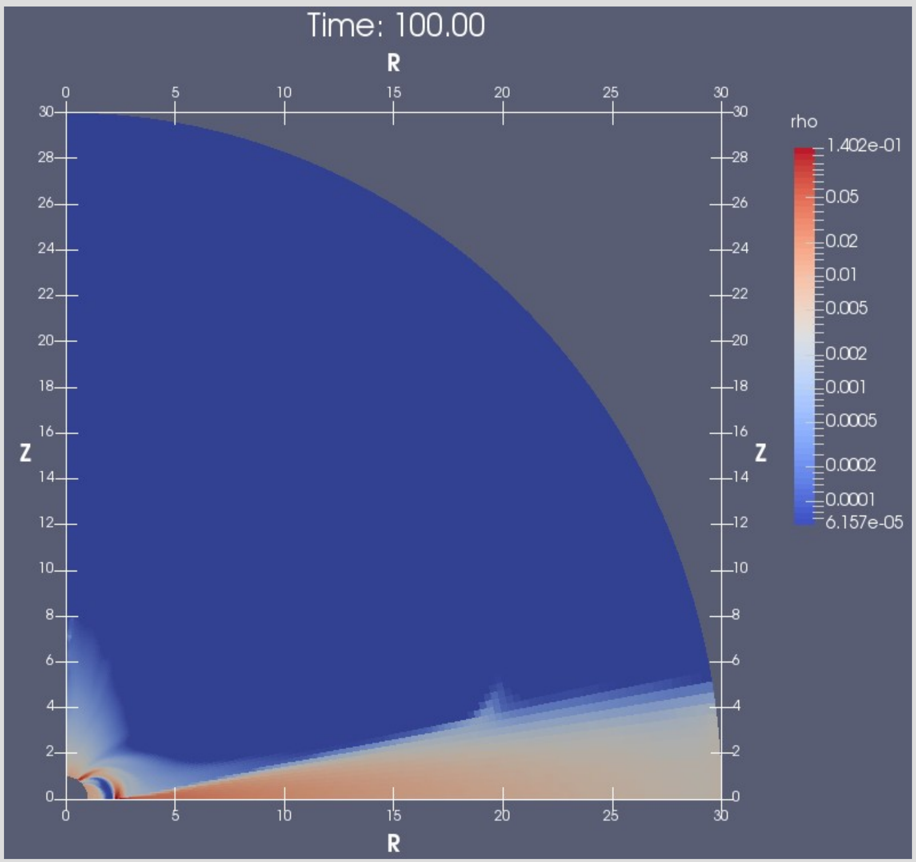
Fig. A.1. Effective rotation rate of the magnetic surfaces measured on the surface of the star as a function of the polar angle θ. The curves correspond to different boundary conditions on the toroidal field: the boundary condition used in this paper (solid line), $\partial\left(RB_\phi\right)/\partial R = 0$ 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.

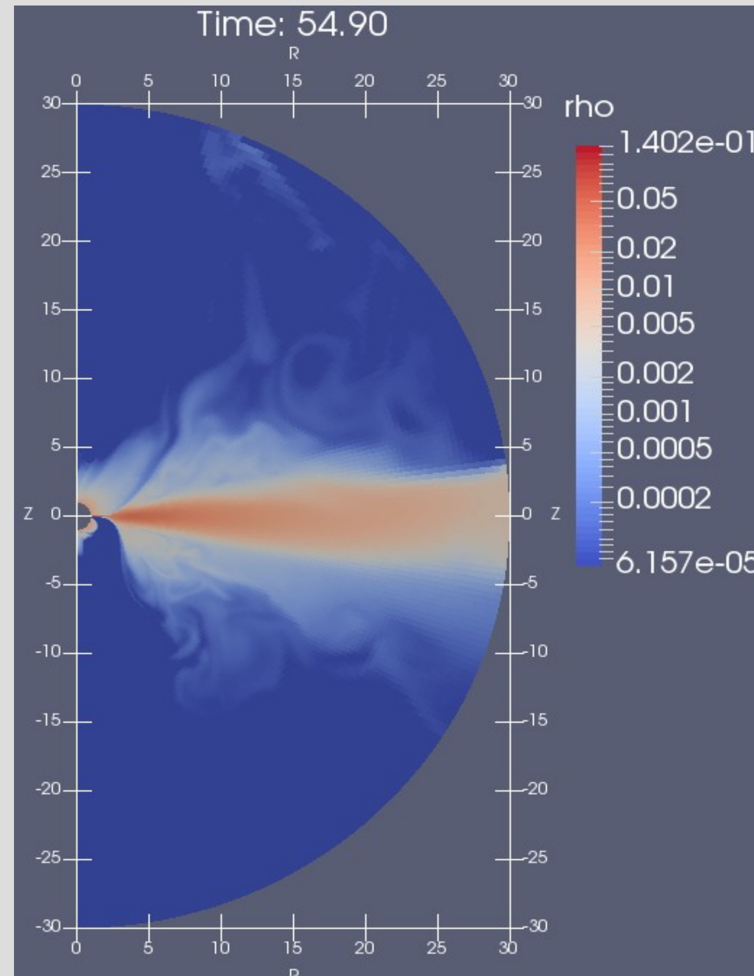
- In addition to this, we need to set the correct magnetic torque to drive the plasma rotation atop the star. We measure the matching by the comparison of the stellar angular velocity and the effective rotation rate of the field lines:

