Numerical simulations of accretion disks and auroras on exoplanets

Miljenko Čemeljić

SGMK Nicolaus Copernicus Superior School, The College of Astronomy and Natural Sciences, Warsaw

&

Nicolaus Copernicus Astronomical Center, PAN

Warsaw

&

Institute of Physics, Silesian University in Opava, Czech Republic

&

ASIAA Visiting Scholar, Taipei, Taiwan

Outline

- Our group
- Star-disk and star-planet magnetospheric interaction with PLUTO code
- Works with PhD students, Master and Summer students
- Potential project opportunities
- CAMK small radio telescope

Our group


Prof. Włodzimierz Kluźniak
CAMK, Warsaw
International Collaborators
PhD students at CAMK, Warsaw
Dr. Maciek Wielgus
Max Planck Institute for Radio Astronomy
Dr. Miljenko Čemeljić
Silesian University
CAMK
Dr. Bhupendra Mishra
Los Alamos National Lab
Angelos Karakonstantakis
Fatemeh Kayanikhoo
Ruchi Mishra
Postdoc at CAMK, Warsaw
Dr. Deepika Bollimpalli
Max Planck Institute for
Debora Lančova
Silesian University
Dr. Tomasz Krajewski
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Star-disk magnetospheric interaction with PLUTO code

PLUTO is a code for MHD numerical simulations in ideal, non-ideal (Ohmic and Hall resistive, viscous, thermally conductive,) Newtonian and Special Relativistic approach (Mignone et al. 2007, 2012). Since more than decade I use it for simulations, mostly **star-disk magnetospheric interaction** in young stellar objects, neutron stars and jet formation, but also reconnection.

One example of a simulation result in star-disk magnetospheric interaction:

2 Miljenko Čemeljić, Varadarajan Parthasarathy, Włodek Kluźniak

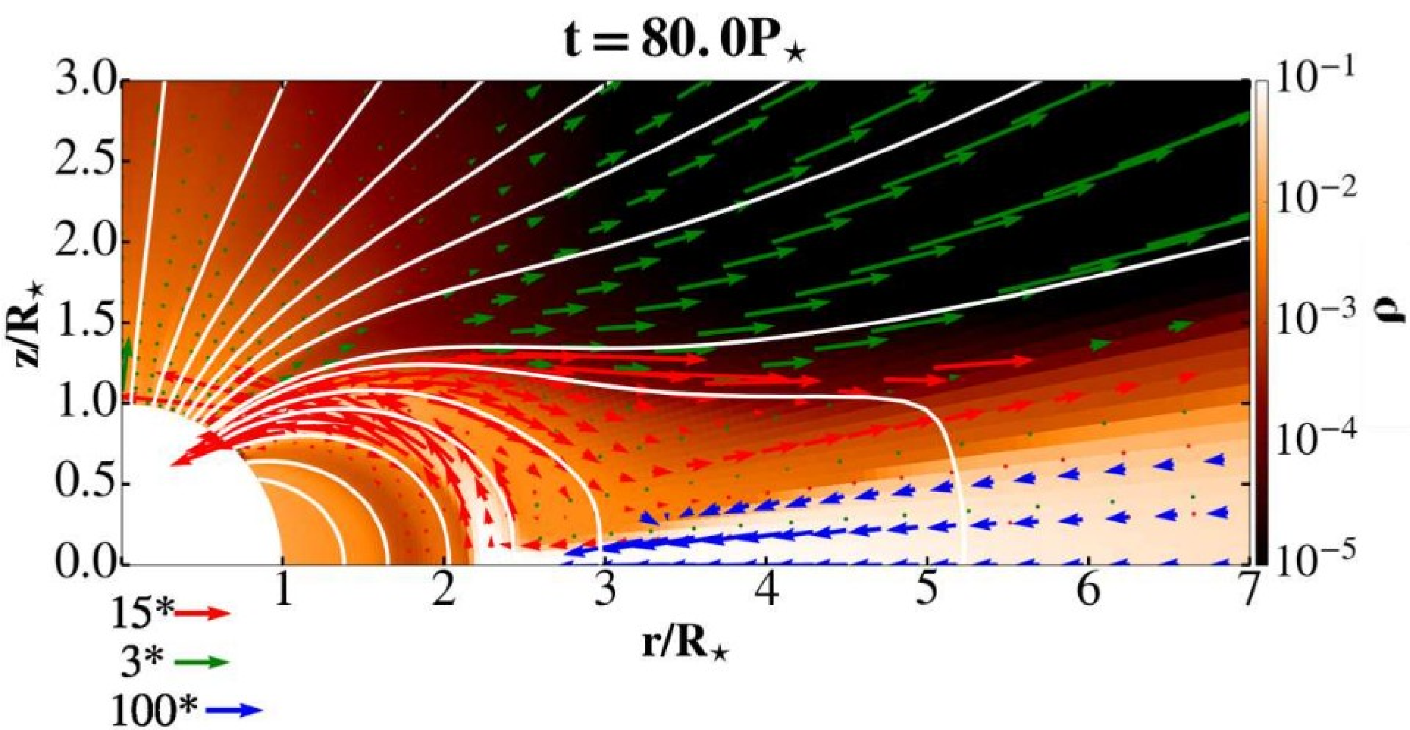
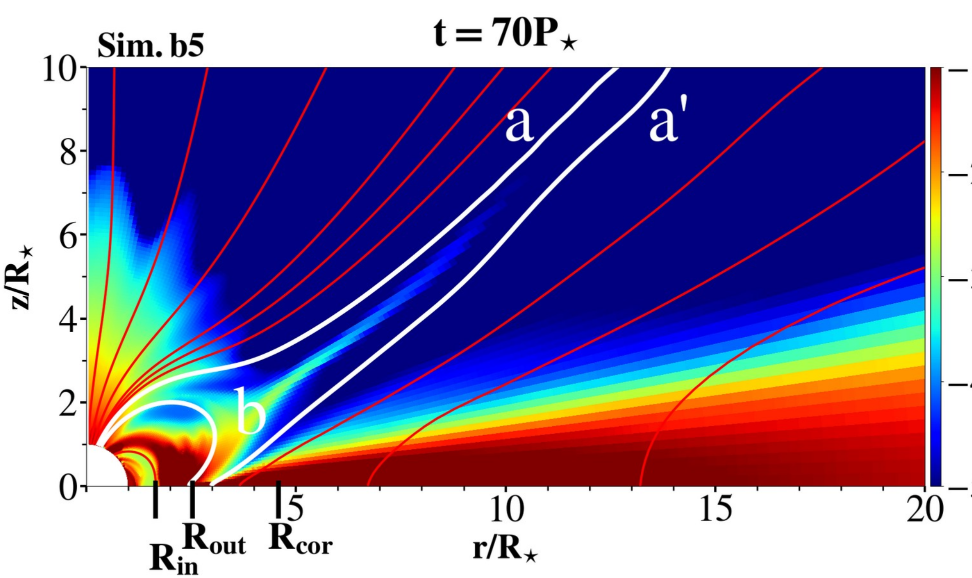
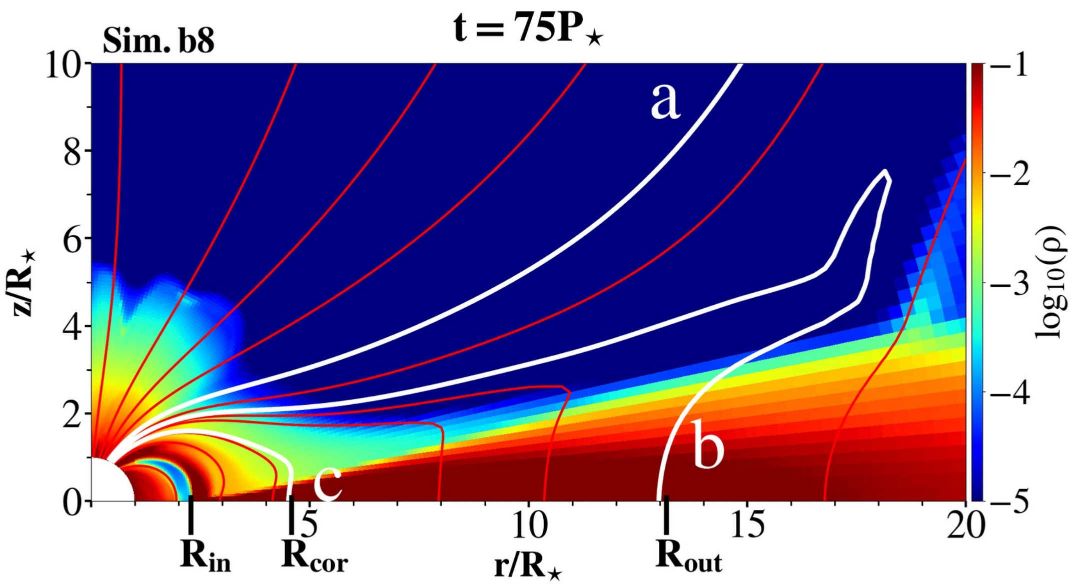


Figure 1. A zoom into our simulation result after T=80 rotations of the underlying star. Shown is the density in logarithmic color grading in code units, with a sample of magnetic field lines, depicted with white solid lines. Velocities in the disk, column and stellar wind are shown with vectors, depicted in different normalizations with respect to the Keplerian velocity at the stellar surface.

