Magnetospheric outflows in star-disk simulations

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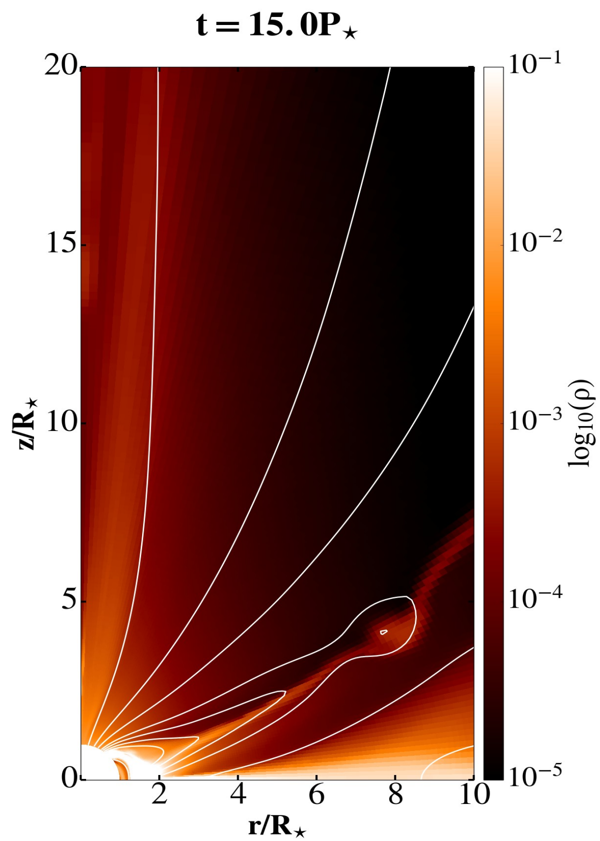


Outline

- Introduction
- Disk solutions
- Axial and conical jets
- Summary

Introduction

•I perform long-lasting simulations of accretion disks, which reach a quasi-stationary state.

•With PLUTO code I solve 2D axi-symmetric viscous & resistive MHD equations:

•We neglect Ohmic and viscous heating in the energy equation. We still include viscosity and resistivity in the equation of motion and in the induction equation.

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

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

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

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

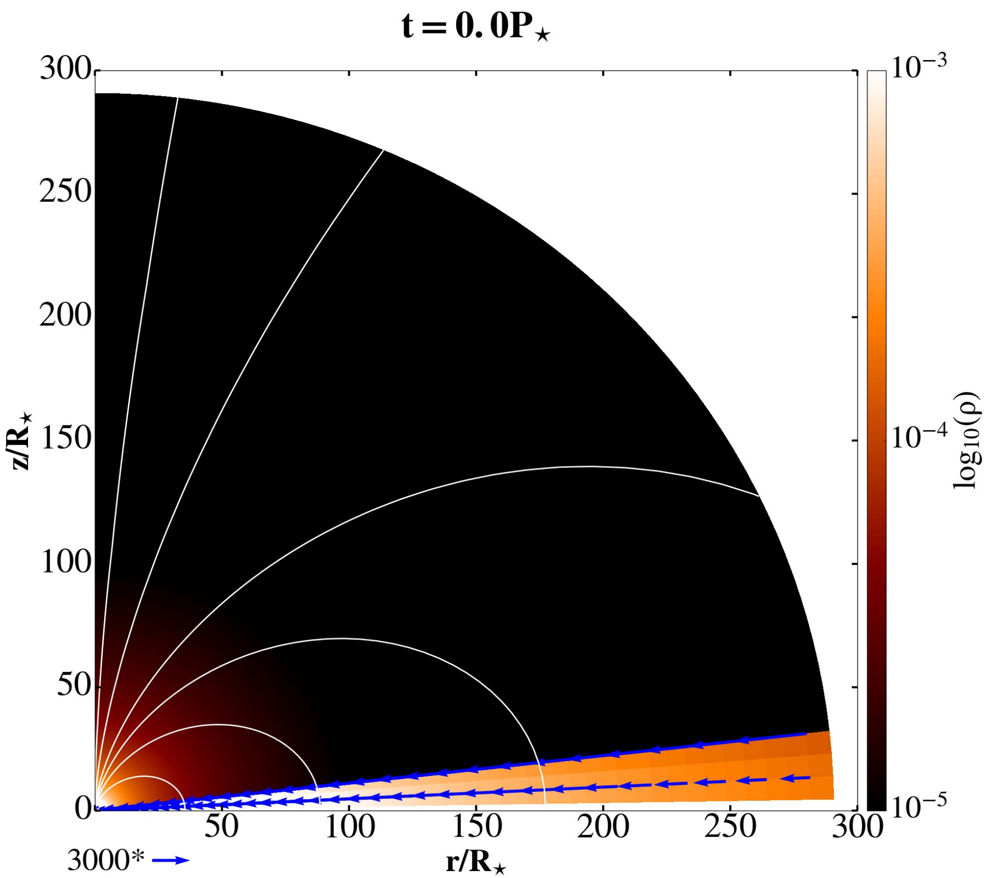
Simulations of the star-disk magnetospheric interaction

All the simulations start with the same initial and boundary conditions, the Kluźniak & Kita (2000) solution of the hydro-dynamical disk in the full 3D (KK00).

Such a disk is an analytic solution, obtained by the method of asymptotic approximation.

We do not have the solution for the MHD case, so we perform numerical simulations. We add the stellar dipole field to the KK00 solution.

We add a star as a boundary condition at the origin of the (spherical) computational domain. We assume the star to be a solid magnetized rotator. The initial corona is non-rotating, in a hydrostatic balance.

