Numerical simulations in accreting systems with Pluto and Koral codes

Miljenko Čemeljić

with

W. Kluźniak,

R. Mishra, F. Kayanikhoo, A. Karakonstantakis

Nicolaus Copernicus Astronomical Center, PAN

Warsaw

&

ASIAA Visiting Scholar, Taipei, Taiwan

PAN
POLSKA AKADEMIA NAUK

Centrum Astronomiczne
im. Mikołaja Kopernika
Polskiej Akademii Nauk

中央研究院
ASIAA

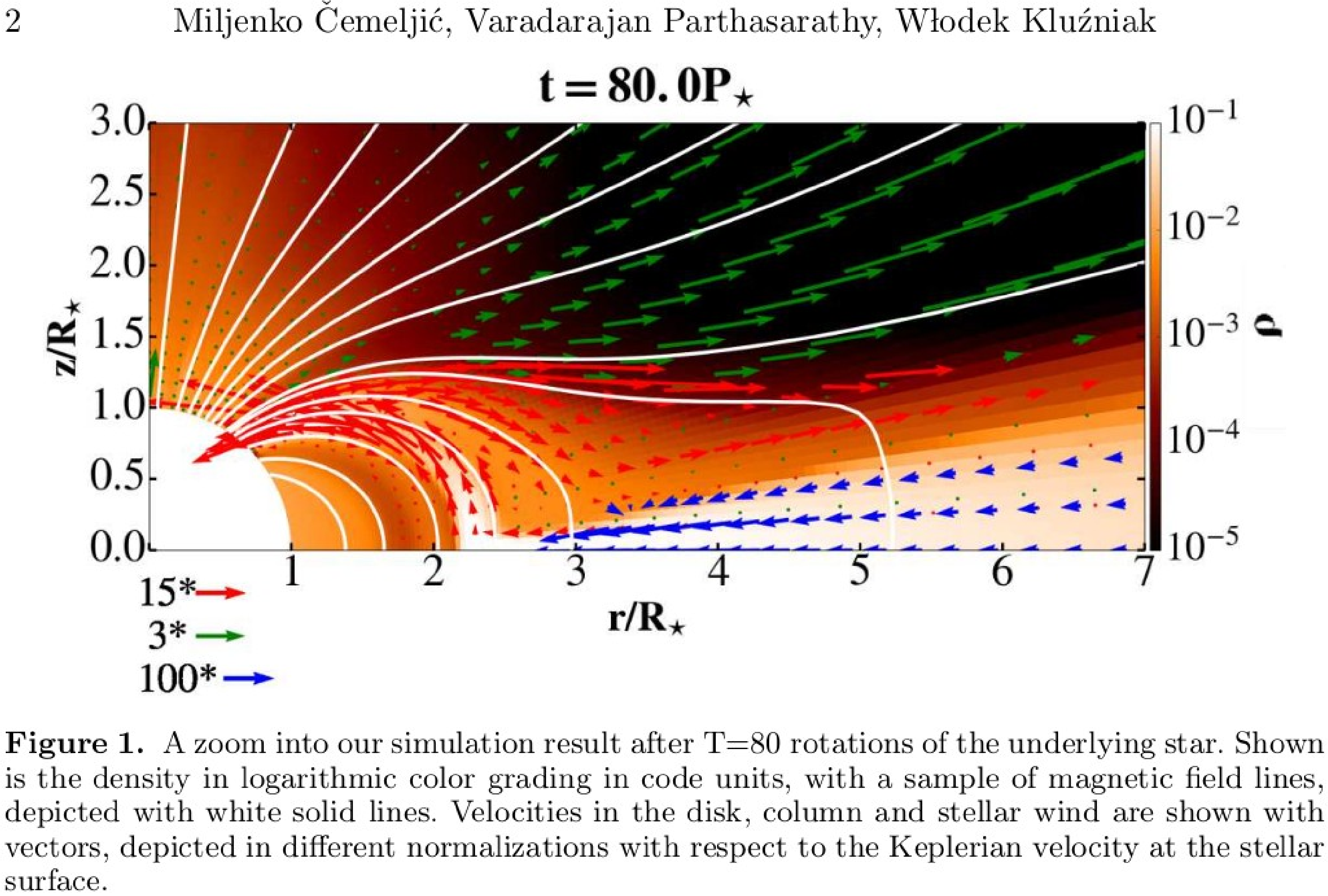
Outline

- Star-disk magnetospheric interaction with PLUTO code
- Various works with PLUTO and KORAL code
- PhD students and Summer students
- Potential project opportunities