Star-disk magnetospheric interaction

With different parameters in the simulation (we change stellar rotation rate, strength of the stellar magnetic field and coefficient of resistivity) we obtain different geometries of the quasi-stationary solution (“Atlas” paper, Čemeljić, 2019). Solutions with and without conical outflow:

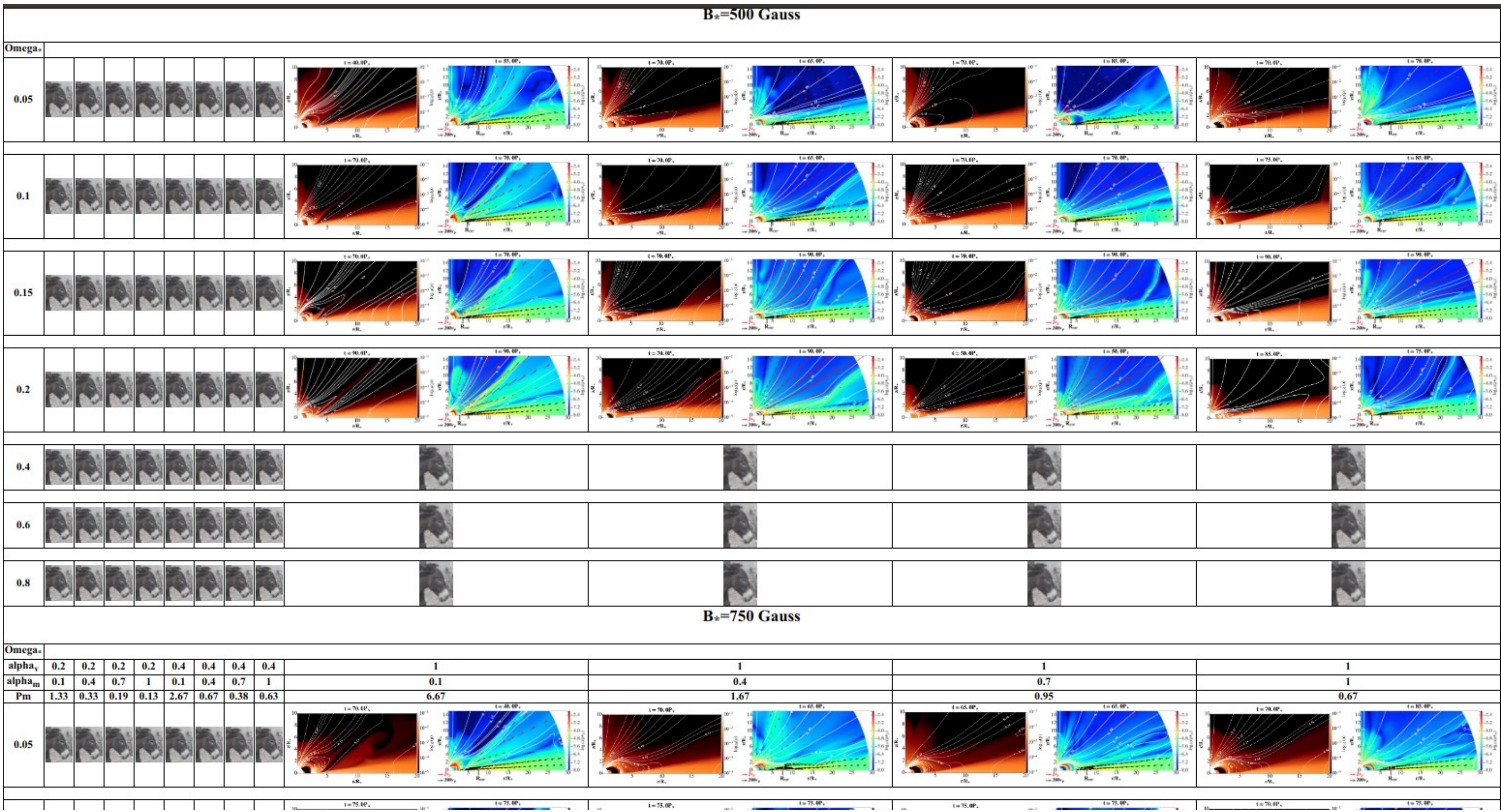




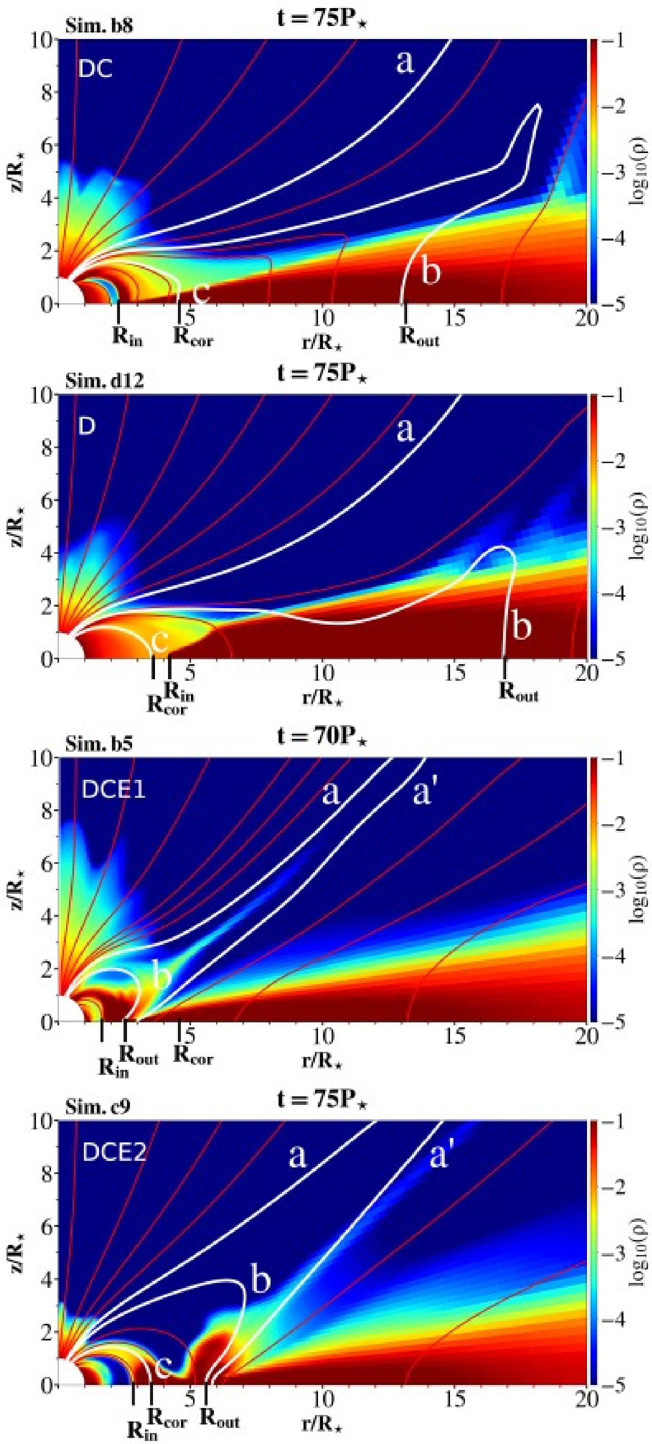
Depending on the position of corotation radius R_{cor} (where the disk corotates with the stellar surface at the equator) and the furthest anchor point of the stellar magnetic field in the disk R_{out}, the exerted torque on the star is spinning the star up-or down.

"Atlas" of results

- In "Atlas" paper I performed a systematic study for slowly rotating star (up to 20% of the star breakup velocity). Below is shown part of our solutions, there were 64 of them. We are also interested in a similar study with other geometries of magnetic field—initial study is already done, as I will show later!