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

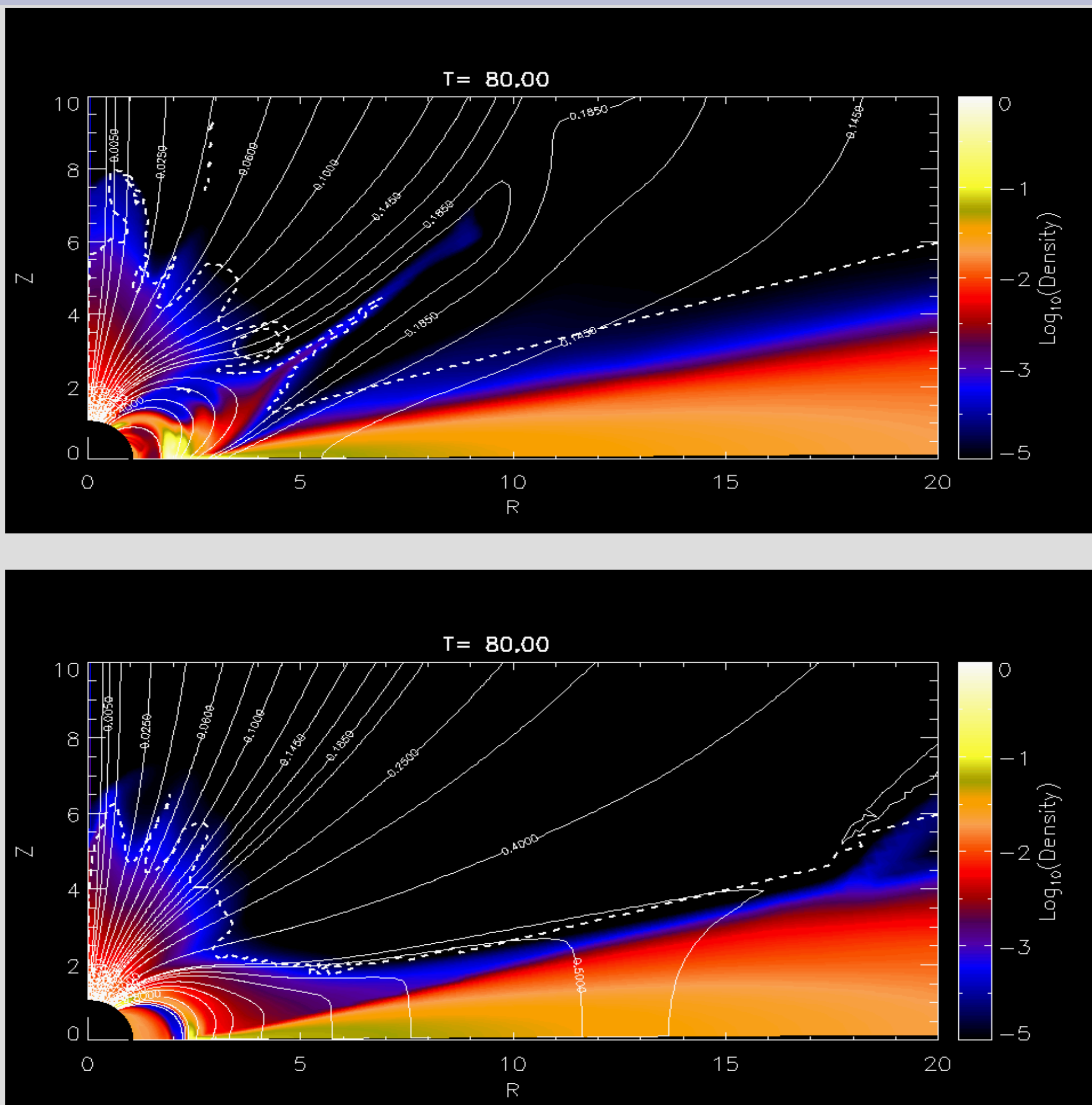
Preliminary results: YSO

- I show the preliminary results with the **dipole** and **quadrupole** stellar magnetic field. Shown is the density in the whole computational box.



