MHD simulations of resistive viscous accretion disk around millisecond pulsar

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Abstract. We perform MHD simulations of a thin resistive and viscous accretion disk around a neutron star with the surface dipolar magnetic field of 10^8 Gauss. The system evolution is followed during the interval of 500 millisecond pulsar rotations. Matter is accreted through a stable accretion column from the disk onto the star. We also show propagation of the stellar wind through the corona. Analysis of the mass accretion flux and torques on the star shows that the disk reaches the quasi-stationary state.
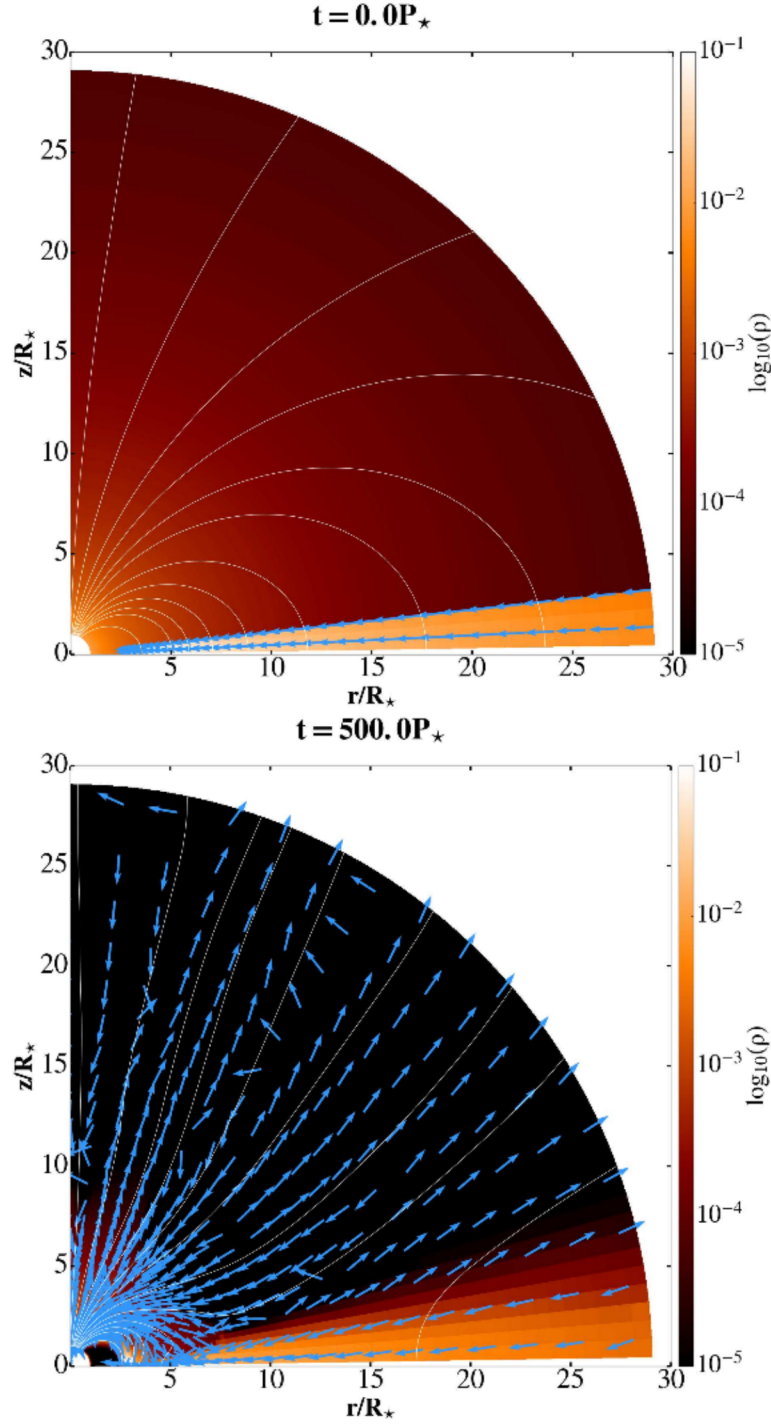
1. Introduction