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:

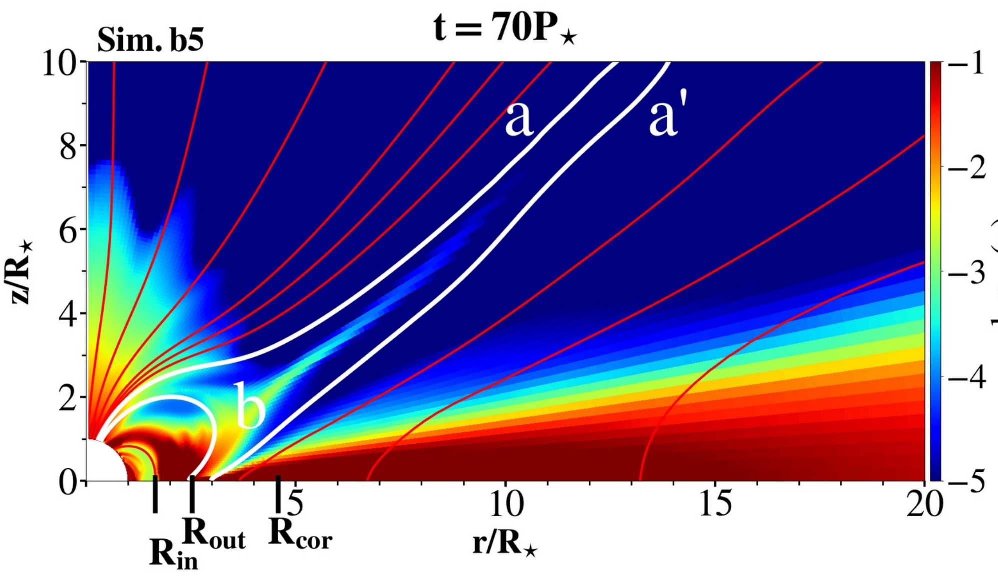


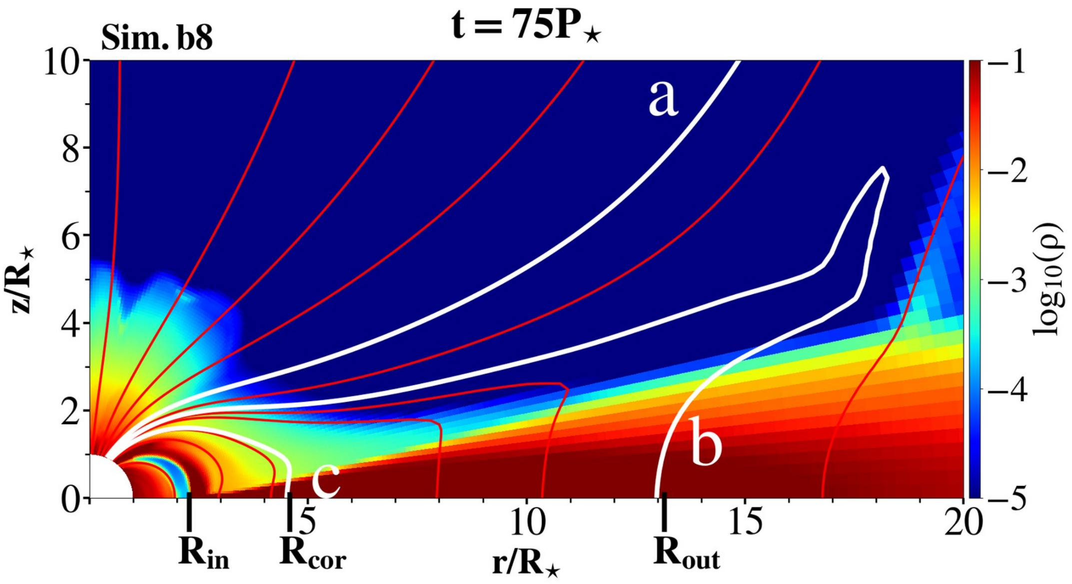
2 Miljenko Čemeljić, Varadarajan Parthasarathy, Włodek Kluźniak