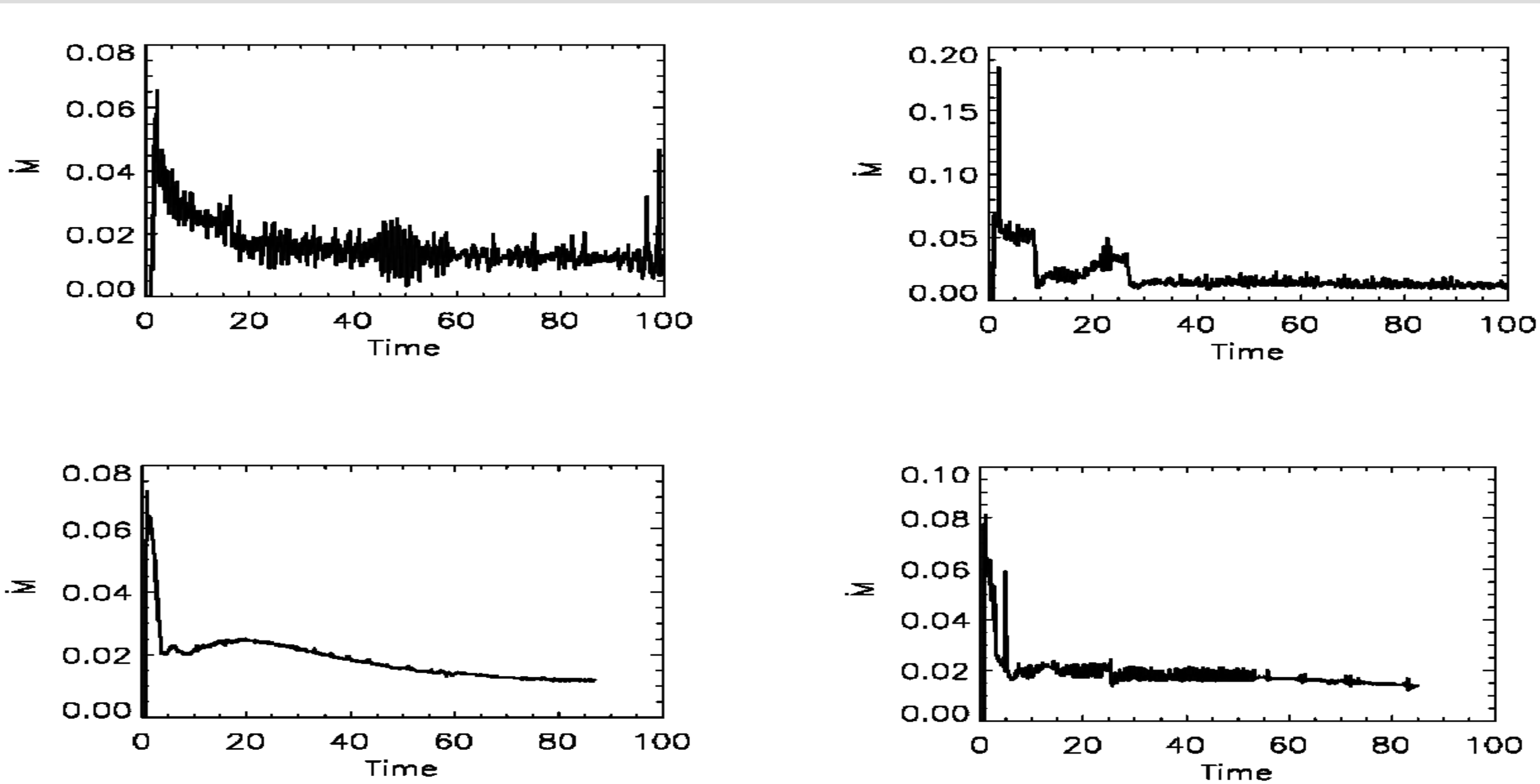


Preliminary results: YSO



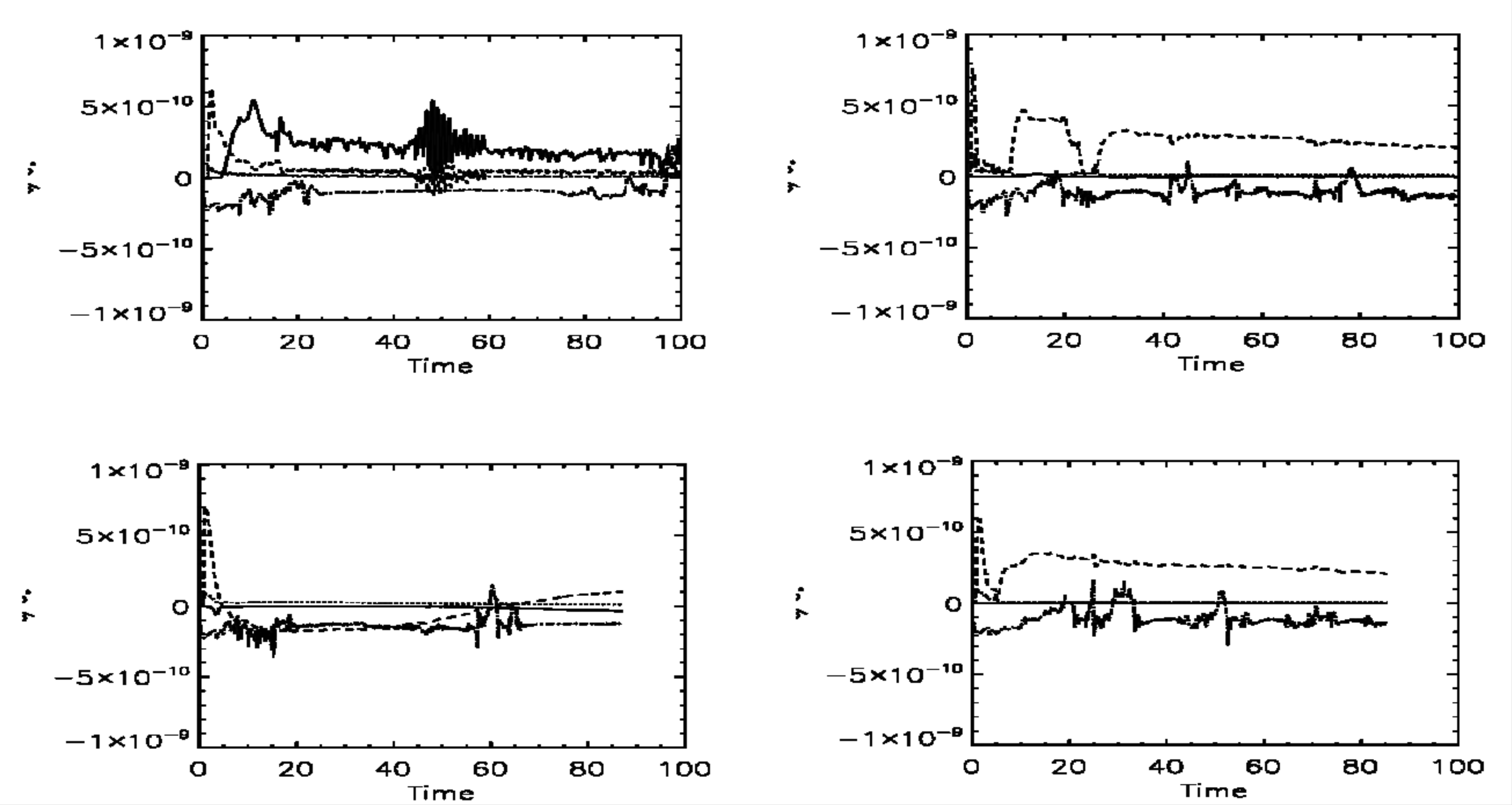
- Zoom into the preliminary results with the **dipole** stellar magnetic field in simulations with different resistivity. In the top panel, alpha_m=0.1, in the bottom, it is 1.0
- In the more resistive simulations, magnetic field lines connecting the star and the disk, extend well beyond the corotation radius, which is R_cor=4.65 R_* in our setup.