In the interaction of a neutron star (NS) with its close companion star, an accretion disk is formed around the NS. Properties of a binary system depend on the type of companion star, the neutron star mass and the magnetic field strength and geometry. Kluźniak & Kita suggested a hydro-dynamical model for the accretion disk [1], with viscosity parameterized by Shakura & Sunyaev α-prescription [2]. We extend this model to the non-ideal MHD, and include the magnetosphere in the innermost part of a star-disk system. One example of such object is a millisecond pulsar: $M = 1.4 M_\odot$, $R \sim 10$ km, $B \sim 10^8$ Gauss, $P = 0.05$ sec (5 msec), $\rho_0 = 4.62 \times 10^{-6}$ g/cm^3, $\dot{M}_0 = 10^{-9} M_\odot$/yr.

2. Numerical setup

We use the PLUTO v.4.1 code [3,4] in spherical coordinates with logarithmically stretched grid in radial direction to perform axisymmetric 2D star-disk simulations in $\Theta = [0, \pi/2]$ half-plane. The resolution is $R \times \Theta = [109 \times 50]$ grid cells, with the maximal radius of 30 stellar radii. Following [5] we set up the disk as in [1] assuming that the corona is in a hydrostatic equilibrium. The viscosity and the resistivity are parameterized as $\alpha c^2/\Omega$ (Shakura & Sunyaev), where c is the sound speed, Ω is the Keplerian speed and α is a free parameter, which values are between 0 and 1. We use a split-field method in which only changes from the initial stellar magnetic field evolve in time while the initial stellar field is held constant. Our initial setup is shown in figure 1.
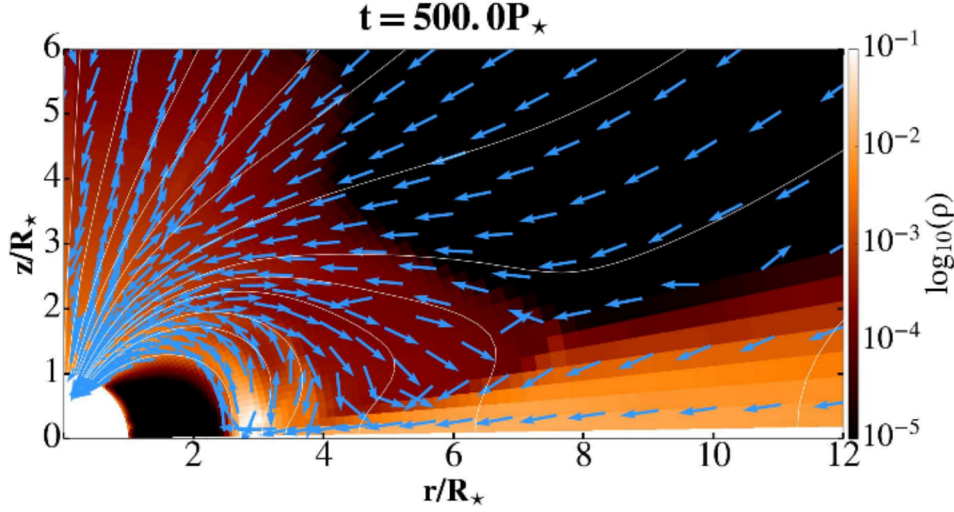
The equations we solve using the PLUTO code are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \quad \frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{8\pi} \boldsymbol{I} \right) - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} - \boldsymbol{\tau} \right] = -\rho \nabla \Psi_G$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{8\pi} \right) \cdot \boldsymbol{v} - \frac{(\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B}}{4\pi} \right] = -\rho \nabla \Psi_G \cdot \boldsymbol{v}$$

Figure 1. Simulated matter density distribution is shown with the logarithmic color grading. The initial setup is in the top panel and the system after 500 pulsar rotations is shown in the bottom panel. Magnetic field lines are plotted by solid lines and the poloidal velocity distribution is displayed by blue vectors (that are not normalized).