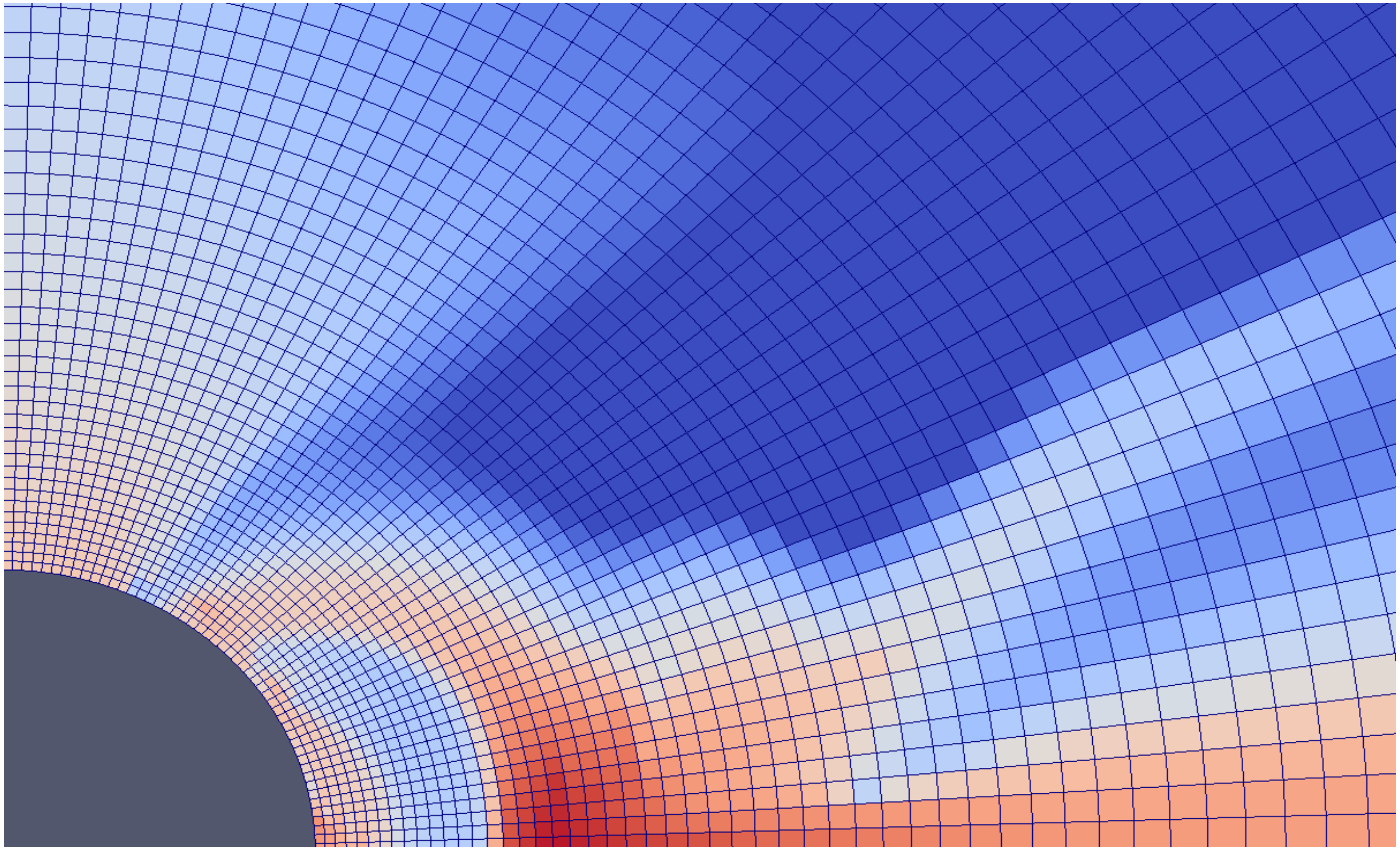


I performed a systematic study with magnetic star-disk numerical simulations where the disk quasi-stationarity is reached-I will show a part of it later.

