Asymmetric jet launching in magnetospheric star-disk interaction

Miljenko Čemeljić, Aleksandra Kotek and Włodek Kluźniak

Nicolaus Copernicus Astronomical Center, Warsaw, Poland

Abstract: In our numerical simulations of the star-disk magnetospheric interaction in a regime relevant to Young Stellar Objects, we obtained pairs of axial jets launched from the close vicinity of a star. The two jets moving in the opposing directions do not have identical properties. We measure the propagation and rotation velocity of these jets, and estimate the angular momentum extracted from the system.

Introduction:

Accretion disk theory, in combination with magneto-hydrodynamical simulations and observations, provides models for explaining the launching mechanism of jets and outflows. In numerical simulations, the solution was presented in Romanova et al. (2009 and references therein), and Zanni & Ferreira (2009, 2013). In Čemeljić (2019) we repeated those results, and performed the extensive parameter study for the slowly rotating Young Stellar Objects with different magnetic field strengths and disk resistivities. Here we present a continuation of this study into the part of the parameter space where axial jets are launched from the magnetosphere of a star-disk system. To capture the asymmetric jets launched in the opposite directions from the vicinity of a central object, we perform simulations in a full meridional plane.

Numerical setup:

We use the PLUTO code (Mignone et al. 2007, 2012) with logarithmically stretched radial grid in spherical coordinates, to perform 2D-axisymmetric star-disk simulations in the complete [0,π] half-plane, in resolution Rxθ = [125x100] grid cells, with the maximal radius of 50 stellar radii. The disk is set up following Kluzniak & Kita (2000), as shown in Fig.1, with the addition of hydrostatic, initially non-rotating corona above the rotating star. Their hydrodynamic solution for a thin polytropic accretion disk in full 3D was obtained with the method of Taylor expansion in terms of the small parameter, the disk height to length ratio. The viscosity and resistivity are parameterized by the Shakura-Sunyaev prescription as αc²/Ω, where c is the sound speed, Ω is the Keplerian angular velocity, and α the free parameter, coefficient of viscosity with value between 0 and 1. We used α=1 in our simulation shown here, with the resistive coefficient α_m=0.4. We use a split-field method, in which only changes from the initial stellar magnetic field are evolved in time. Here we investigated the case with the initial stellar dipole field. The equations solved by the PLUTO code are:

$$
\begin{aligned}
&\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=0\\
&\frac{\partial\rho\boldsymbol{u}}{\partial t}+\nabla\cdot\left[\rho\boldsymbol{u}\boldsymbol{u}+\left(P+\frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi}\right)\boldsymbol{I}-\frac{\boldsymbol{B}\boldsymbol{B}}{4\pi}-\boldsymbol{\tau}\right]=\rho\boldsymbol{g}\\
&\frac{\partial E}{\partial t}+\nabla\cdot\left[\left(E+P+\frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi}\right)\boldsymbol{u}-\frac{(\boldsymbol{u}\cdot\boldsymbol{B})\,\boldsymbol{B}}{4\pi}\right]\\
&\qquad\qquad+\cancel{\nabla\cdot[\eta_{\rm m}\boldsymbol{J}\times\boldsymbol{B}/4\pi-\boldsymbol{u}\cdot\boldsymbol{\tau}]}=\rho\boldsymbol{g}\cdot\boldsymbol{u}-\cancel{\Lambda_{\rm cool}}\\
&\frac{\partial\boldsymbol{B}}{\partial t}+\nabla\times(\boldsymbol{B}\times\boldsymbol{u}+\eta_{\rm m}\boldsymbol{J})=0.
\end{aligned}
$$

We removed the Ohmic and viscous heating terms in the PLUTO energy equation, to prevent the thermal thickening of the accretion disk. Because of the viscous term in the momentum equation and the resistive term in the induction equation, we are still in the non-ideal MHD regime. The setup is described in detail in Čemeljić (2019).