$$\text{with} \quad E = \frac{P}{\gamma - 1} + \rho \frac{\boldsymbol{v}^2}{2} + \frac{\boldsymbol{B}^2}{8\pi} \quad \text{and} \quad \frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{v} - \eta_m \boldsymbol{J}) = 0 \;,$$

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Figure 2. Central part of the system after 500 pulsar rotations is presented to visualize the accretion column and the magnetic field lines connected to the disk beyond the corotation radius $R_{cor} = 4.65\ R_*$.
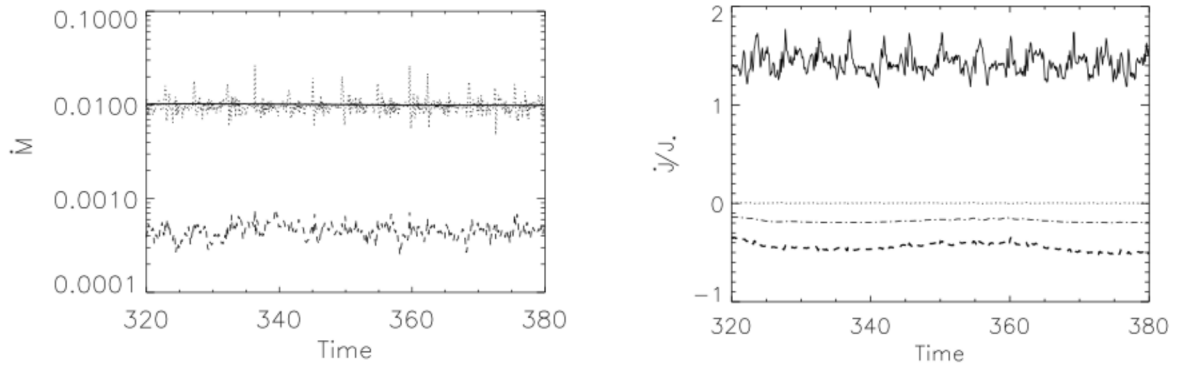
Figure 3. The left panel shows the time dependence of the mass flux. The mass flux is measured in the code units $M_0 = \rho_0 R_*^2 v_{K,*}$, and the time is measured in the pulsar rotation periods. The time interval during the quasi-stationary state is shown. Solid line shows the mass flux through the disk at $R = 12R_*$. This mass flux is distributed onto the star (dotted line) and into the stellar wind (thin dashed line). Right panel shows the torque acting on the stellar surface in the units of the stellar angular momentum for the same time interval. Dotted line shows the kinetic torque which is negligible in this case and dot-dashed line shows the magnetic torque on the star produced by the stellar wind. Solid and dashed lines show the magnetic torque acting on the star surface from the field lines below and beyond the corotation radius. Positive torque spins-up and negative spins-down the star.

where η_m and τ are the resistivity and the viscous stress tensor respectively. Following [5] we remove the Ohmic and the viscous heating terms in the PLUTO energy equation to prevent the thermal thickening of the accretion disk. The resistive and the viscous terms are still present in the momentum and the induction equations. In the boundary conditions we assume the stellar

surface to be a rotating perfect conductor so the electric field is zero in the stellar reference frame and the flow velocity is parallel to the magnetic field. We additionally prescribe the rotation of the matter atop the star to match the magnetic field evolution.

3. Results

We obtain long-lasting solutions for the millisecond pulsar as shown in figure 1. In figure 2 we show a zoom into this solution to show the accretion column and magnetospheric region in more detail.

Mass fluxes and torques obtained in our star-disk interaction simulation are shown in figure 3. Most of the mass from the disk is accreted onto the star and only about 1/100 of it goes into the stellar wind. The torque of mass infalling onto the star depends on the origin of the mass: when it comes from the region beyond the corotation radius it slows down the star and when it comes from the region below the corotation radius it spins-up the star.

4. Conclusions

We present the preliminary results of the long-lasting numerical simulations of a star-disk system with magnetospheric interaction in the case of a millisecond pulsar. The disk in our viscous and resistive MHD simulations reaches the quasi-stationary state. In further work we will investigate properties and stability of such a disk. To completely address the stability of the disk and the accretion column the 3D simulations should also be performed.

References

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