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:

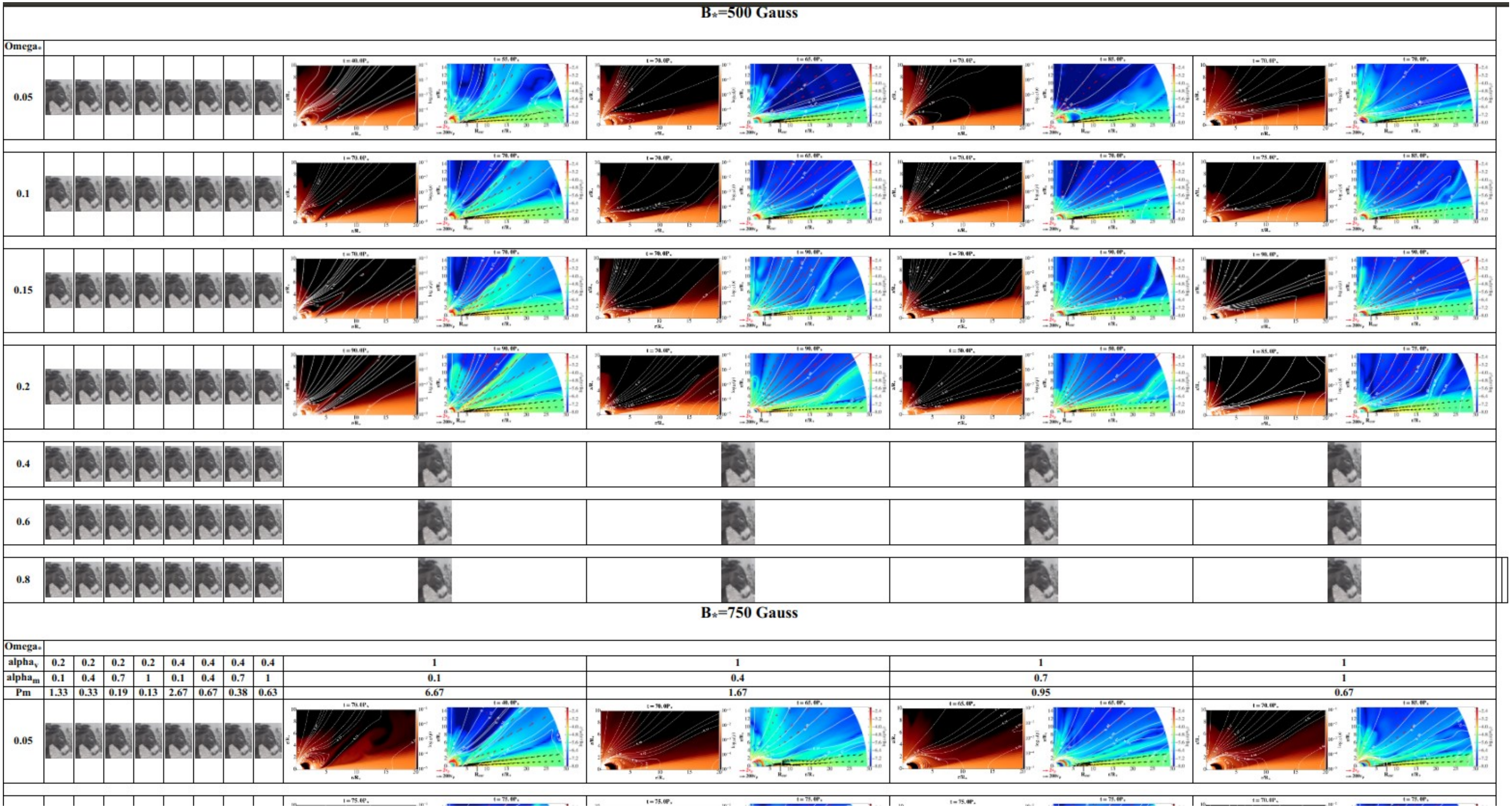




Depending on the position of corotation radius R_{cor} (where the disk corotates with the stellar surface at the equator) and the furthest anchor point of the stellar magnetic field in the disk R_{out}, the exerted torque on the star is spinning the star up-or down.