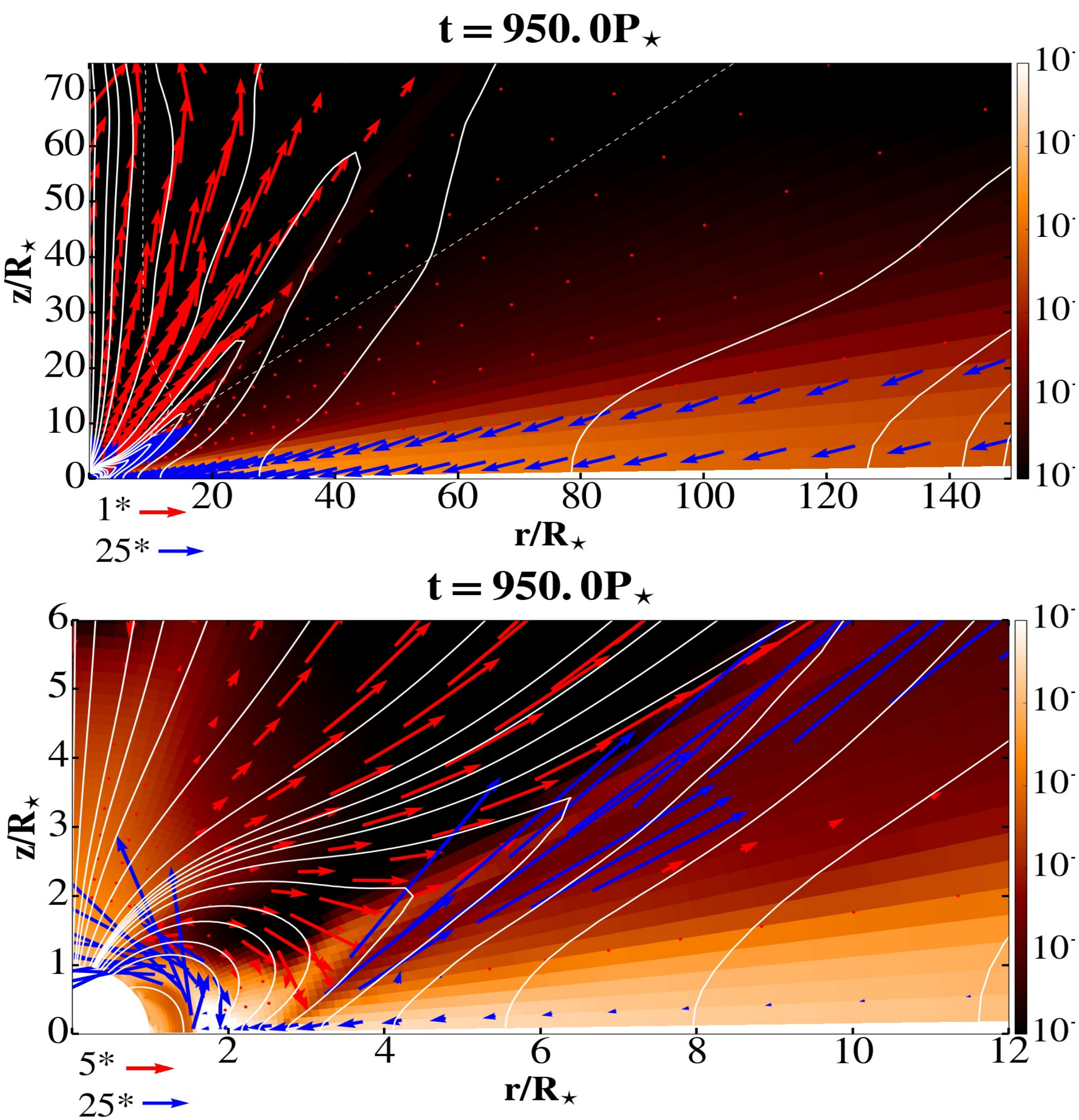
Star-disk simulation setup

- Resolution is Rxϑ=[182x50] grid cells in ϑ=[0,π/2], with a logarithmic grid spacing in the radial direction. The accretion column is well resolved.
- Star rotates at about 1/5 of the breakup rotational velocity.