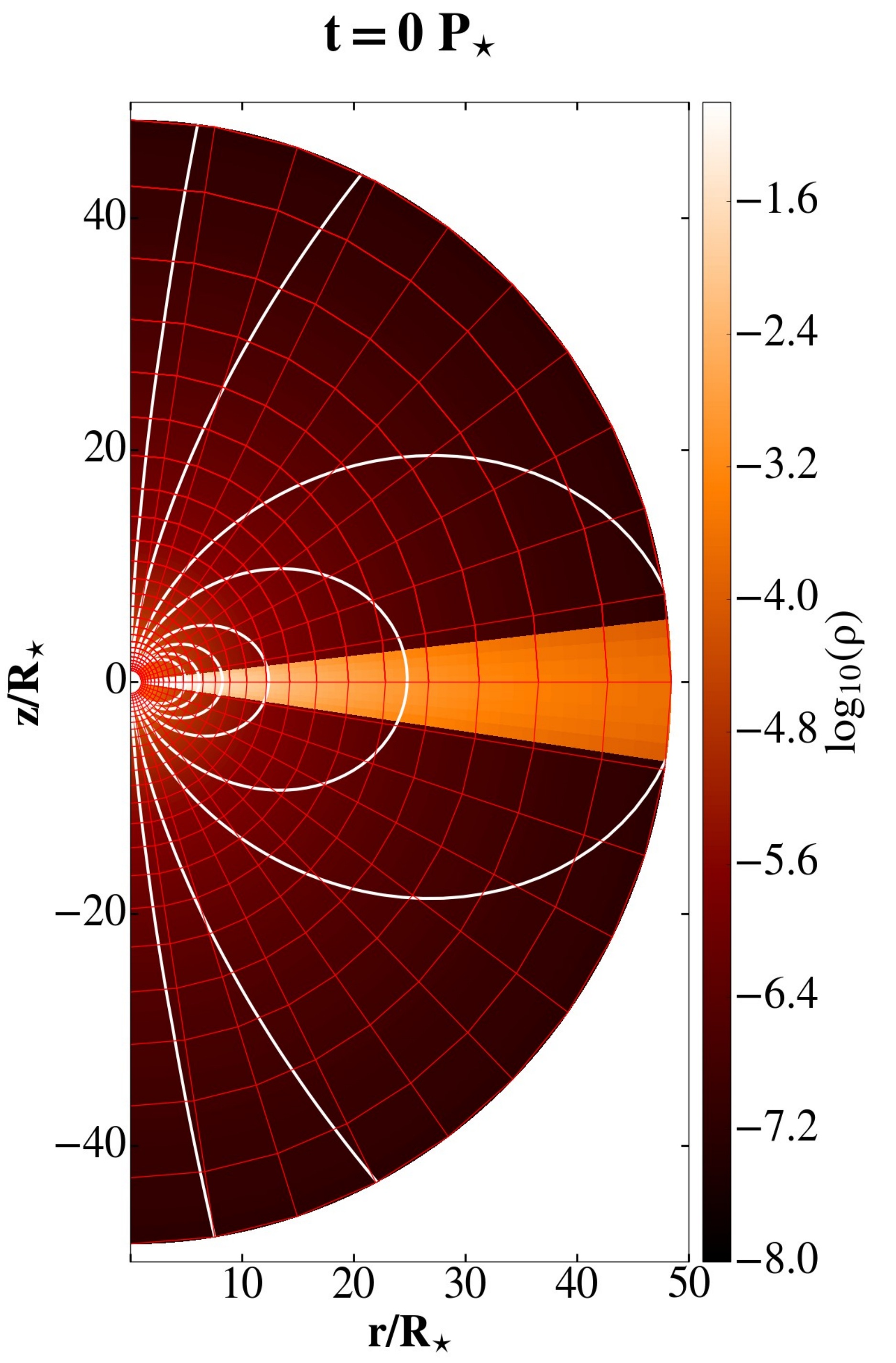

Figure 1: *Initial matter density distribution in our simulations, shown in a logarithmic color grading. White solid lines show a sample of magnetic field lines, and vectors show the initial poloidal velocity in the disk. The computational grid is shown in 5x5 blocks of cells.*