- Torque exerted on the star by the infalling material, is different in both amount and sign.

Preliminary results: YSO



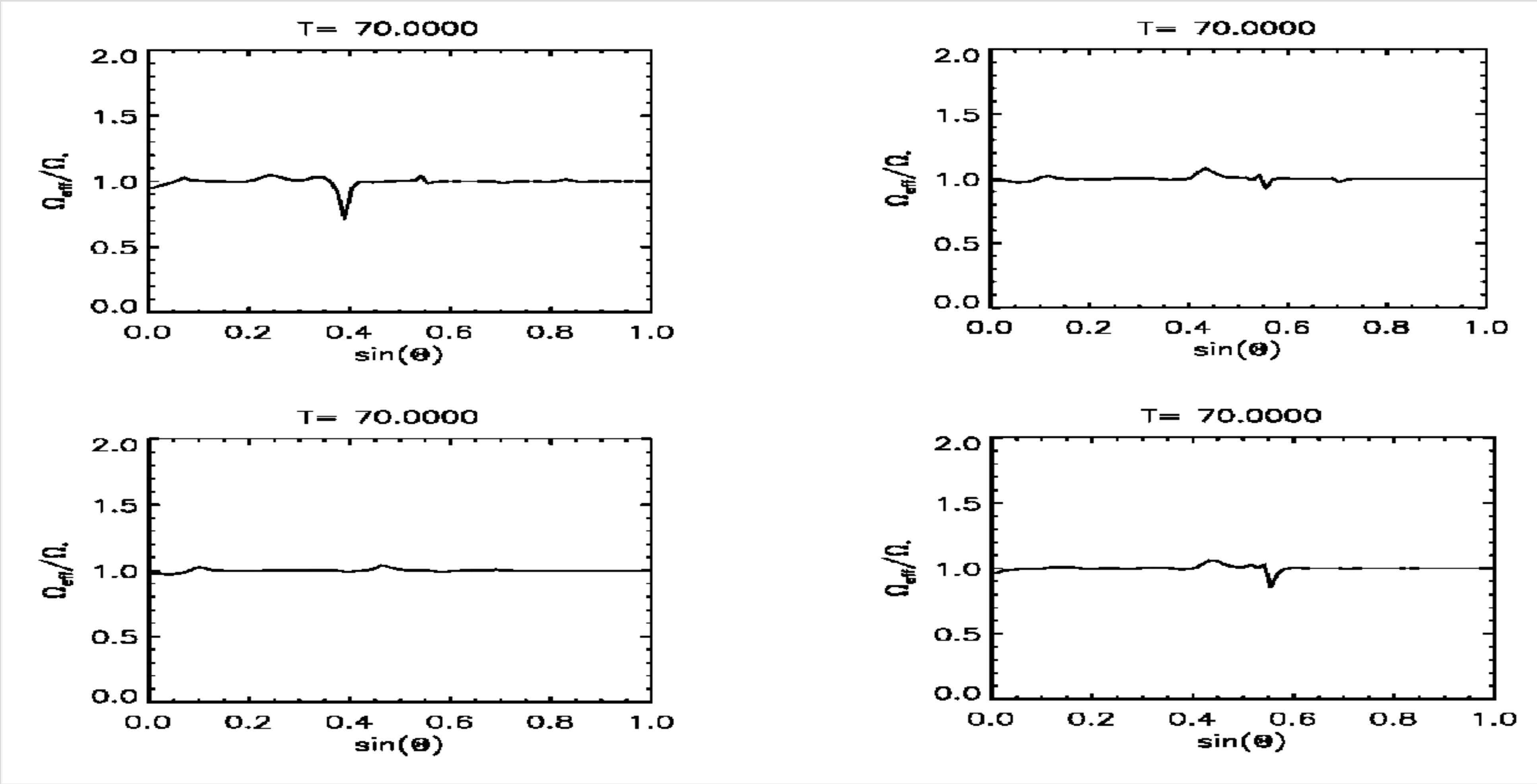
- S2, mass accretion rates with alpha_v=1, alpha_m=0.1,0.4,0.7,1.0, respectively.
- For KK00 disk: $\dot{M}_{\rm d} \sim 0.014\, \alpha_{\rm v} \left(\frac{\epsilon}{0.1}\right)^{3} \dot{M}_0.$