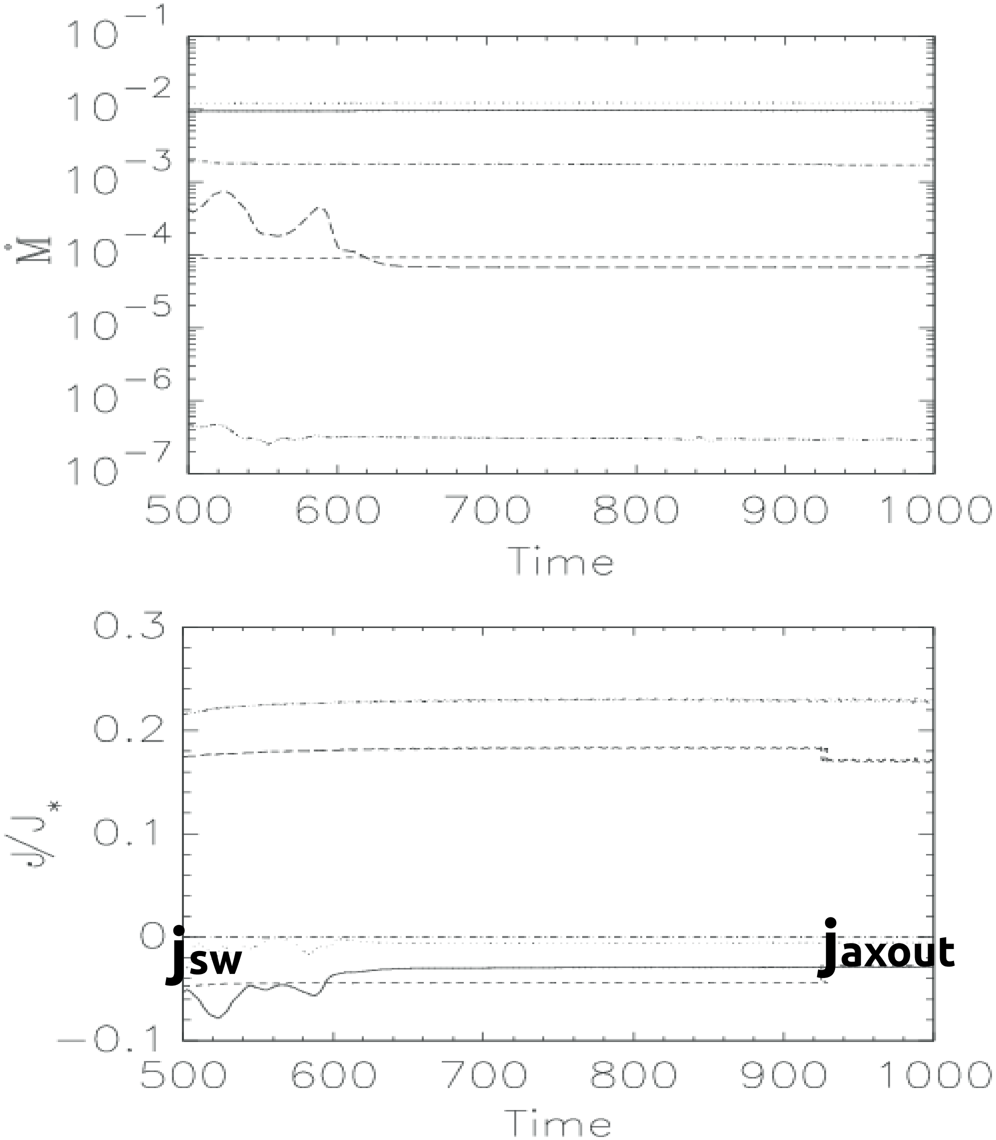
T=950



Reincarnated stars: Star-disk simulations of millisecond pulsars



Zoom into the central part of the system after 950 pulsar rotations to visualize the accretion column and the magnetic field lines connected to the disk beyond the corotation radius Rcor=2.92 Rs.



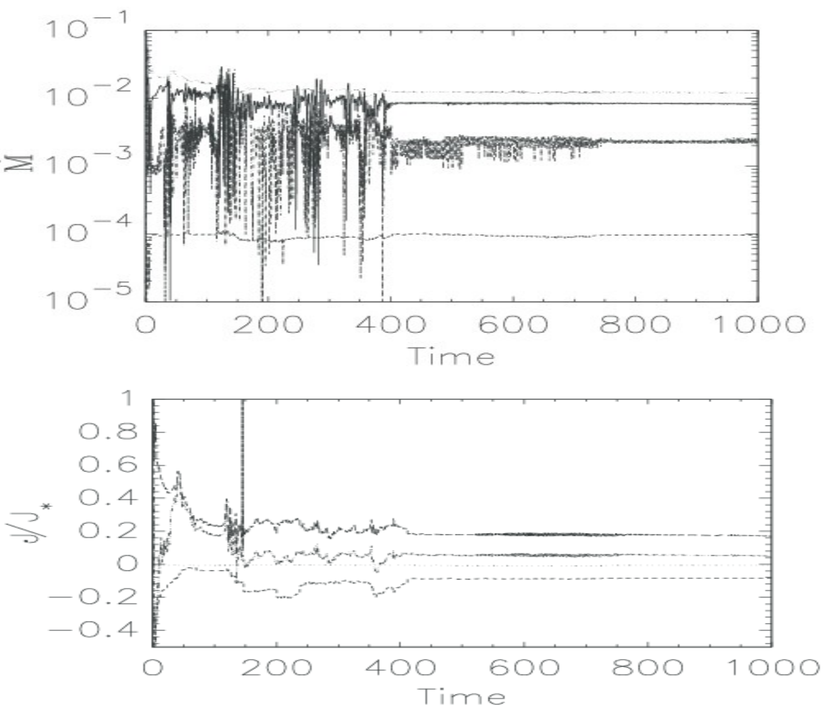
The time dependence of the mass and angular momentum fluxes in the various components in our simulations after the quasi-stationarity is reached.

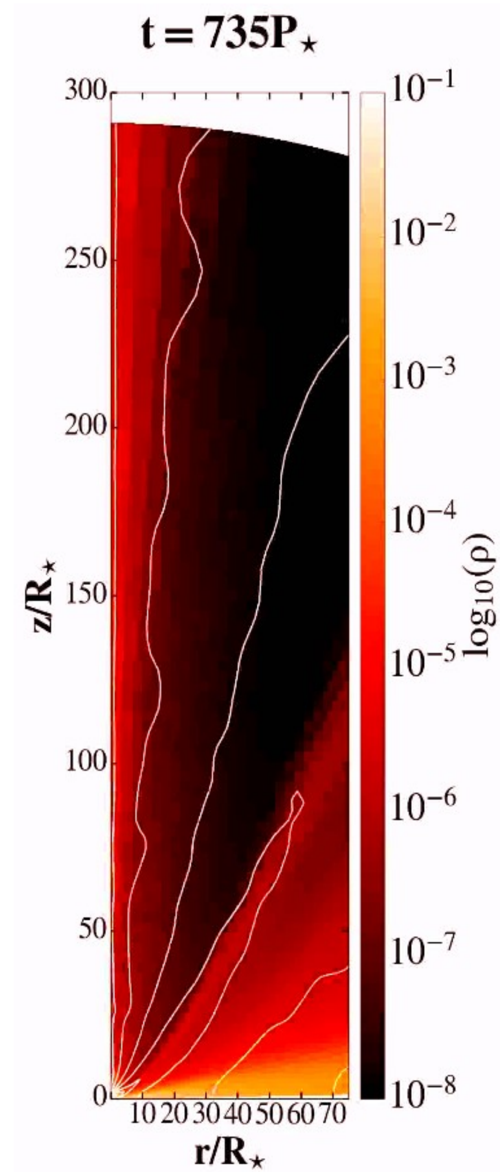
Miljenko Čemeljić, March 2018, INAF Rome, Italy