Solutions for slowly rotating stars come in 4 configurations:

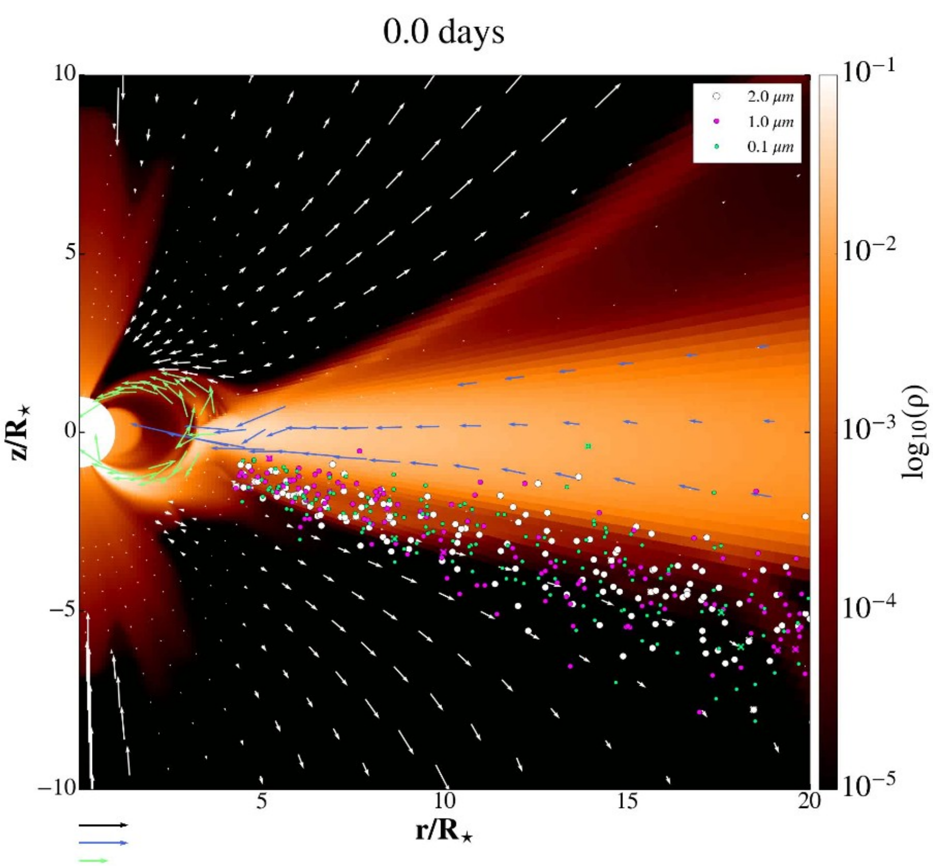


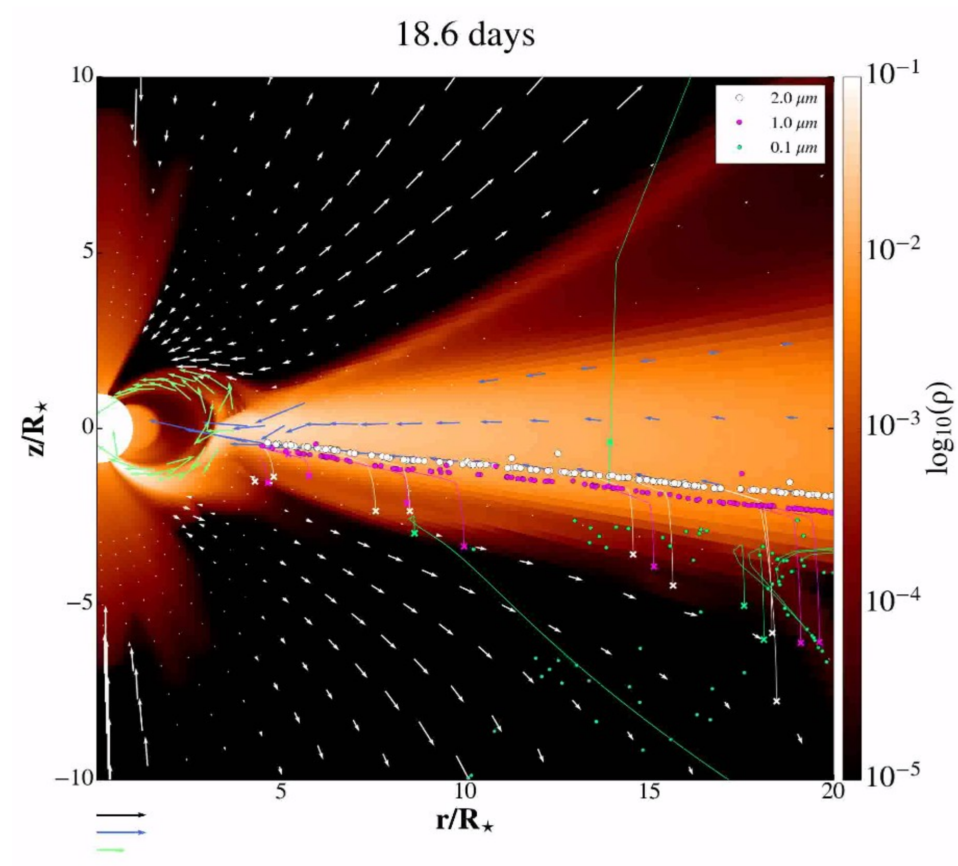
$\alpha_{\rm m}$ =	0.1	0.4	0.7	1
$P_{\rm m}$ =	6.7	1.67	0.95	0.67
$\Omega_\star/\Omega_{\rm br}$				
	$B_\star$ = 250 G			
0.05	**a1**(DCE1)	**a2**(DC)	**a3**(DC)	**a4**(DC)
0.1	**a5**(DCE1)	**a6**(DC)	a7(DC)	**a8**(DC)
0.15	**a9**(DCE1)	**a10**(DC)	a11(DC)	**a12**(DC)
0.2	a13(DCE1)	a14(DC)	a15(DC)	a16(DC)
	$B_\star$ = 500 G			
0.05	**b1**(DCE1)	**b2**(DC)	**b3**(DC)	**b4**(DC)
0.1	$\boxed{\mathbf{b5}}$(DCE1)	b6(DC)	b7(DC)	$\boxed{\text{b8}}$(DC)
0.15	**b9**(DCE1)	b10(DC)	b11(DC)	b12(DC)
0.2	b13(DCE1)	b14(DC)	b15(DC)	b16(DC)
	$B_\star$ = 750 G			
0.05	**c1**(DCE1)	c2(DC)	**c3**(DC)	c4(DC)
0.1	**c5**(DCE1)	c6(DC)	c7(DC)	c8(DC)
0.15	$\boxed{\text{c9}}$(DCE2)	c10(DC)	c11(DC)	c12(DC)
0.2	c13(DCE2)	c14(DC)	c15(DC)	c16(DC)
	$B_\star$ = 1000 G			
0.05	**d1**(DCE1)	d2(DC)	**d3**(DC)	d4(DC)
0.1	**d5**(DCE1)	d6(DC)	d7(DC)	d8(DC)
0.15	d9(DCE2)	d10(D)	d11(D)	$\boxed{\text{d12}}$(D)
0.2	d13(DCE2)	d14(D)	d15(D)	d16(D)

Notes. There are all together 64 runs with all the combinations of parameters as listed in the table. The magnetic Prandtl number $P_{\rm m} = \frac{2}{3}\alpha_{\rm v}/\alpha_{\rm m}$ is also listed – in all the cases the anomalous viscosity parameter is $\alpha_{\rm v} = 1$. The four simulations shown in Fig. 1 are highlighted with boxed letters. Simulations in which $\dot{J}_{\rm tot} > 0$ are marked in bold. Annotated type of solution for each combination of parameters are shown in brackets, as illustrated in Fig. 1.

“DUSTER”: Dusty disk in Young Stellar Objects (with C. Turski)

Results from “Atlas” can be further used for different purposes. A Summer Program student C. Turski wrote the Python script “DUSTER” for post-processing of the quasi-stationary results in star-disk solutions. He added the dust particles and computed their movement in the disk-corona solution as a background. The results are used to improve the model of dust distribution in the disk (with D. Vinković in a Croatian collaboration project “Stardust”).





Comparison with observations, “hiccups” in light curves

- When we perform our simulations in a full latitudinal plane, sometimes is obtained a curious case with switching of the hemisphere to which the column is attached (Čemeljić & Siwak, 2020) .