Preliminary results: YSO



- S2, torques onto the star with alpha_v=1, alpha_m=0.1,0.4,0.7,1.0, respectively.

Preliminary results: YSO



- S2, Omega_eff/Omega_* with alpha_v=1, alpha_m=0.1,0.4,0.7,1.0, respectively.

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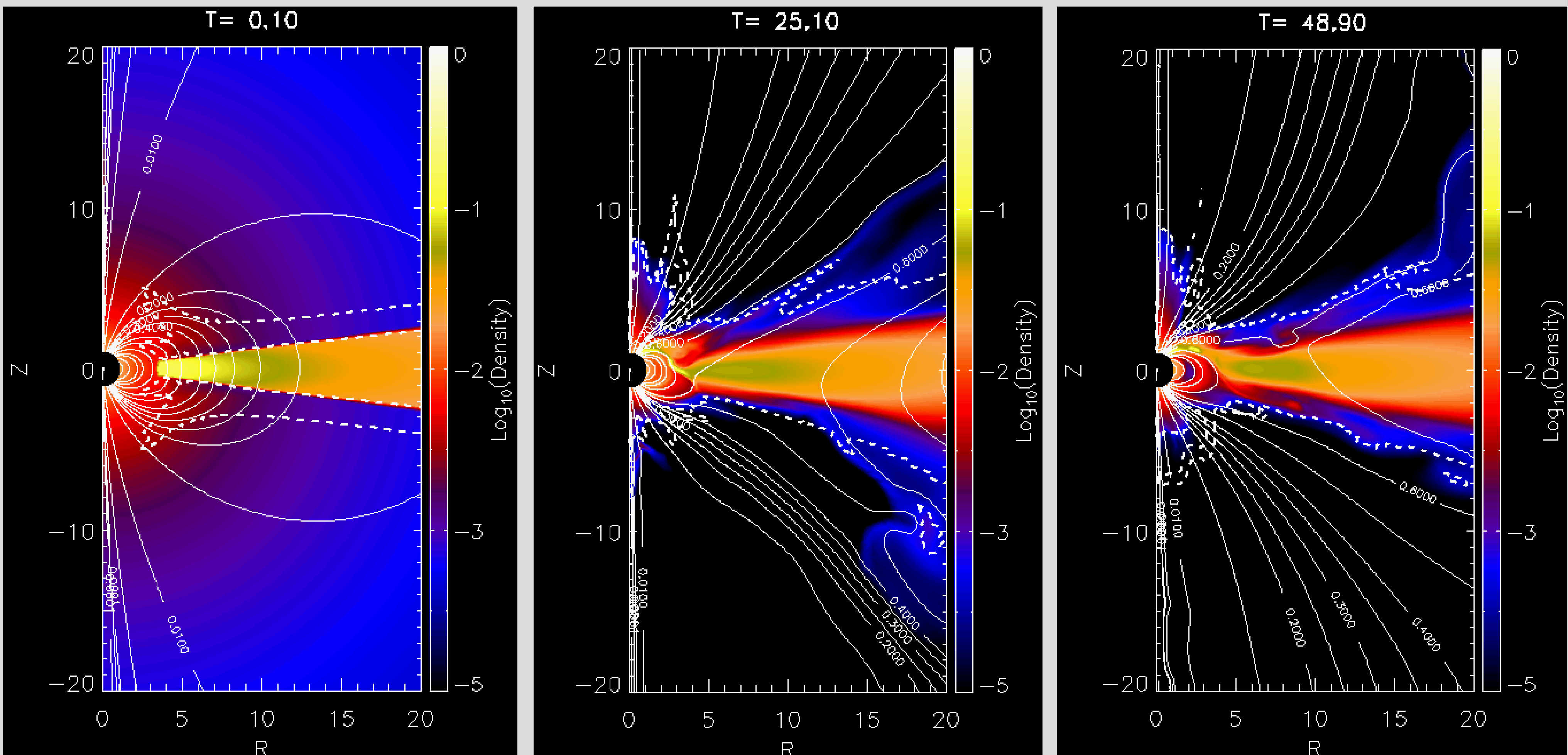
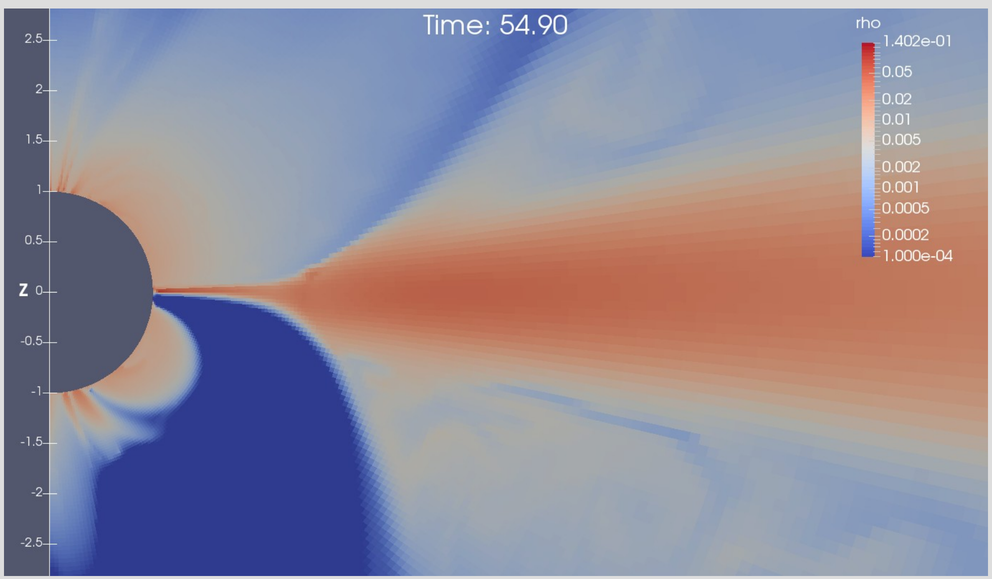
Preliminary results: YSO