“Atlas” of results

In “Atlas” paper I performed a systematic study for slowly rotating star (up to 20% of the star breakup velocity). Faster rotating cases are further investigated. We are also interested in a similar study with other geometries of magnetic field—initial study is already done, as I will show later! Below is shown part of our solutions:



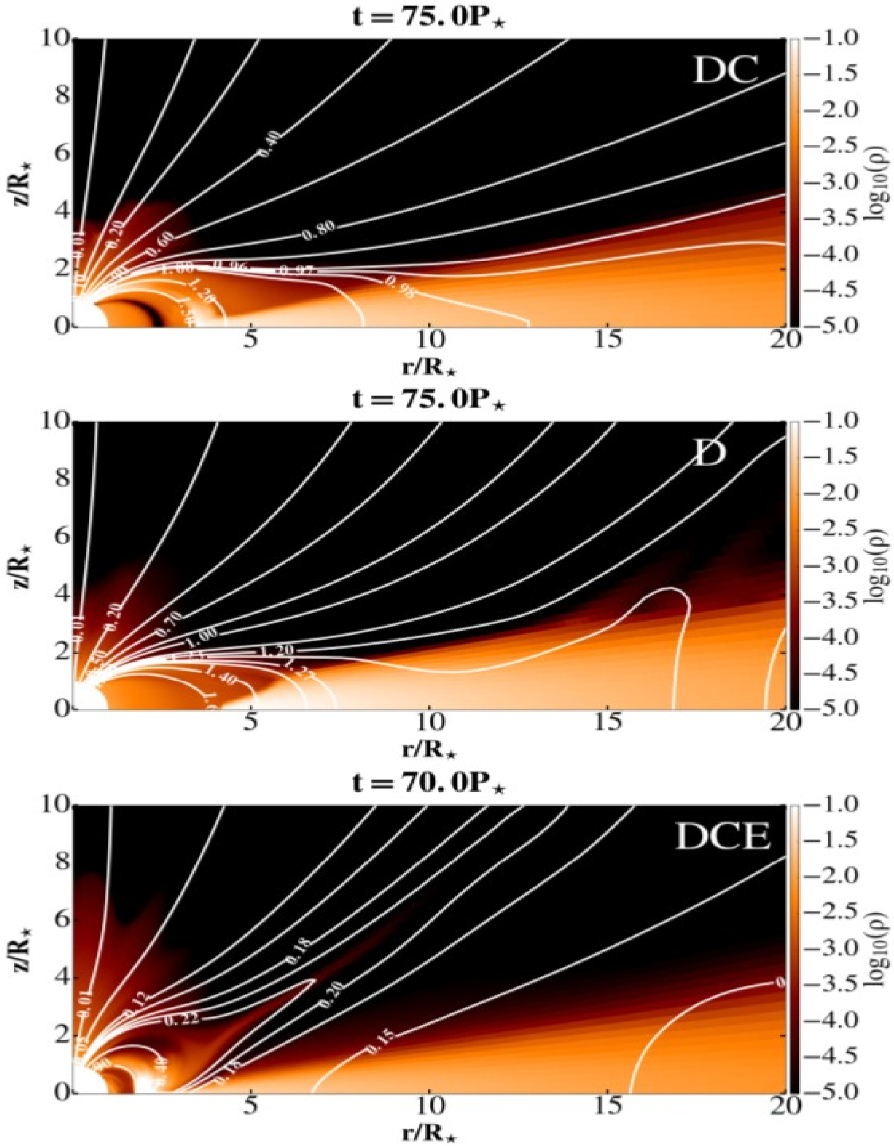
B*=500 Gauss

Omega*												
0.05												
0.1												
0.15												
0.2												
0.4												
0.6												
0.8												