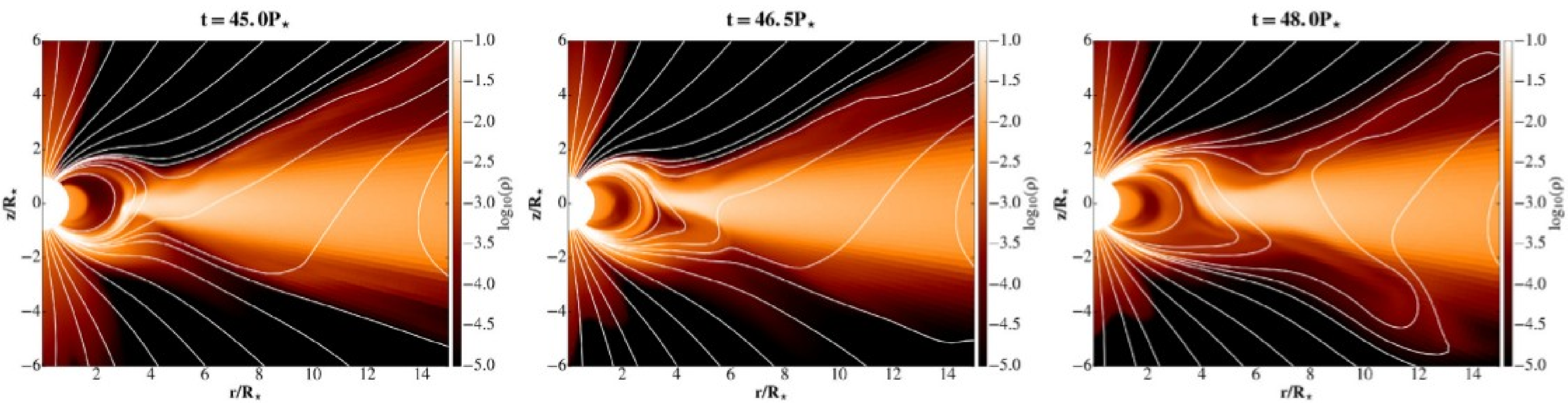
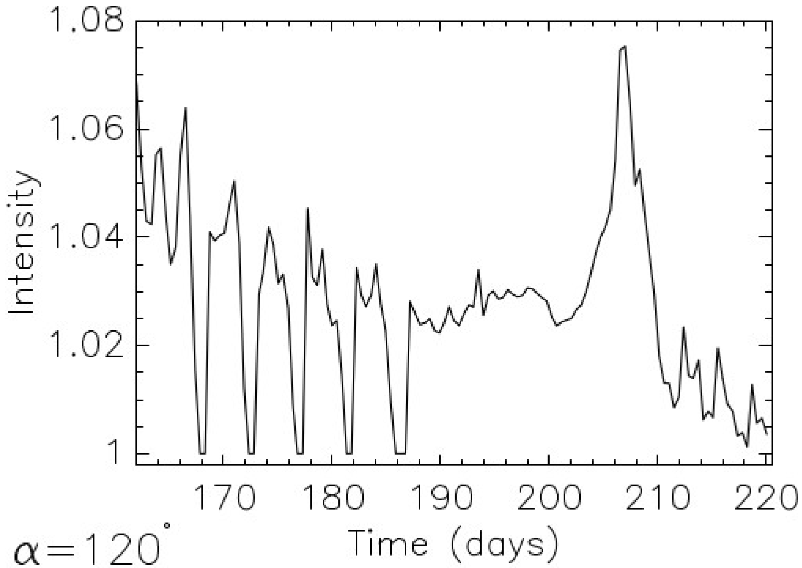


Figure 4. A sequence of snapshots from the results in the interval when switching of the accretion column from the Southern to the Northern hemisphere occurs.

Comparison with observations, “hiccups” in light curves

- Such switching, when matching the time of variations with observed sistems, could explain non-periodicity in the Young Stellar Objects:



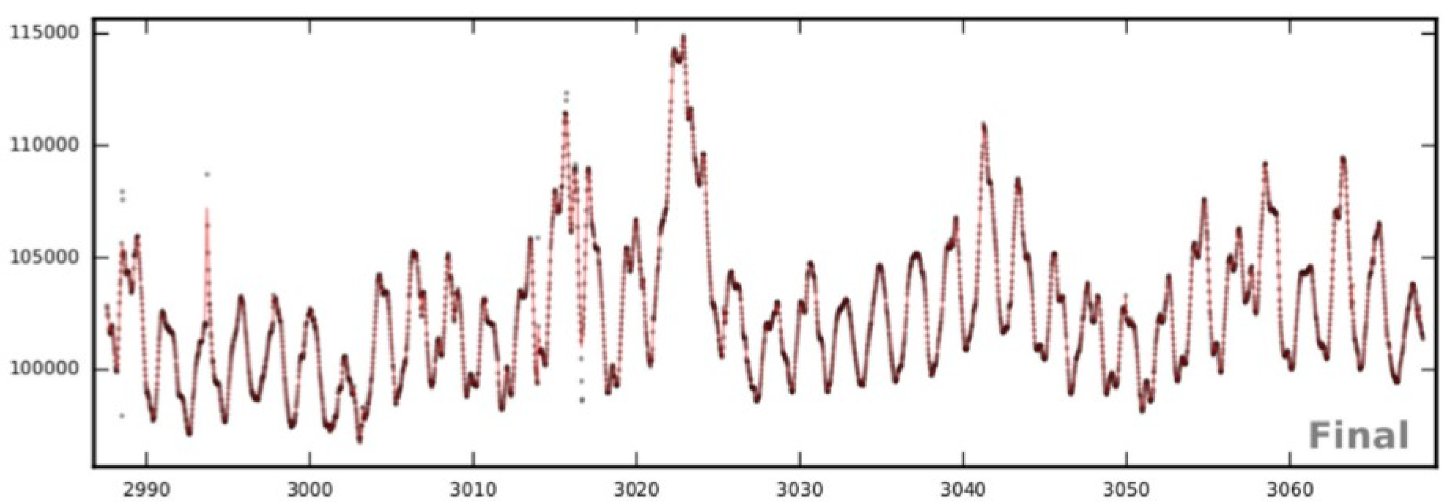
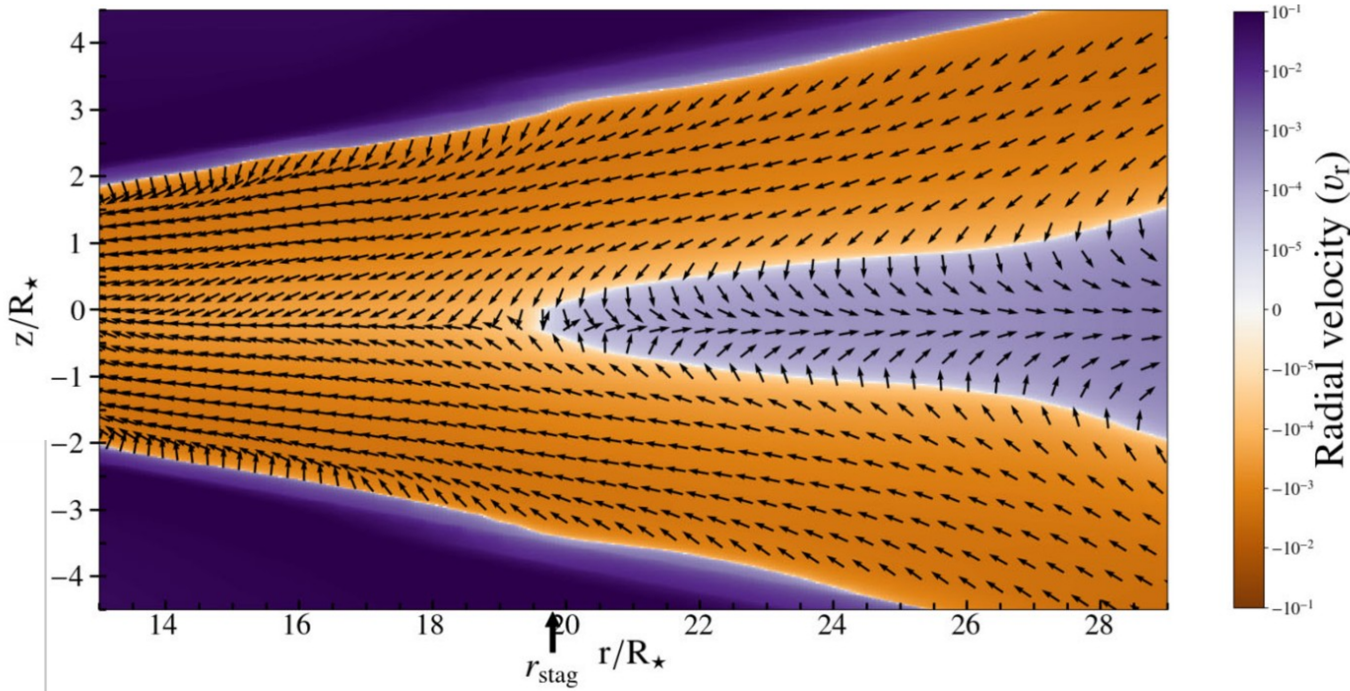
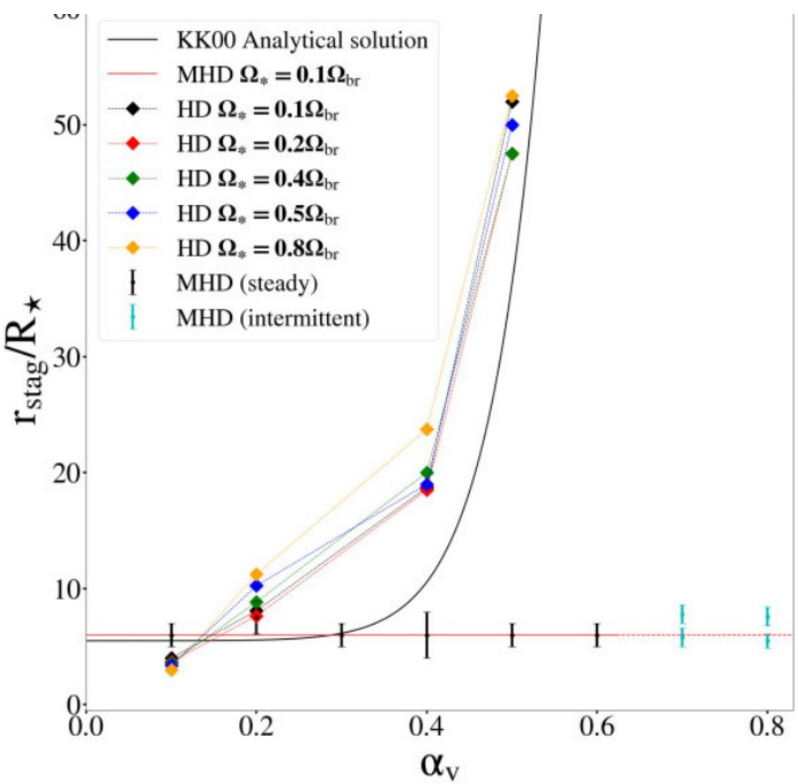