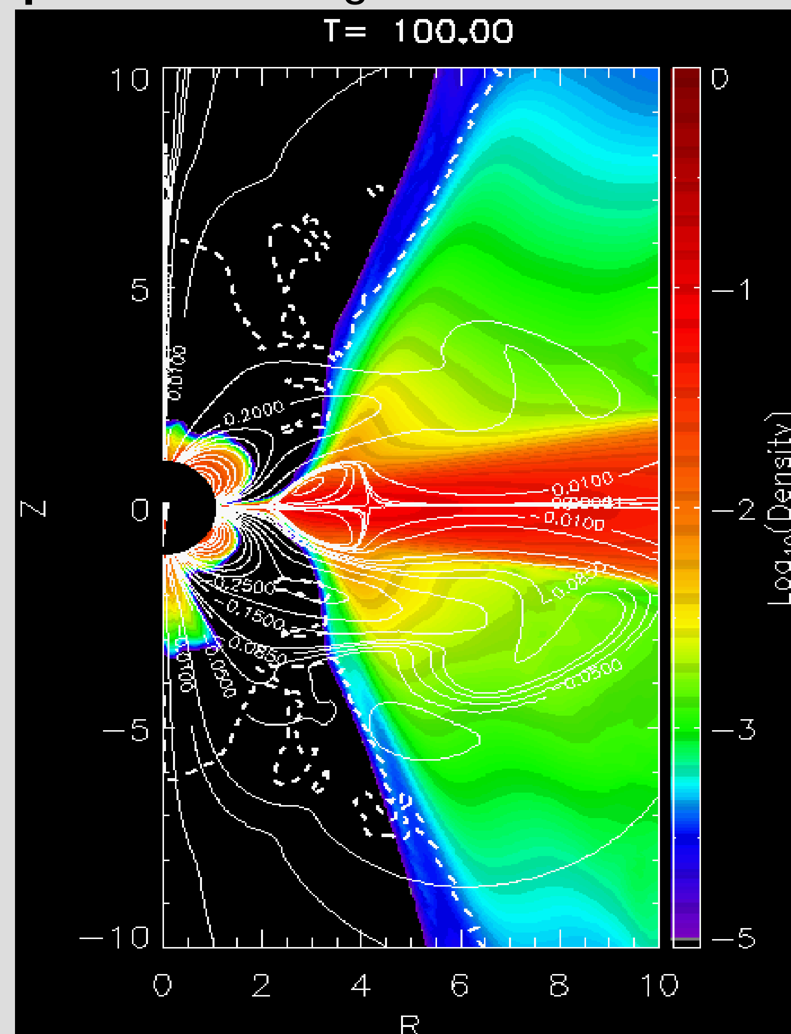
- Stills from the animation of results with **dipole** magnetic field.



Preliminary results: YSO

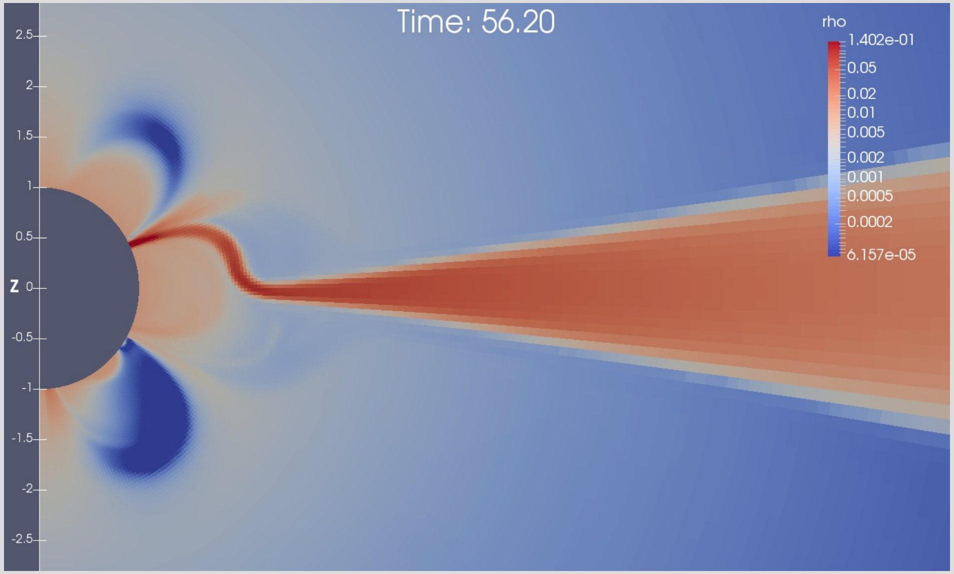
- Zoom into the preliminary results with the **quadrupole** stellar magnetic field.