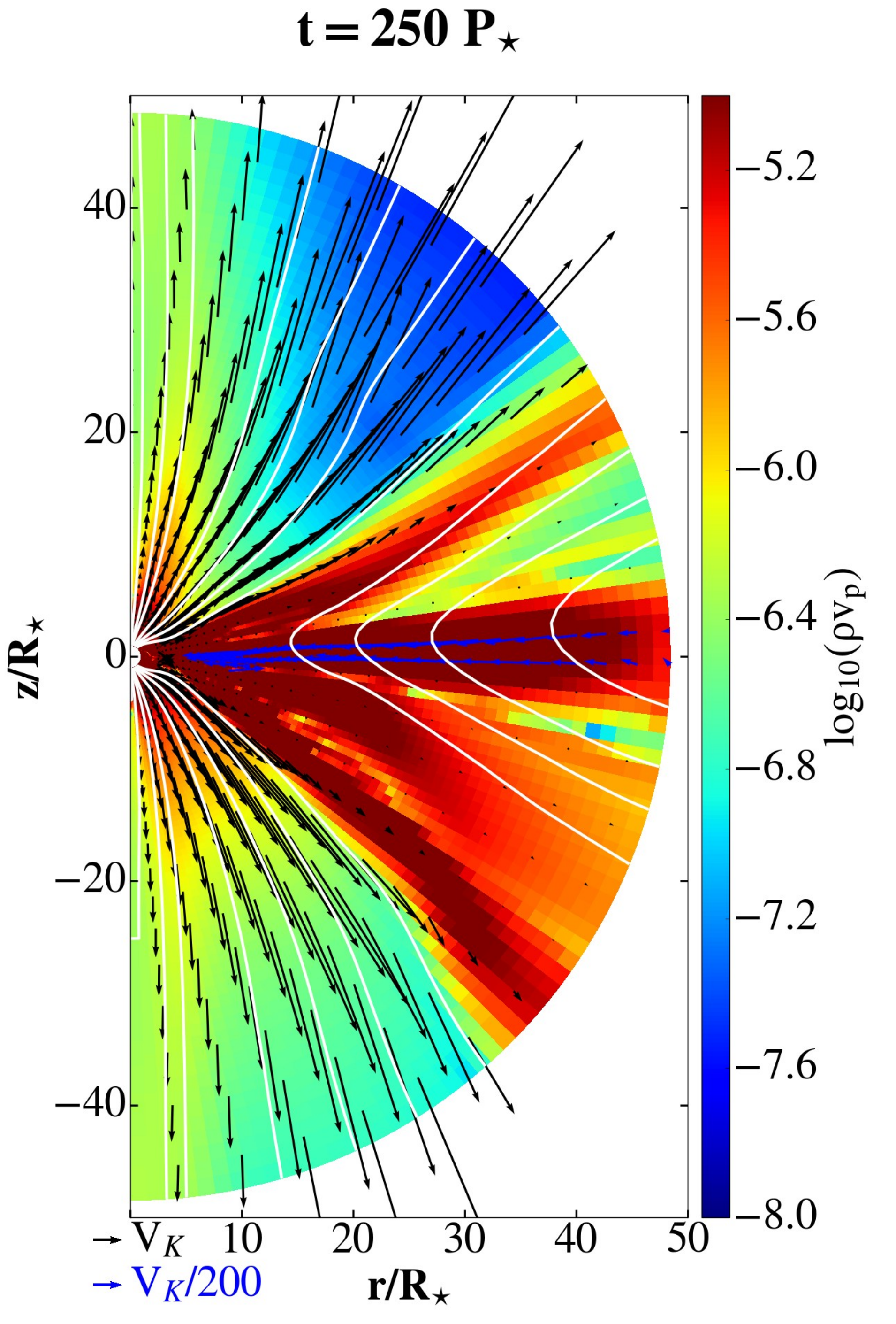

Figure 2: *Mass flux in units of 10^{-7}M☉/yr in our simulation after 250 stellar rotations, with axial jets shown in yellow-green color. The mass flux in the disk and conical outflows are about two orders of magnitude larger. Velocity vectors in the disk and above it are shown with different normalizations to the Keplerian velocity at the stellar equator, V_K. A sample of magnetic field lines is shown with white solid lines.*