Figure 8. Top panel: intensity in a 3D model made from the longer time sequence than shown in Fig. 7. Shifts in the phase of the observed light (‘hiccups’) occur during the switch of the accretion column from the southern to northern stellar hemisphere between the 190 and 210 d. Bottom panel: light curve from the *Kepler* observation of V1000 Tau in which part of the contribution could occur because of the column switching. Time in the abscissa is annotated in Julian days.

Work with CAMK PhD students

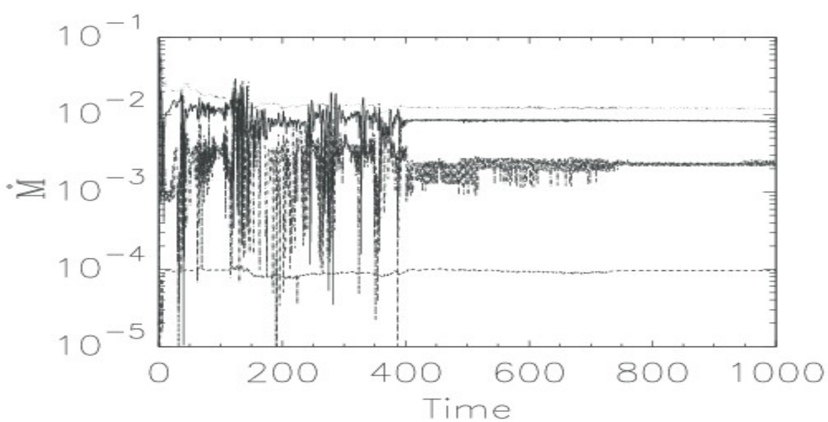
Another use of such results is to investigate the cases with midplane backflow-when the flow in the disk is not towards the star, but away from it! Our PhD student Ruchi Mishra performed-and published-first extensive study of such solutions. Each dot in a graph below is a many weeks simulation… Lots of work, but it pays off!

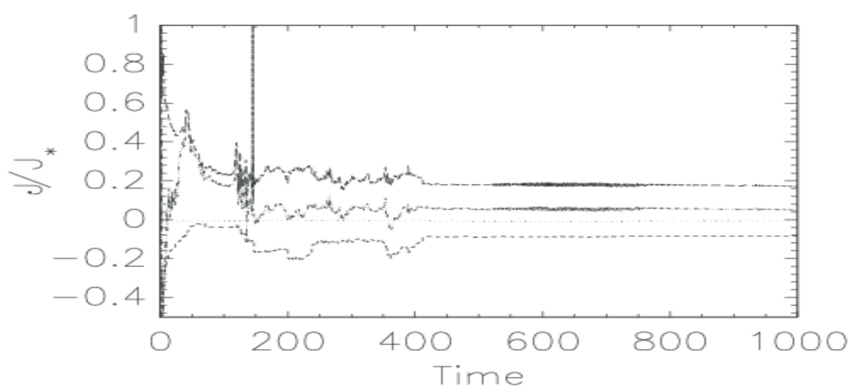


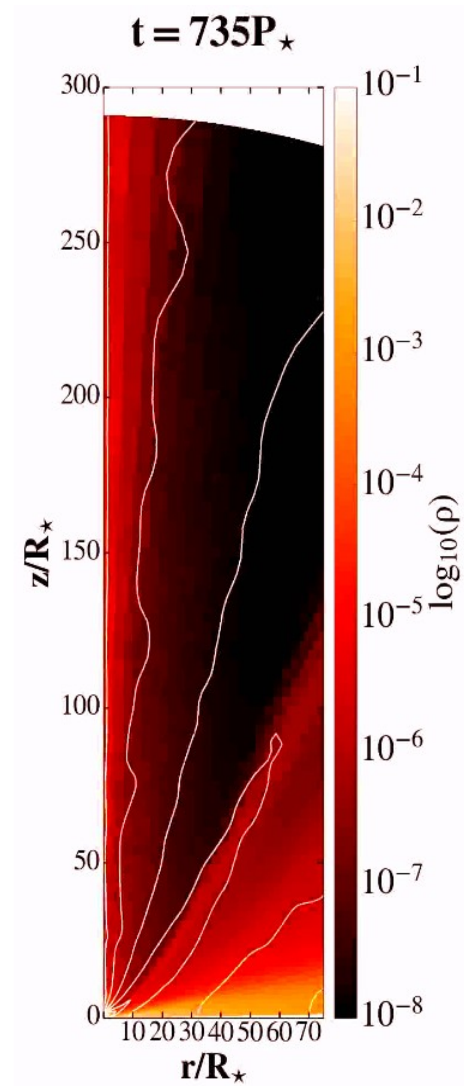


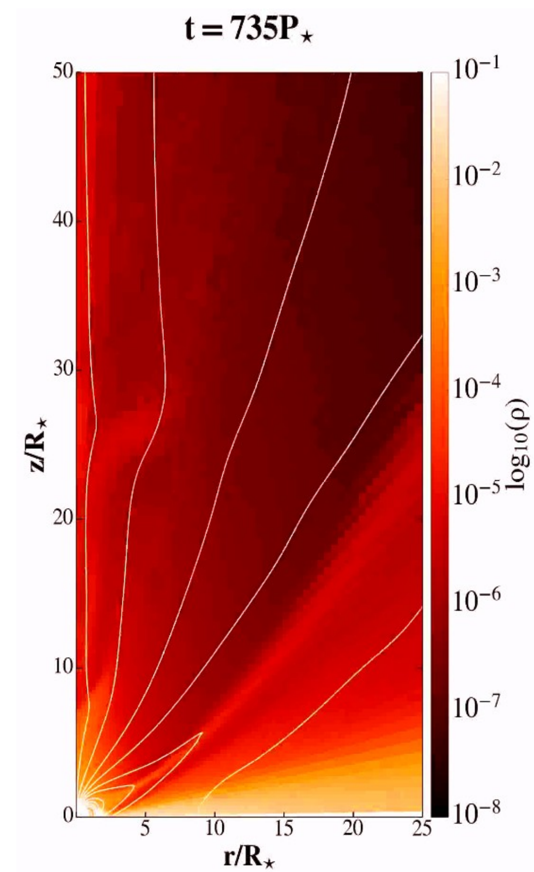
The jet launching

- With a summer student Aleksandra Kotek we made initial study of the axial outflow launching in the simulations-she later defended her Bachelor and Master thesis at the Warsaw University with the results from this work.
- Below are her results with analysis of the magnetospheric jet launching "machinery". Here it was interesting that a stable outflow established only after few hundreds of stellar rotations, so she had to perform much longer simulations than my usual hundred stellar rotations.