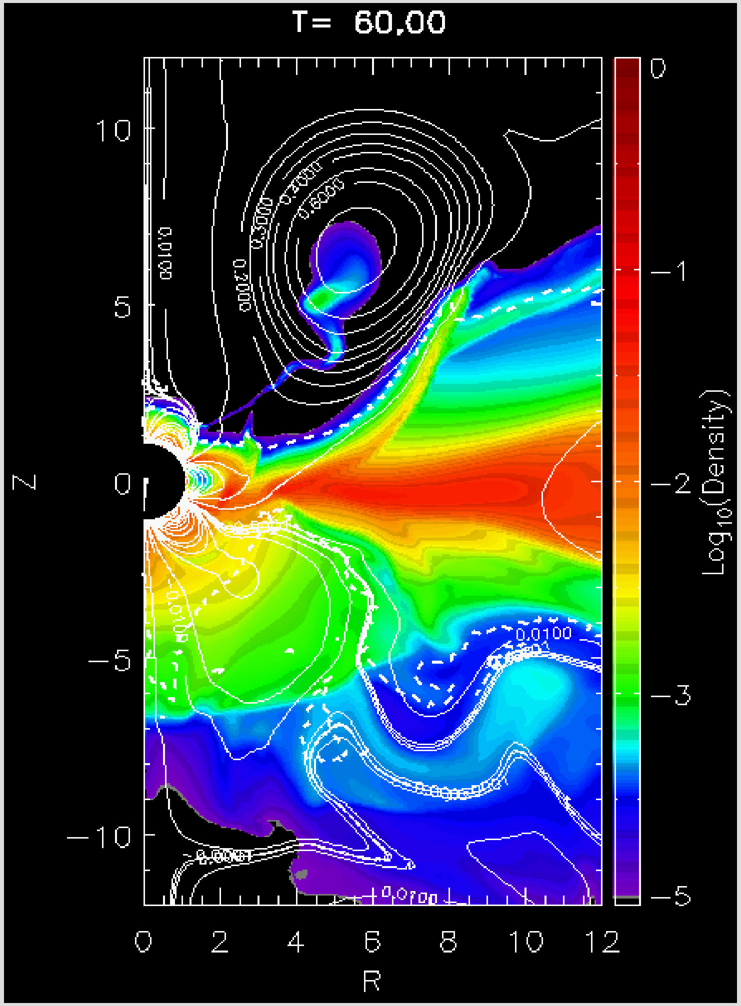




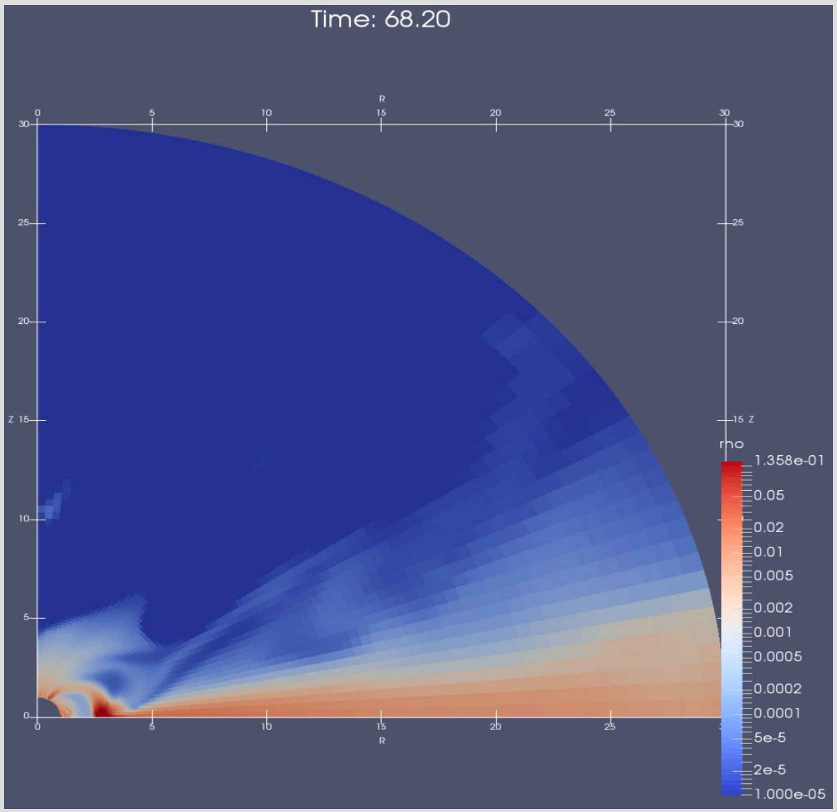
Preliminary results: YSO

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



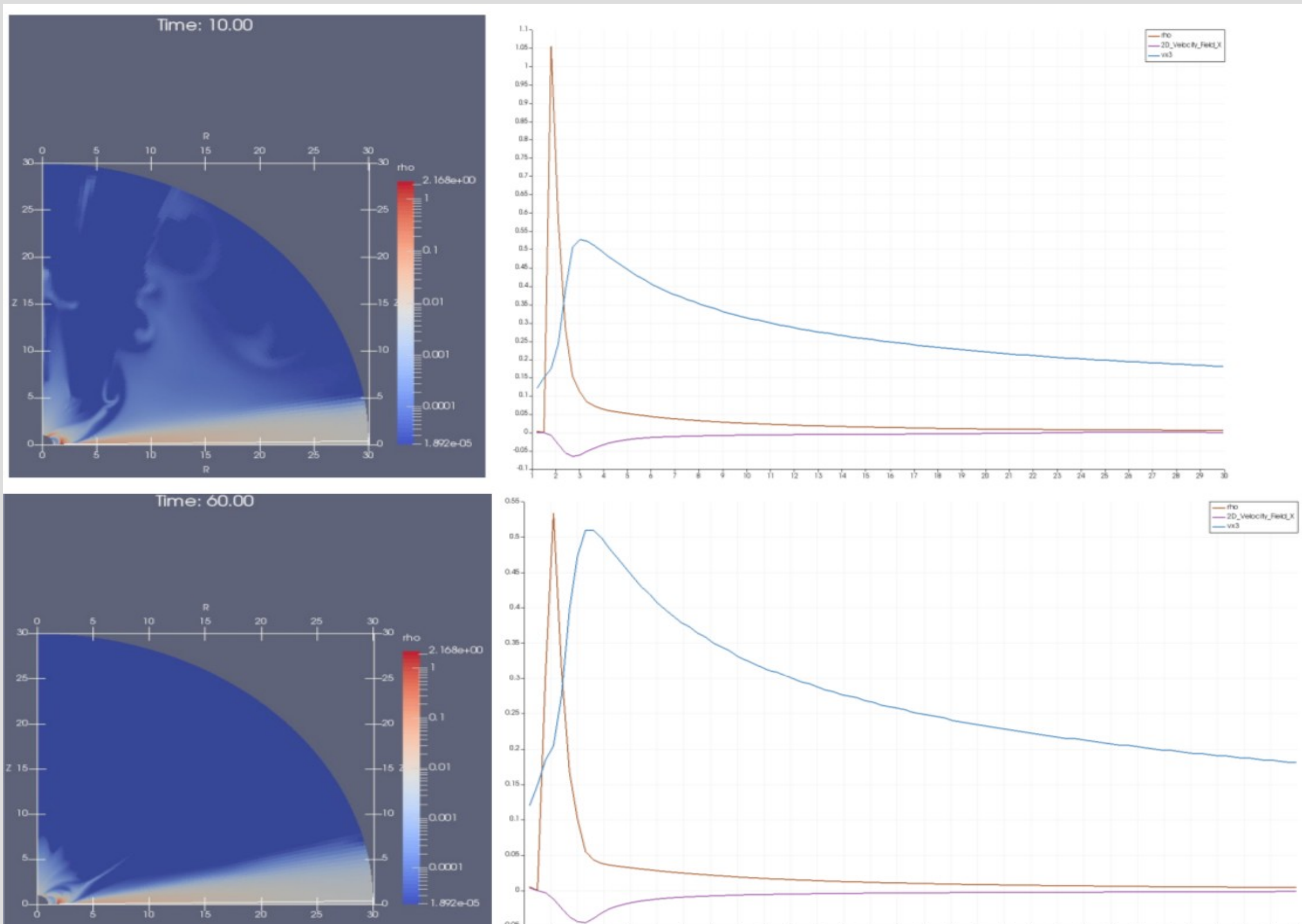


Preliminary results: NS

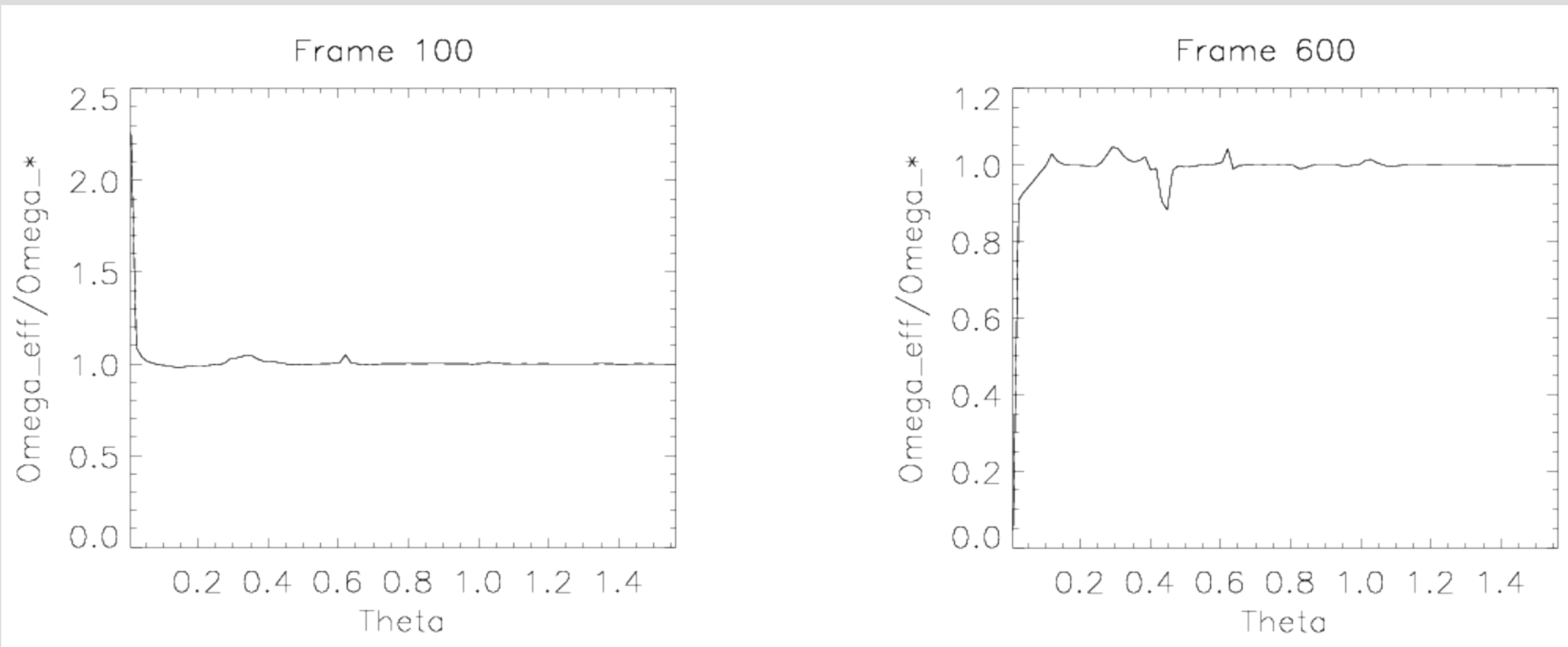


- Solution for the NS case with millisecond pulsar parameters
- For the radiative transfer we will need 3D simulations. I investigate which is the lowest resolution in which results in MHD are still reliable. I find that for the [0,PI/2] case it is enough to have Rxϑ=109x50 grid cells.
- For other types of objects, we need to increase the stellar magnetic field. I would like to reach magnetar field strength, B=10^14 Gauss.