Results: We obtained long-lasting solutions in our simulations with 500 Gauss stellar dipole magnetic field, with a star rotating with 50% of breakup velocity, which reach a quasi-stationary state. In Figure 2 is shown a case with axial jets launched above the opposite hemispheres of the central object. The jets are asymmetric, with different propagation and rotation speeds, as shown in Figs. 3 and 4. Their mass loads are also different, as shown in Figure 5.

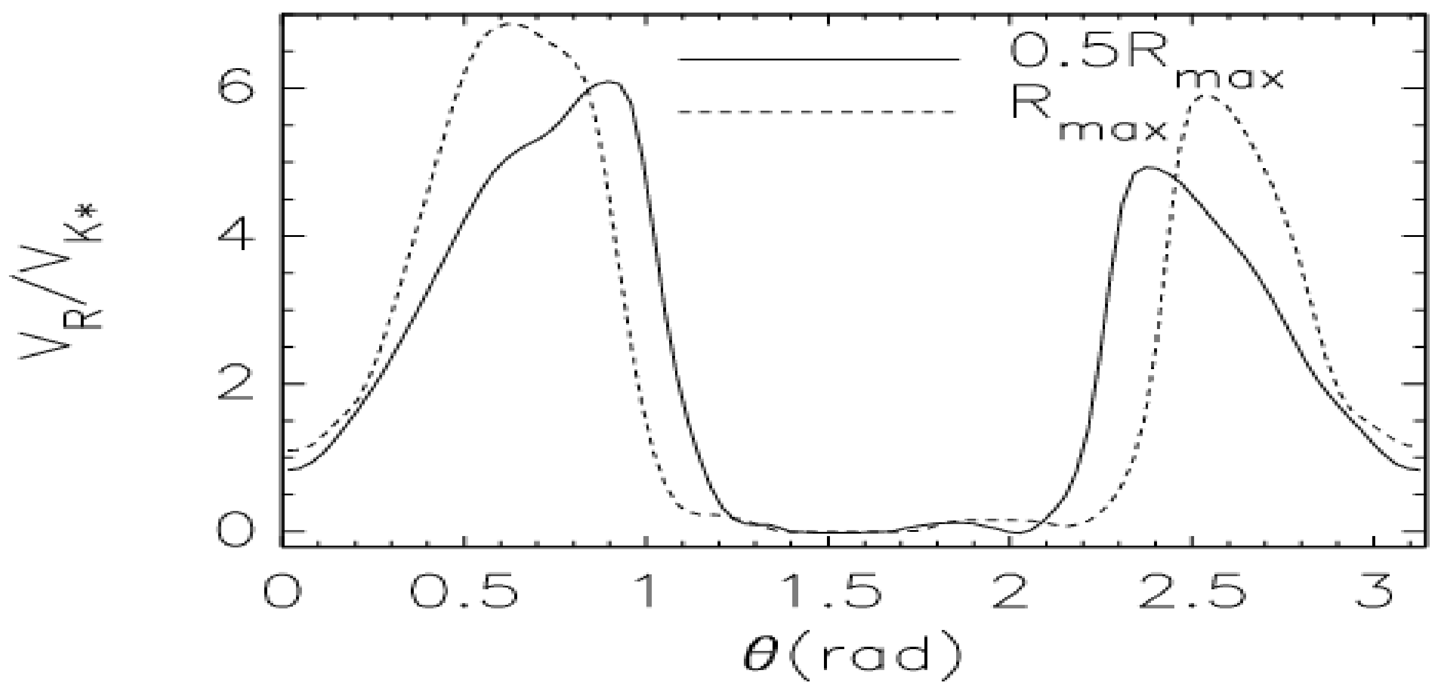

Figure 3: *Radial propagation velocity of the obtained jets. In all the plots the velocities are in units of Keplerian velocity at the stellar equator, computed along the half-circles in the meridional plane at R=0.5 Rmax and at R=Rmax.*

