Resistive, viscous MHD simulations of accretion disk around millisecond pulsar

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Abstract: **In our resistive and viscous MHD simulations of a thin accretion disk around neutron star with the dipolar magnetic field of 10^8 Gauss, we capture 500 millisecond pulsar rotations. Matter is accreted from the disk onto the star through a stable accretion column. We also show propagation of stellar wind through the corona. We analyze the mass accretion flux and torques on the star from various components of the flow in the system.**

Introduction:

In the interaction of neutron star (NS) with a 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) α- prescription.

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=0.05 sec (5 msec), ρ_0=4.62x10^-6 g/cm^3, Mdot_0=10^-9 M_sun/yr.

Numerical setup:

We use the PLUTO v.4.1 code (Mignone et al. 2007, 2012), with logarithmically stretched grid in radial direction in spherical coordinates, to perform axisymmetric 2D star-disk simulations in Θ=[0,π/2] half-plane. The resolution is RxZ = [109x50] grid cells, with the maximal radius of 30 stellar radii. Following Zanni & Ferreira (2009), the disk is set by Kluzniak & Kita (2000), with a corona in hydrostatic equilibrium, as shown in Fig.1. The viscosity and resistivity are parameterized by the Shakura-Sunyaev, as αc2/Ω, where c is the sound speed, Ω is the Keplerian speed, and α is the free parameter between 0 and 1. We use a split-field method, in which only changes from the initial stellar magnetic field are evolved in time, with the initial stellar field held constant. The initial setup is shown in Fig.1. The equations we solve using the PLUTO code are:

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

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

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

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

We remove the Ohmic and viscous heating terms in the PLUTO energy equation, to prevent the thermal thickening of the accretion disk.

In the boundary conditions, we set the stellar surface as a rotating perfect conductor. In the stellar reference frame the electric field is then zero, and the flow speed is parallel to the magnetic field. We additionally prescribe the rotation of the matter atop the star, to match the magnetic field evolution.

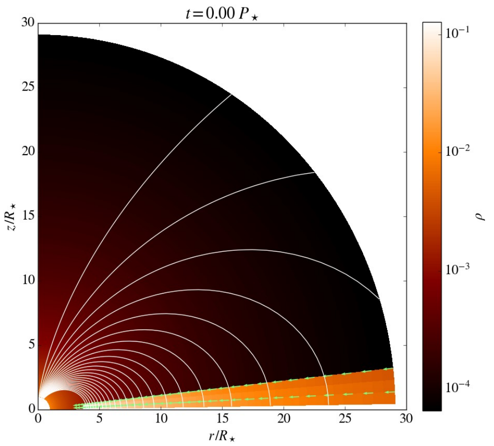

Figure 1: *The initial matter density distribution in our simulations, shown in logarithmic color grading. In solid lines is shown the initial magnetic field, and vectors (not normalized) show the initial poloidal velocity distribution in the disk.*

Results:

We obtained long-lasting solutions in the millisecond pulsar case, as shown in Fig. 2.

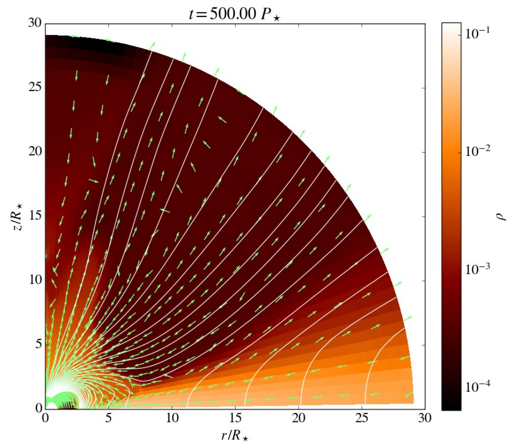

Figure 2: *Solution in our simulation after T=500 rotations of the underlying millisecond pulsar. Color and lines have the same meaning as in Figure 1.*

In Fig.3 we show a zoom into our solution, to show the accretion column and magnetospheric region in more detail.

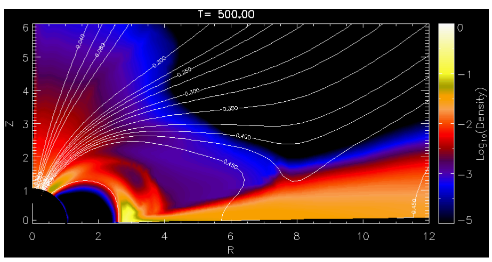

Figure 3: *Zoom into the solution after T=500, to show the accretion column and magnetic field line still connected to the disk beyond the corotation radius, Rcor=4.65. Color and lines have the same meaning as in Figure 1.*

Mass fluxes and torques in our SDI simulation, computed at the stellar surface, are shown in Figs. 4 and 5.

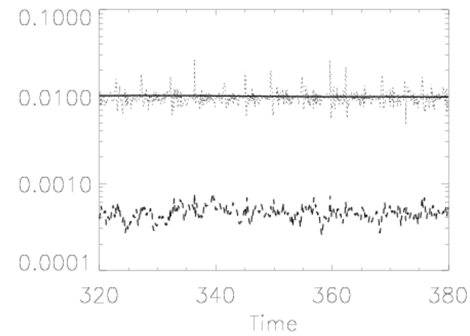

Figure 4: *The mass flux in the system in code units, in the quasi-stationary state. Time is given in units of the stellar rotation period. In dotted line is shown the mass flux through the disk at R=12R_*. This mass flux is then distributed onto the star (solid line) and into the stellar wind (thin dashed line). Note the logarithmic Mdot scale. Most of the mass from the disk is accreted onto the star, and about 1/1000 of it goes into the stellar wind.*

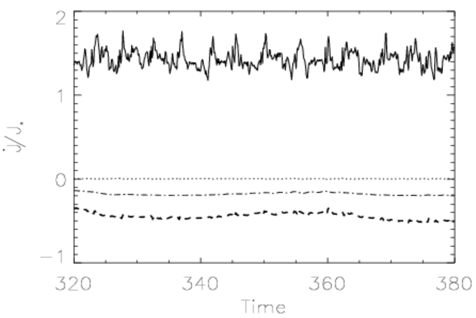

Figure 5: *The torque acting on the stellar surface, in units of the stellar angular momentum, in the quasi-stationary state. Time is given in units of the stellar rotation period. In dotted line is shown the kinetic torque, which is negligible in this case, and in dot-dashed line is shown the magnetic torque on the star by the stellar wind. In solid and dashed lines is shown the magnetic torque acting on the star along the lines below and beyond the corotation radius, respectively. The sign is chosen so that a positive torque spins-up, and a negative torque spins-down the star.*

Conclusions:

We presented preliminary results of the long-lasting numerical simulations of a star-disk system with magnetospheric interaction in the case of millisecond pulsar.

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References:

Kluzniak, W., Kita, D., 2000, arXiv:astro-ph/0006266

Mignone, A., et al., 2007, ApJS, 170, 228

Mignone, A., Zanni, C., Tzeferacos, et al., 2012, ApJS, 198, 7

Zanni, C., Ferreira, J., 2009, A&A, 508, 1117