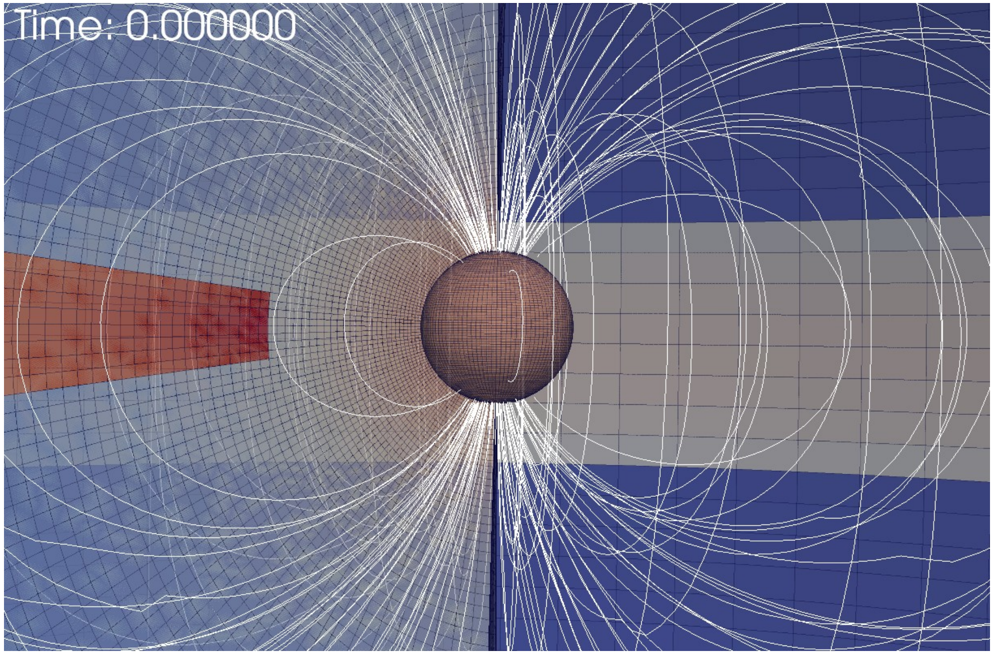


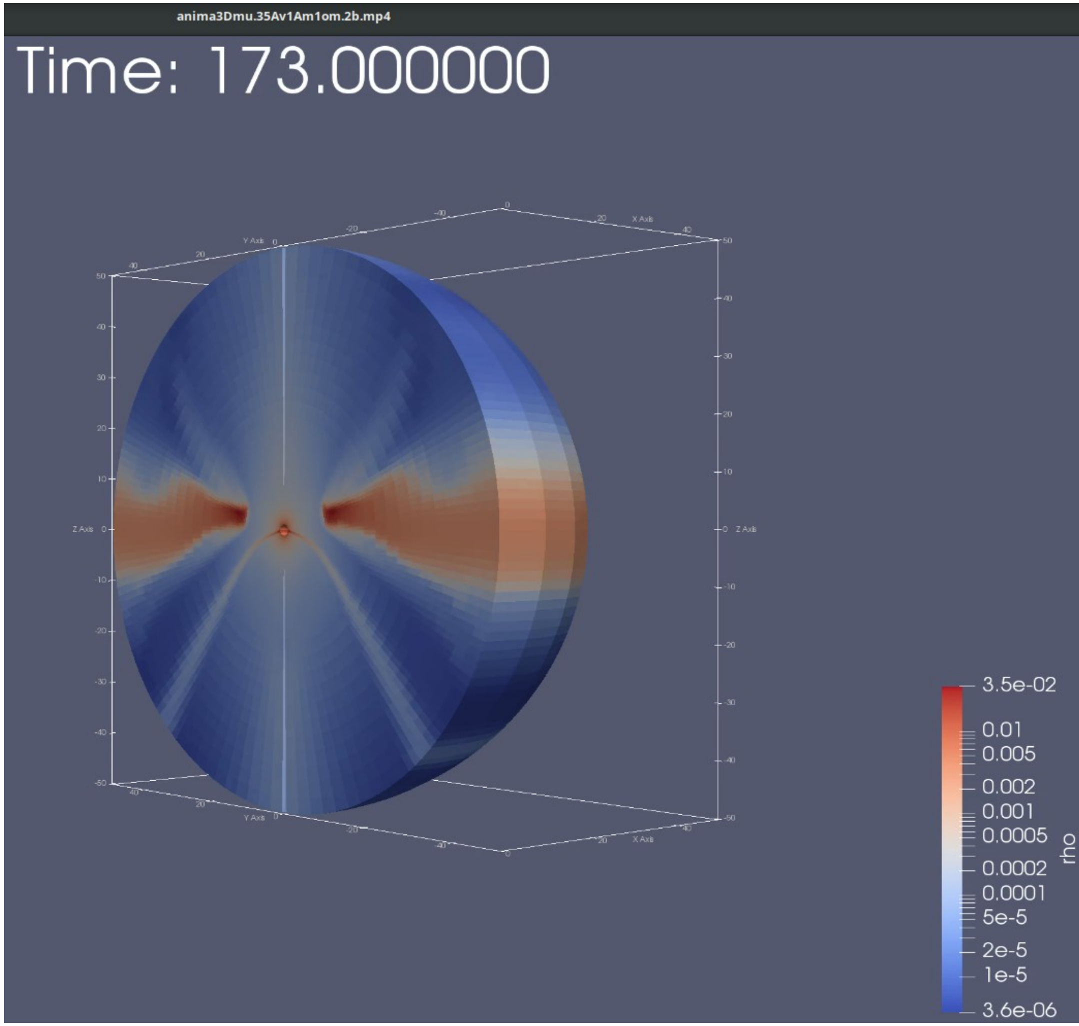


Zoom into the launching region.

3D simulations, cases where magnetic field dipole is aligned/misaligned with stellar rotation axis

- The magnetic field can be aligned with the rotation axis or misaligned, as in the case of pulsars. This is still an active field of research, not many such simulations are available.
- I show a zoom into the vicinity of the star at T=0 and at a later time.





Summer students in our group

- I worked with more than 20 Summer students during the last almost two descades in Taipei and Warsaw.
- Projects were mostly based on a work with PLUTO code, to give the starting experience in MHD numerical simulations. Some former projects with PLUTO:

  – magnetospheric star-disk interaction with non-dipolar stellar magnetic fields

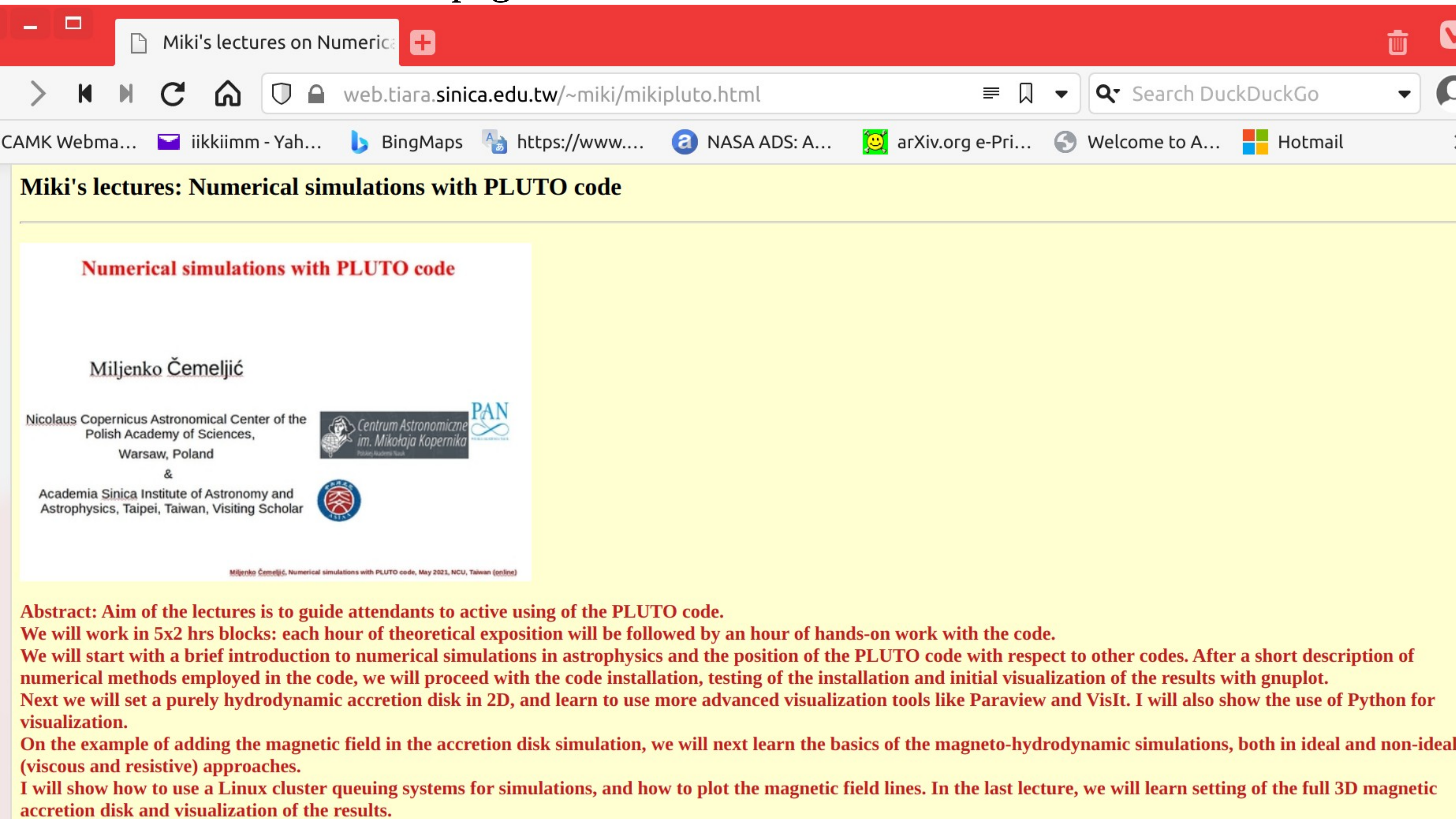
  – thin accretion disk around a black hole