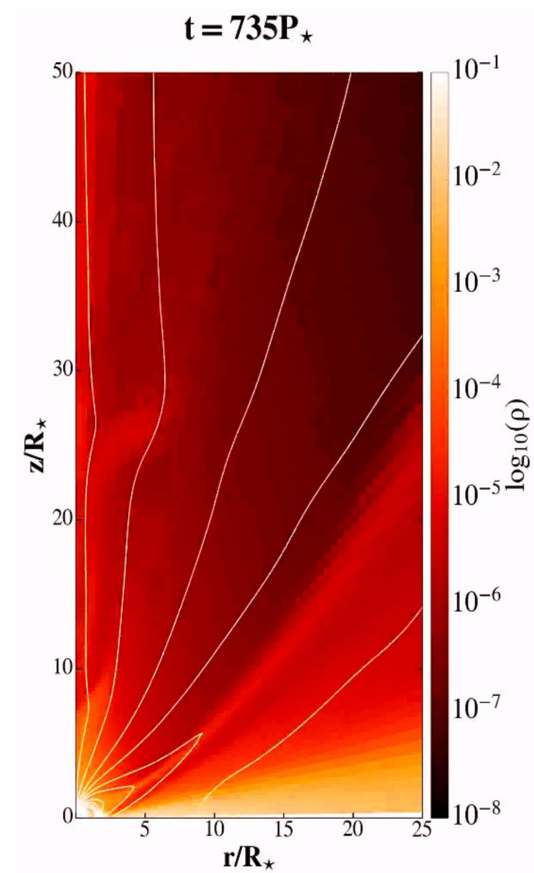
The jet launching

I obtained a continuous launching of an axial jet from the star-disk magnetosphere.

The axial jet and the conical outflow are launched after the relaxation from the initial conditions. They are similar to the results in Romanova et al. (2009) and Zanni & Ferreira (2013).