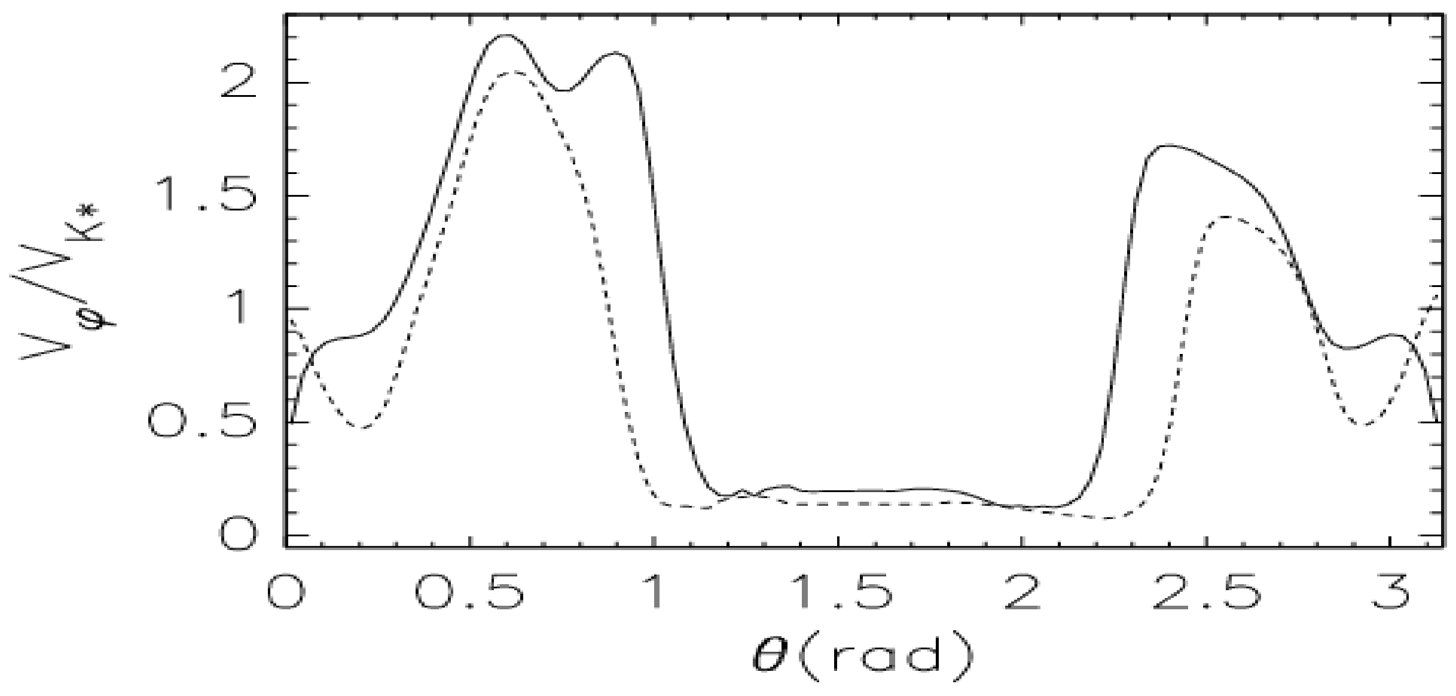

Figure 4: *Rotation velocity of the obtained jets.*

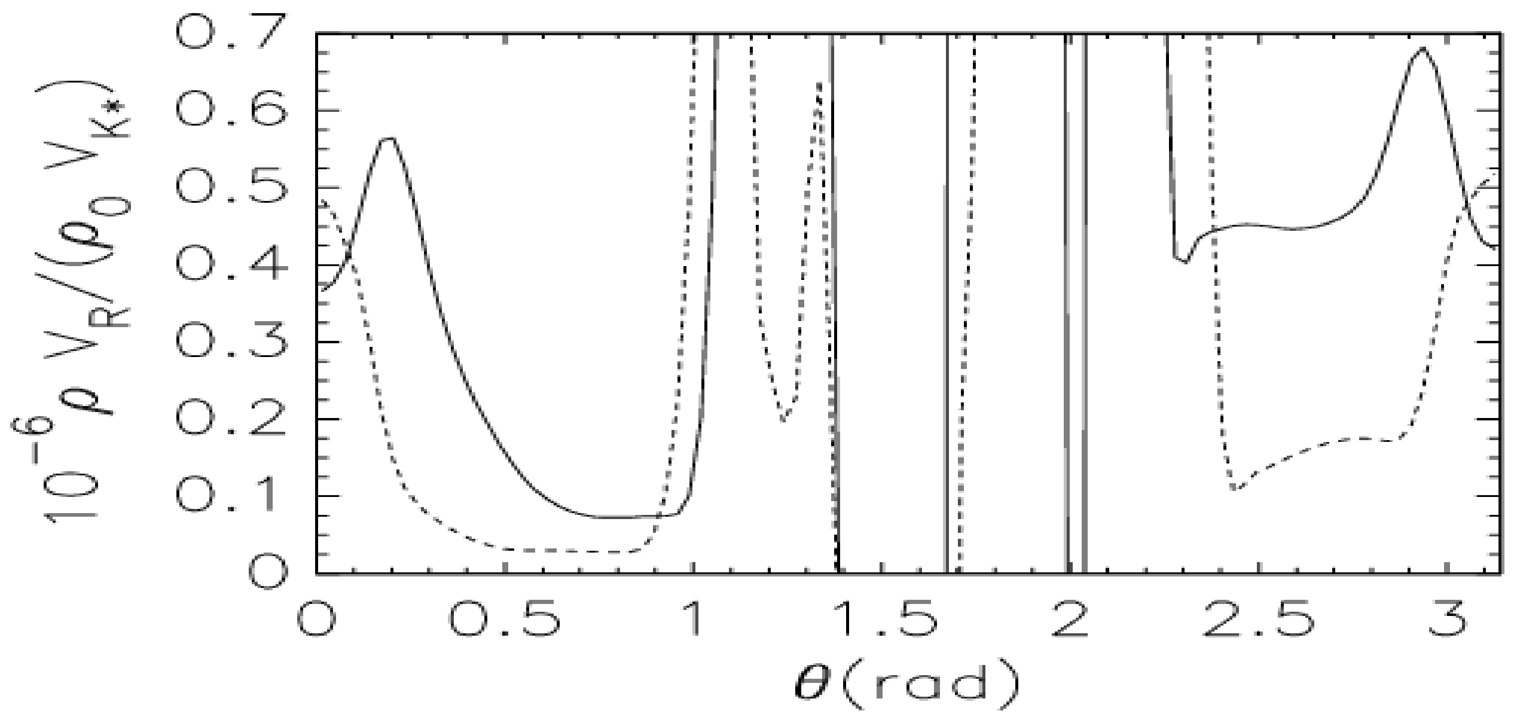

Figure 5: *Mass flux in the obtained solutions. Inside the disk mass flux is much larger, axial jets are positioned about 0.3 and 2.7 rad. The unit density $\rho_0=10^{-10}$ g/cm³.*

Conclusions and future work:

We present preliminary results with asymmetric jets launched from the magnetosphere of a star-disk system. We find that two jets are launched, in the opposite directions, with different propagation and rotation speeds and mass loads. In a following parameter study we will analyse the results with different strengths of magnetic field, stellar rotation rates and viscous and resistive coefficients. The stability of the results in simulations with different disk accretion rates will also be checked, to relate results to the different stages in the evolution of a system.

Acknowledgements:

Work in Warsaw is funded by NCN Polish grant no. 2013/08/A/ST9/00795. MČ developed the PLUTO setup under ANR Toupies funding in CEA Saclay, France, and the Croatian HRZZ grant IP-2014-09-8656 is acknowledged. We thank A. Mignone and his team of contributors for the possibility to use the PLUTO code, and ASIAA/TIARA for use of their Linux clusters PX and XL.

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