  – star-planet magnetospheric interaction, auroras on exoplanets

- I made a point in publishing the research with Summer students, as their first publication. When possible, we send them to a conference to present results and publish in Proceedings publications-as first authors.

Lectures “Introduction to PLUTO code”

To ease the work for students, I prepared lectures to introduce them to simulations- from scratch. PLUTO is well documented and public, it is a good starting point. In few hrs lectures, depending on a level, a student is brought to active working with the code. Visit the webpage below:



Miki's lectures: Numerical simulations with PLUTO code

Numerical simulations with PLUTO code

Miljenko Čemeljić

Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Warsaw, Poland
&
Academia Sinica Institute of Astronomy and Astrophysics, Taipei, Taiwan, Visiting Scholar

Centrum Astronomiczne im. Mikołaja Kopernika

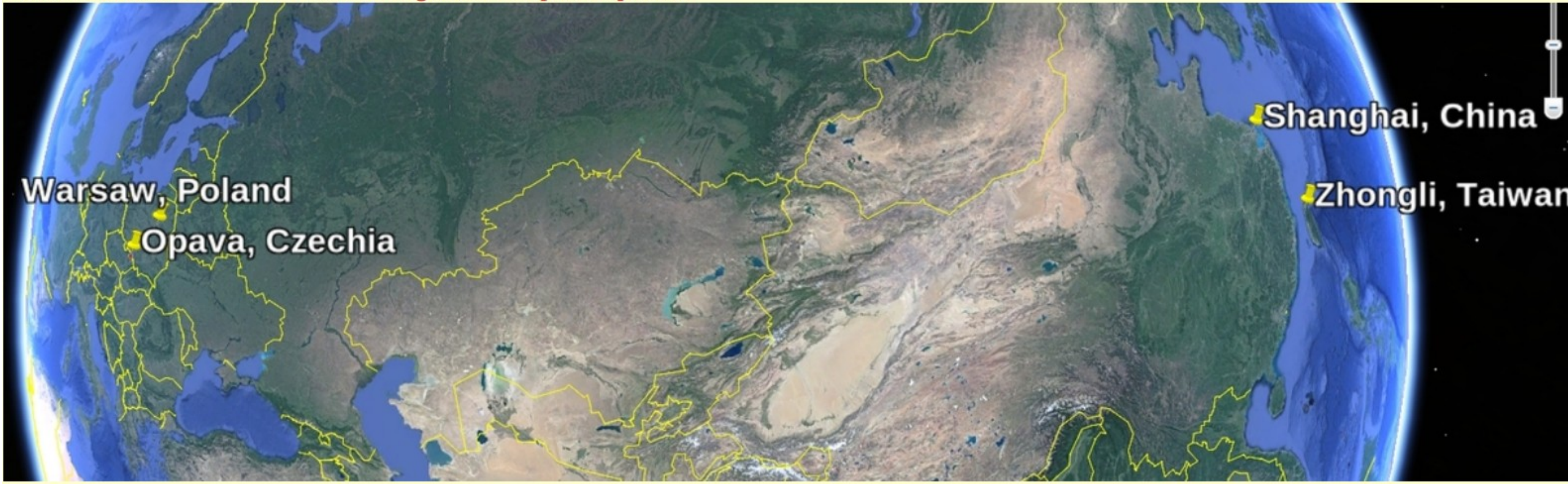
PAN

Miljenko Čemeljić, Numerical simulations with PLUTO code, May 2021, NCU, Taiwan (online)

Abstract: Aim of the lectures is to guide attendants to active using of the PLUTO code.
We will work in 5x2 hrs blocks: each hour of theoretical exposition will be followed by an hour of hands-on work with the code.
We will start with a brief introduction to numerical simulations in astrophysics and the position of the PLUTO code with respect to other codes. After a short description of numerical methods employed in the code, we will proceed with the code installation, testing of the installation and initial visualization of the results with gnuplot.
Next we will set a purely hydrodynamic accretion disk in 2D, and learn to use more advanced visualization tools like Paraview and VisIt. I will also show the use of Python for visualization.
On the example of adding the magnetic field in the accretion disk simulation, we will next learn the basics of the magneto-hydrodynamic simulations, both in ideal and non-ideal (viscous and resistive) approaches.
I will show how to use a Linux cluster queuing systems for simulations, and how to plot the magnetic field lines. In the last lecture, we will learn setting of the full 3D magnetic accretion disk and visualization of the results.

Lectures “Introduction to PLUTO code”

Until now, Miki's PLUTO lectures were given in the pinned places:

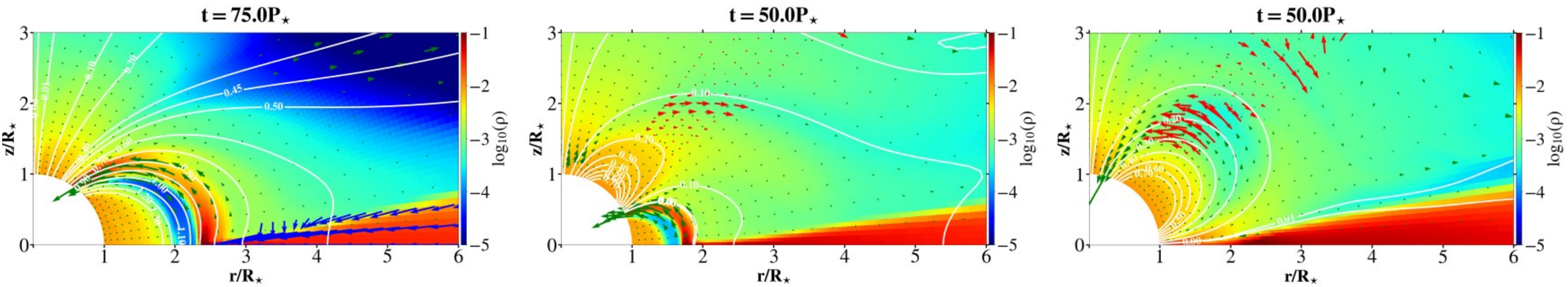


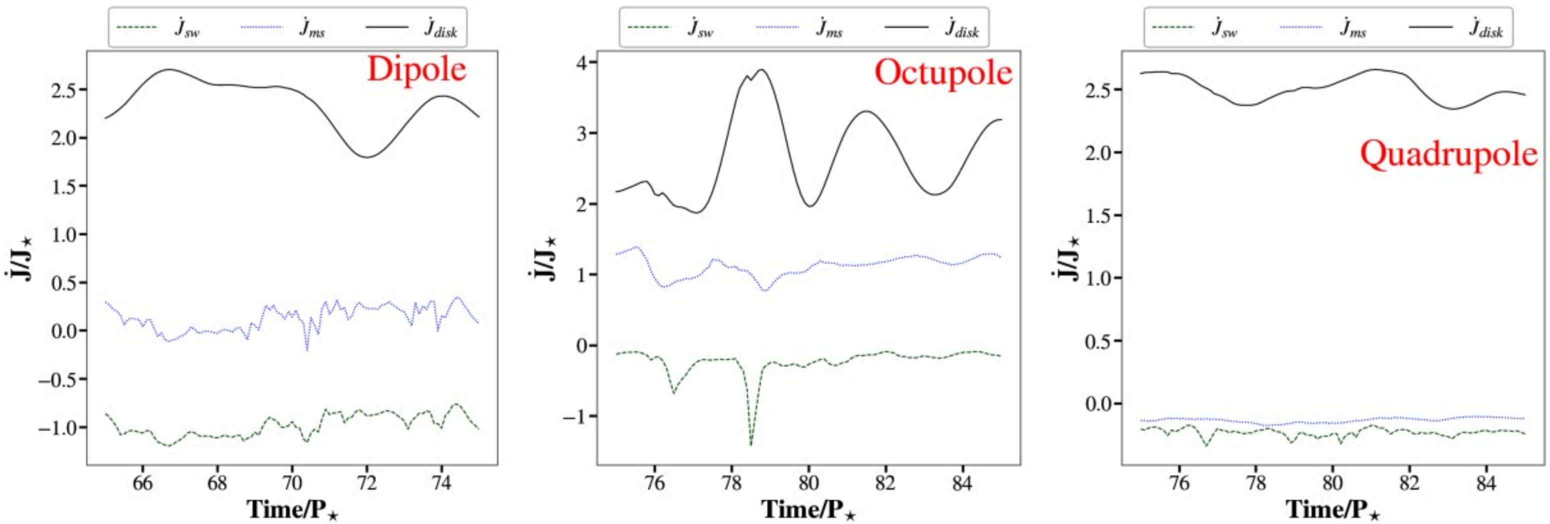
-In 2020 in Shanghai, 2021 year in Warsaw, Zhongli and Opava for groups, elsewhere for individuals. I provide such lectures wherever people find it useful.

-It is good also for starting collaborations in different kinds of problems.

Non-dipolar stelar fields

Magnetospheric interaction with non-dipole stellar fields was done by a student F. Cieciuch from UW-he also presented it as a poster at 40th Polish Astronomical Society meeting, for which he also prepared the Proceedings article. This was his first publication. Some of his results are shown below: geometry of the solutions and torques exerted on the star by different components in the flow. This kind of results is still rare.

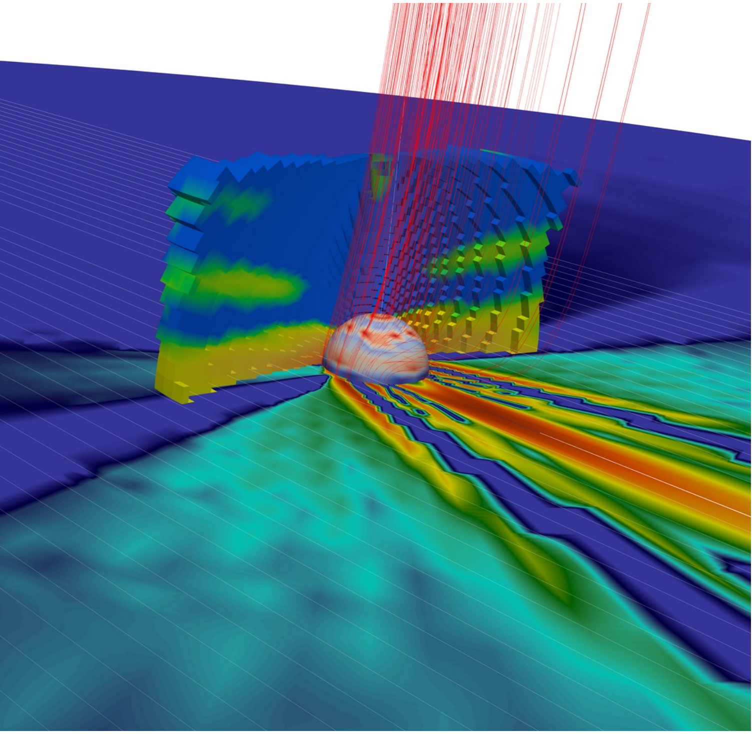


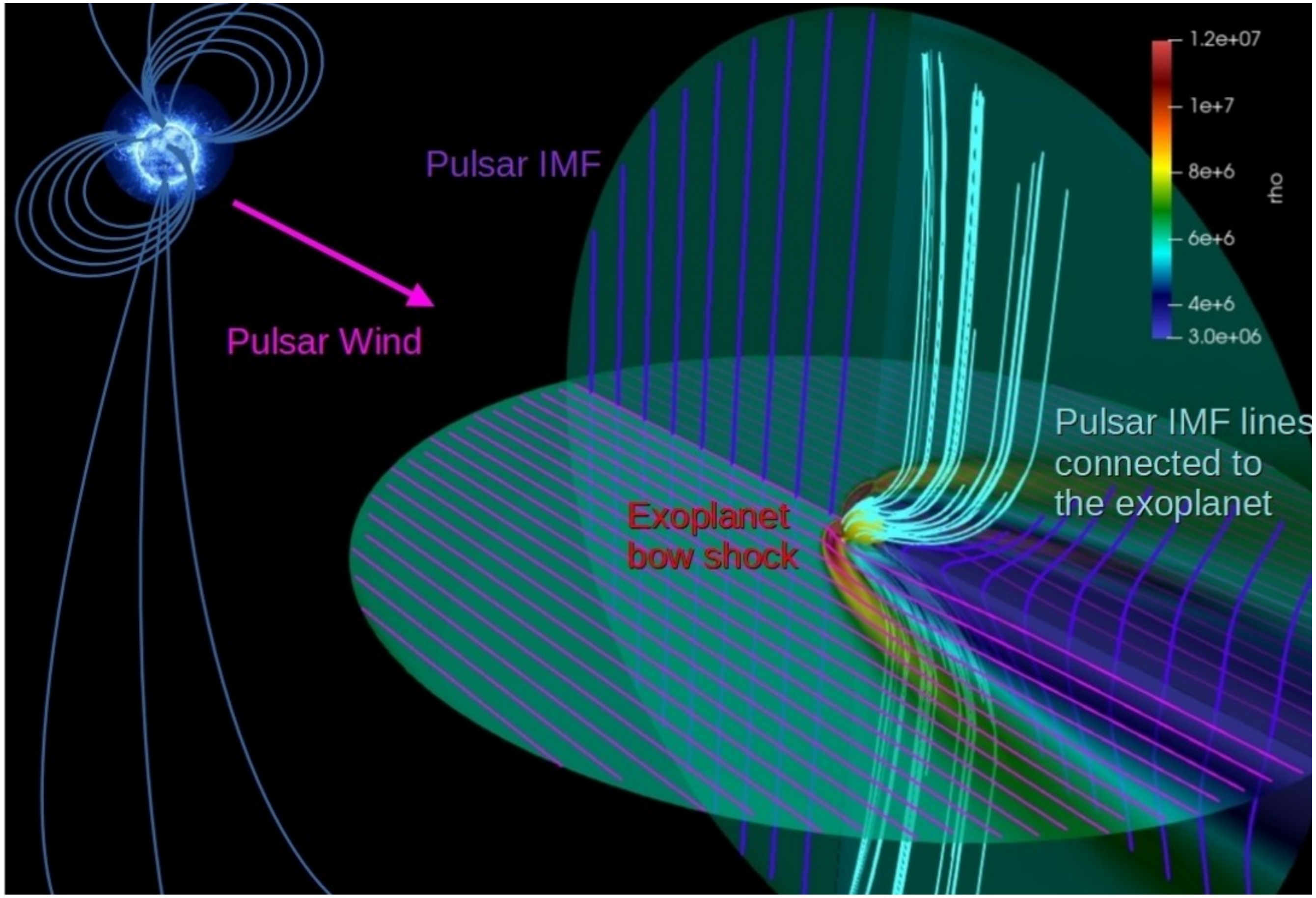


Star-planet interactions, exoplanets

In an international collaboration with J. Varela from Spain, during the last two summers we also went into simulations of the star-planet interactions, for exoplanet studies. Our recent publication on auroras on pulsar planets is the first work on the topic, where we put a direct challenge to the observers.

You are most welcome to join us!





Pulsar-planet system in our simulation with conducting planet surface. T

CAMK small radio telescope

Software defined radio (SDR) revived amateur radio astronomy.

- A good learning device, perfect public engagement tool, good for student projects.
- In CAMK, I started the initiative to build and operate a small radio telescope.
- The first result is here, from CAMK workshop. Learning potential is infinite. **Students are welcome!**