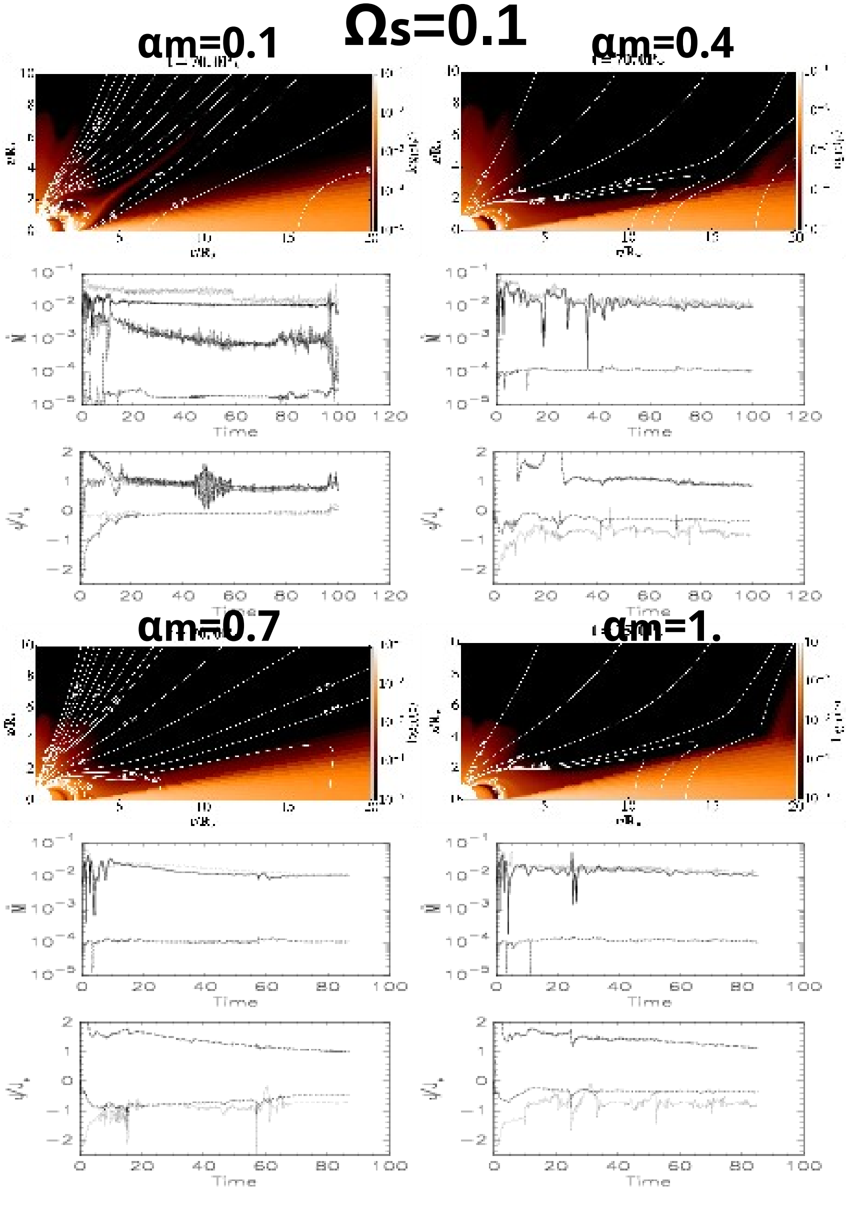




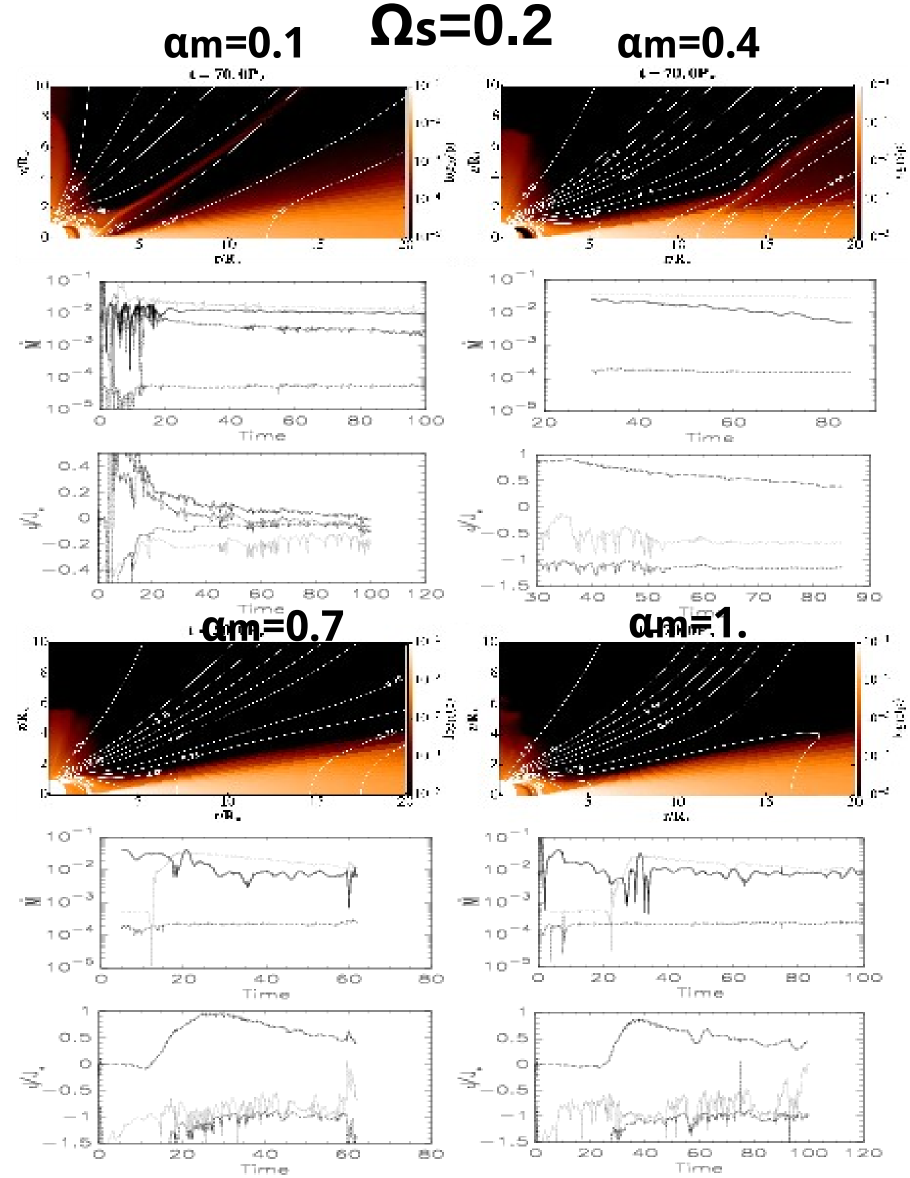
Zoom into the launching region.