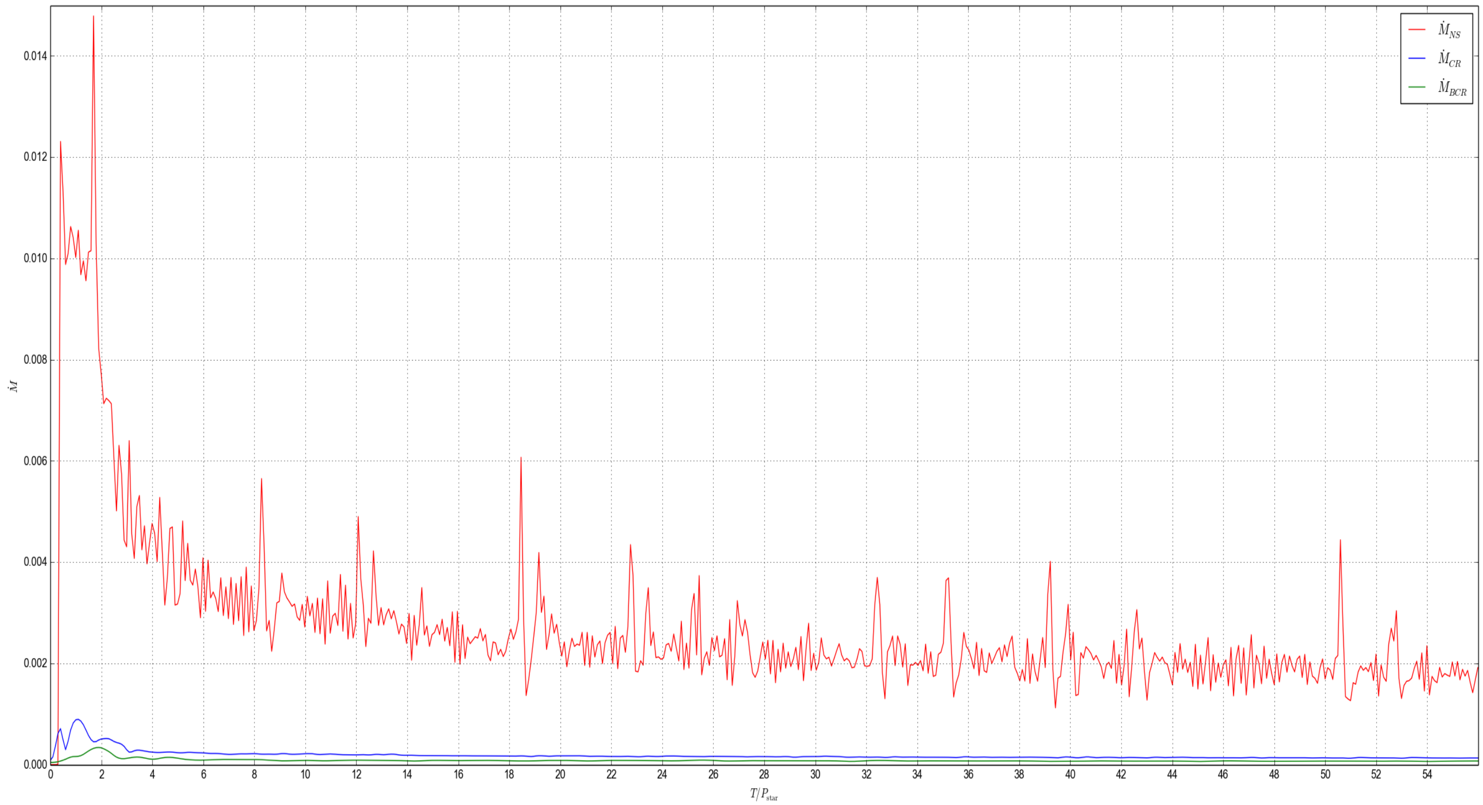
Preliminary results: NS



Preliminary results: NS



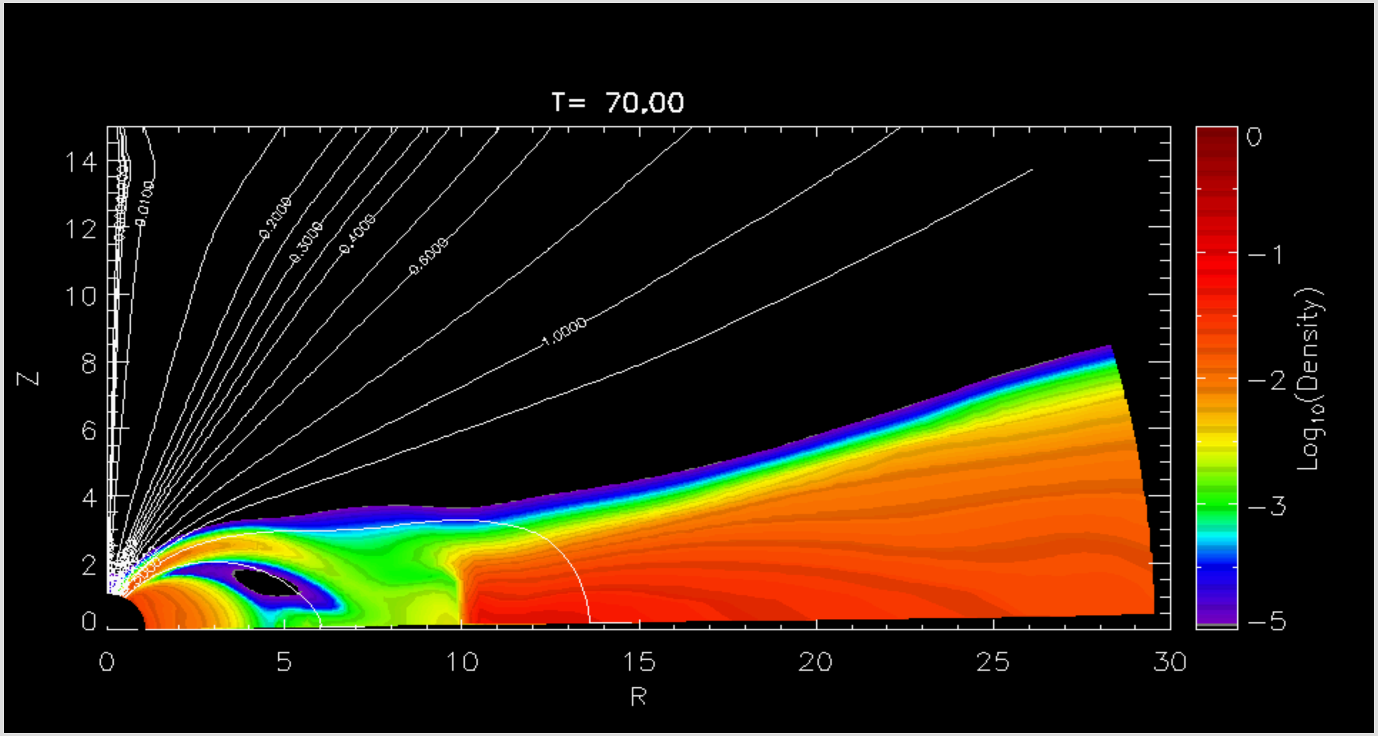
Preliminary results: NS



- Mass accretion rate onto the NS in dependence of time in the simulation.

Very preliminary results: WD

- In the WD case, I set M_*=M_sun, R_*=5000km, P_*=61s, B_*=10kG/100kG, rho_0=9.4e-9 g/cm^3
- Mdot_0=1.9e-8 M_sun/yr, V_K,*=5.15e8 cm/s



- Interesting feature in those simulations, resembling CV behavior.

Summary & Prospects

- I obtained the long lasting star-disk simulations in 2D axi-symmetric case in PLUTO code, with viscous & resistive MHD, in both [0,PI/2] and [0,PI] parts of the ϑ-plane.
- Currently I am investigating the dipole, quadrupole, octupole and multipole magnetic field configurations.
- I obtained relaxed, quasi-stationary results for the setup with parameters of YSOs, NSs and WDs.
- To this setup we will add the radiative transfer. Radiative module for PLUTO by V. Parthasarathy is in preparation.