Part of the “atlas” of solutions with different resistivity

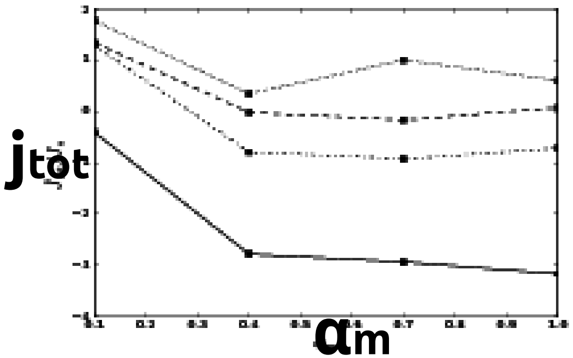
Ωs=0.1

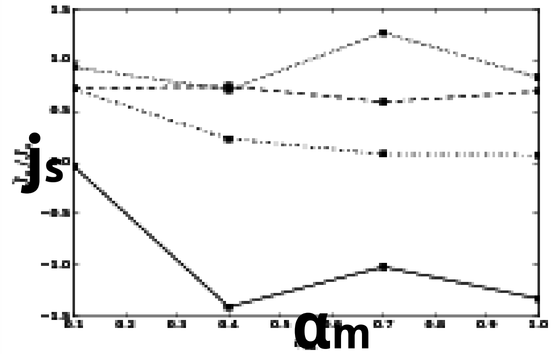


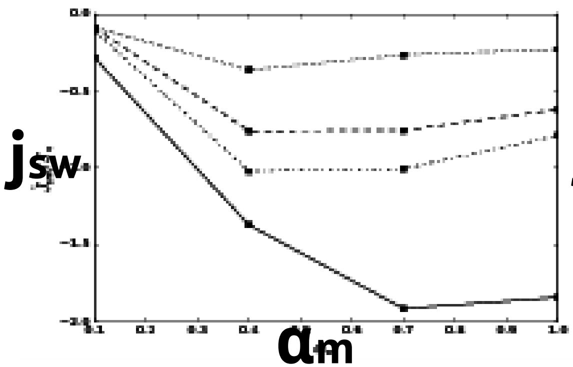
Ωs=0.2

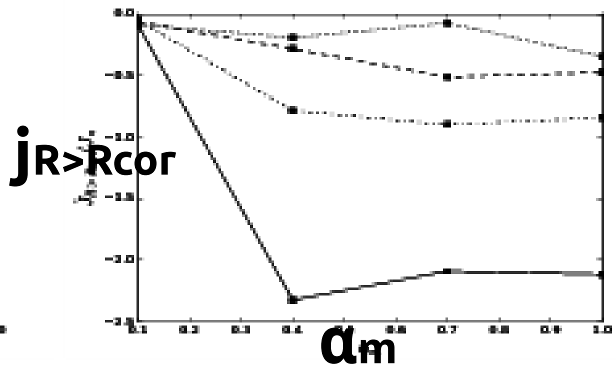


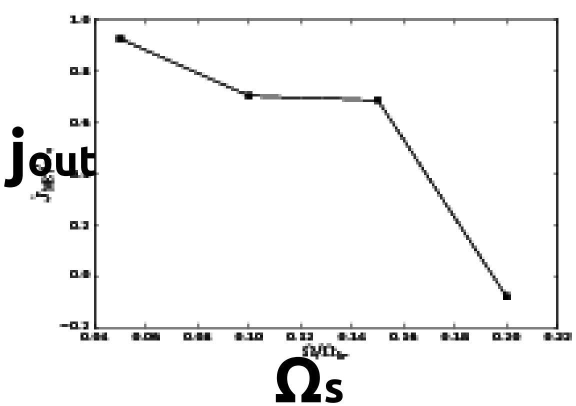
Trends in the simulations results











Shown is the average angular momentum flux change with resistivity (α_m) in various components of the system, normalized to the stellar angular momentum. Dotted, dashed, dot-dashed and solid lines represent fluxes in Ω_s=0.05, 0.1, 0.15 and 0.2 cases.

We are interested in trends. Compared with observations, this will be used to improve the stellar models.

Results presented here will be used to validate the results in our work on the magnetic Kluźniak & Kita disk in the asymptotic approximation.

⟵-- Here is shown angular momentum flux change with Ω_s, in the conical outflow case (with α_m=0.1).

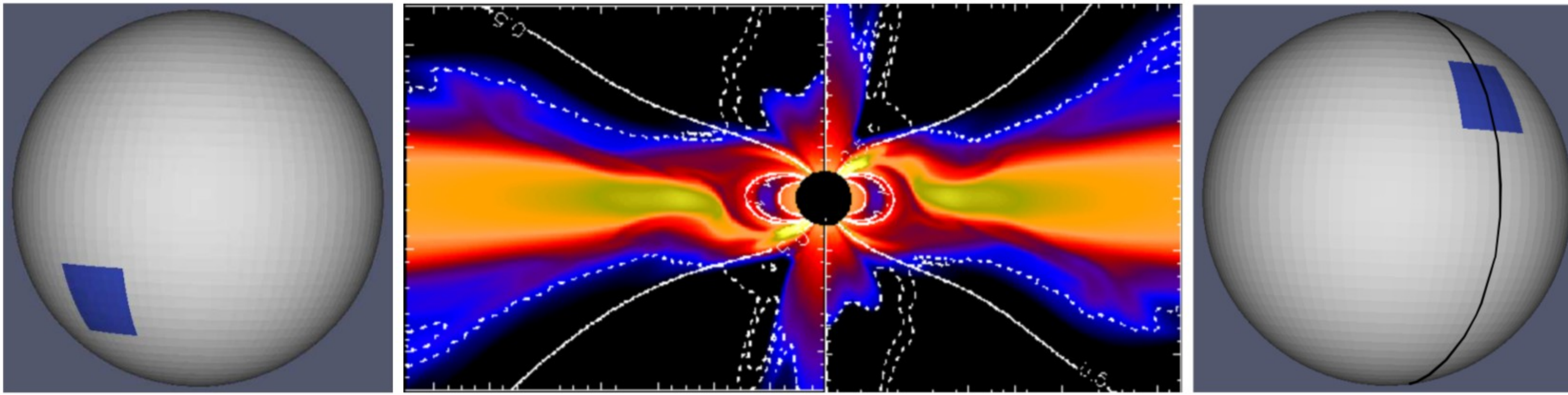
Summary

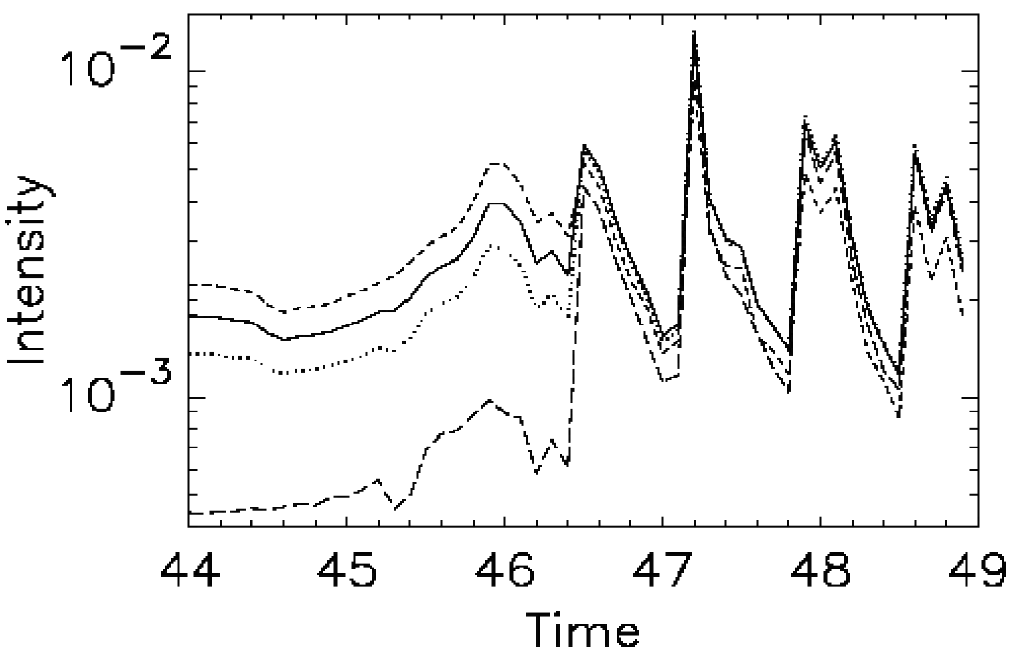
-I performed long-lasting star-disk magnetospheric interaction simulations of millisecond pulsars, to obtain relaxed disk solution.

-Axial and conical jets are launched after the disk relaxation.

-Launching of both, or only one of the outflows, depends on the position in parameter space (Ωs, resistivity, viscosity, B).

Connection to observations: 2D model for 3D light curve





The emission integrated along the stellar rim one grid cell thick in the azimuthal direction. The solid, dotted, long-dashed and short-dashed lines represent the intensities for an observer positioned at a co-latitudinal angle θ =15, 30, 60 and 165 degrees, respectively.

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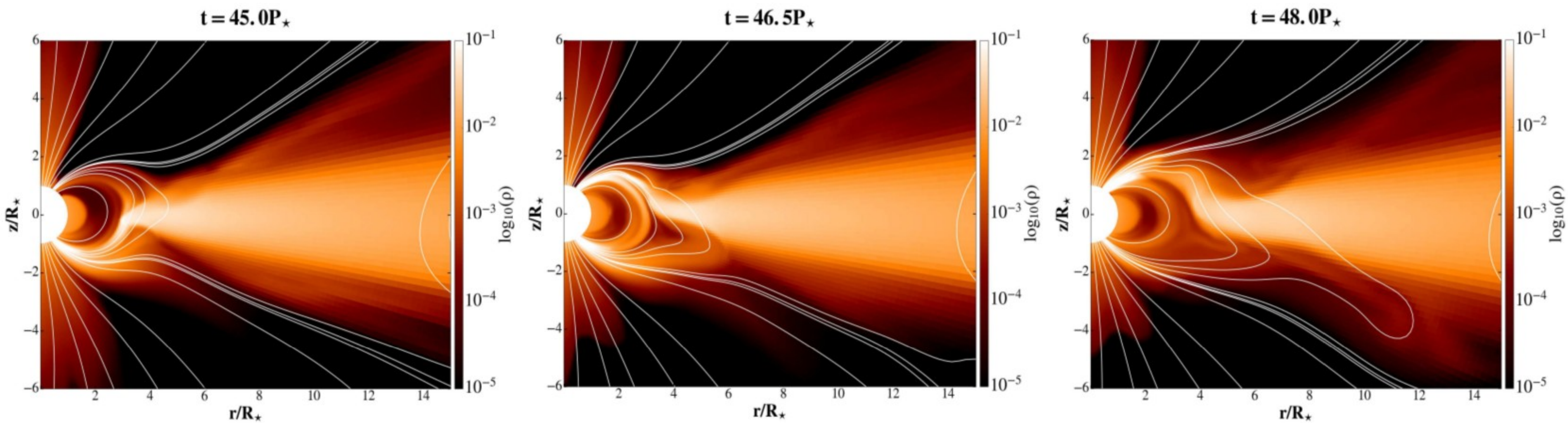
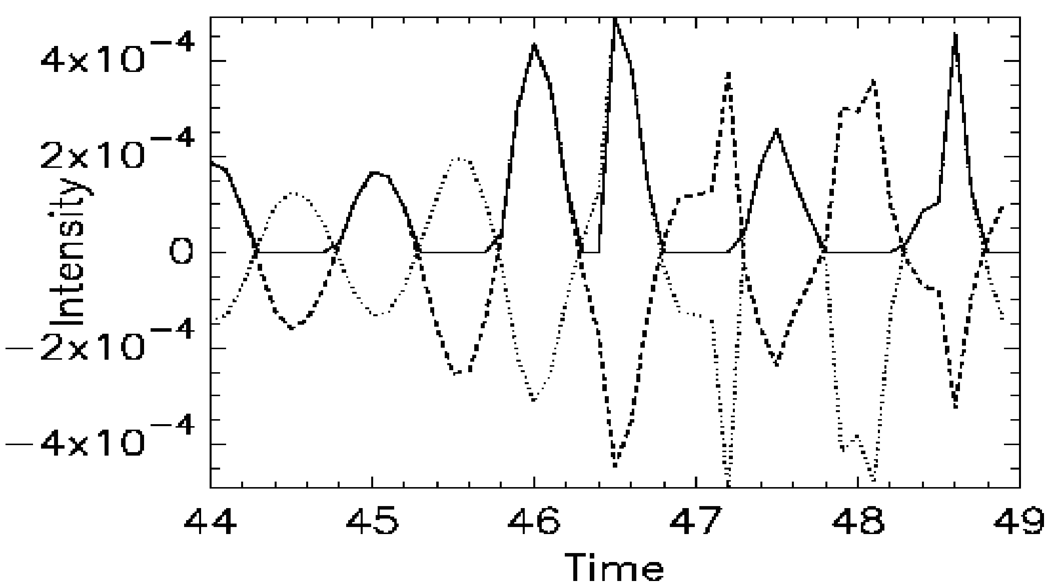
Connection to observations: 2D model for 3D light curve





The dotted and dashed lines show the intensity for modeled hot spots as seen from the co-latitude angles of θ =15 and θ =165 degrees. Intensity is negative when the spot is not visible from a given position. In solid line is shown the total intensity for an observer with θ =165. Switching of the accretion column from the southern to northern hemisphere produces a phase shift in the observed intensity peak as the star rotates.