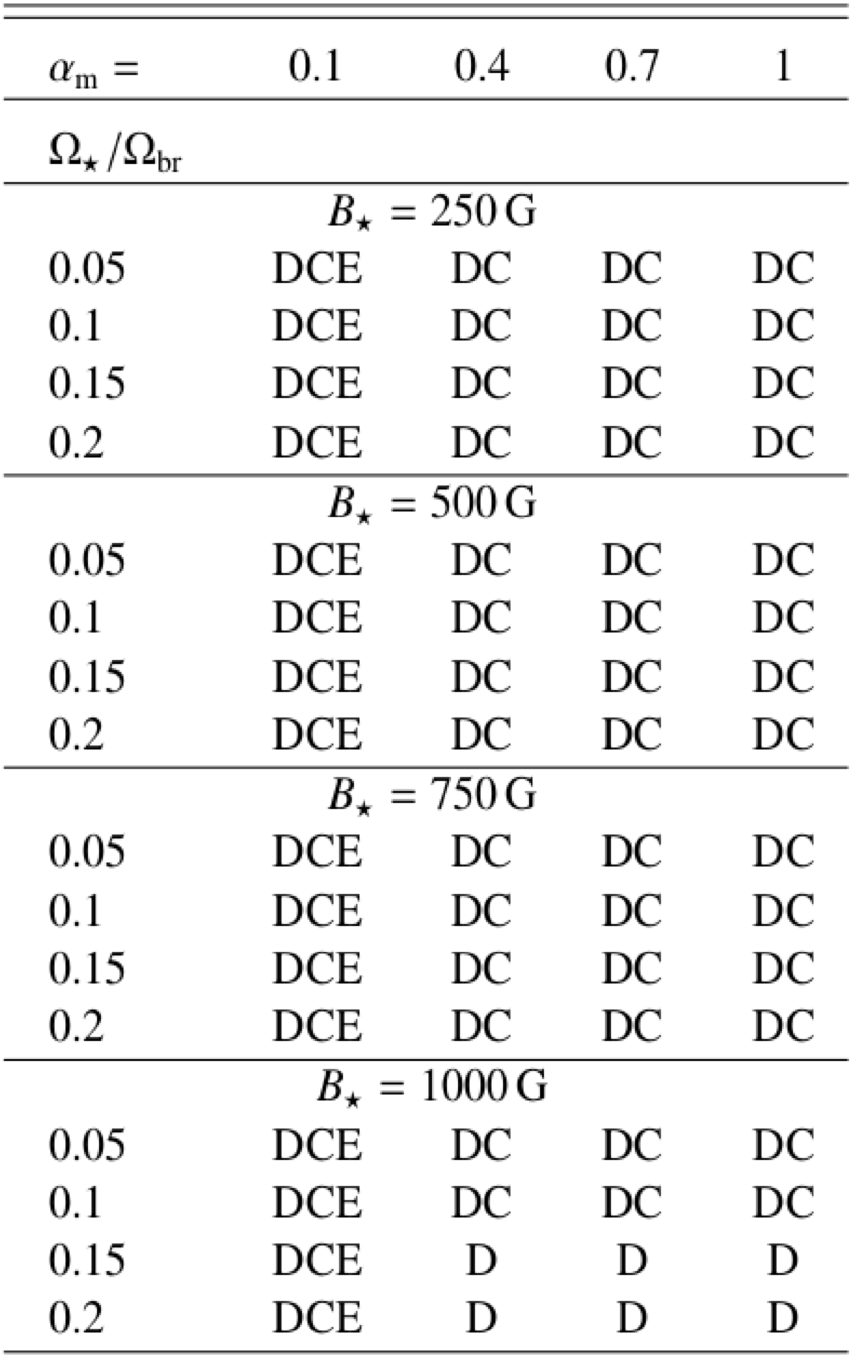
B*=750 Gauss

Omega*												
α_v	0.2	0.2	0.2	0.2	0.4	0.4	0.4	0.4	1	1	1	1
α_m	0.1	0.4	0.7	1	0.1	0.4	0.7	1	0.1	0.4	0.7	1
Pm	1.33	0.33	0.19	0.13	2.67	0.67	0.38	0.63	6.67	1.67	0.95	0.67
0.05												

Configurations in “Atlas” solutions for slowly rotating stars



Three different cases of geometry in the results. In the top and middle panels are shown B_*=1 kG and the resistivity α_m=1, in the cases with Ω_s=0.1 (top panel) and Ωs=0.15 (middle panel). Faster stellar rotation prevents the accretion column formation. In the bottom panel is shown the third case, with B=0.5kG, resistivity α_m=0.1 and Ω_s=0.1, where a conical outflow is formed.



α_m =	0.1	0.4	0.7	1
$\Omega_\star / \Omega_{br}$				
	$B_\star$ = 250 G			
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
	$B_\star$ = 500 G			
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
	$B_\star$ = 750 G			
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
	$B_\star$ = 1000 G			
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	D	D	D
0.2	DCE	D	D	D

Trends in “Atlas” results

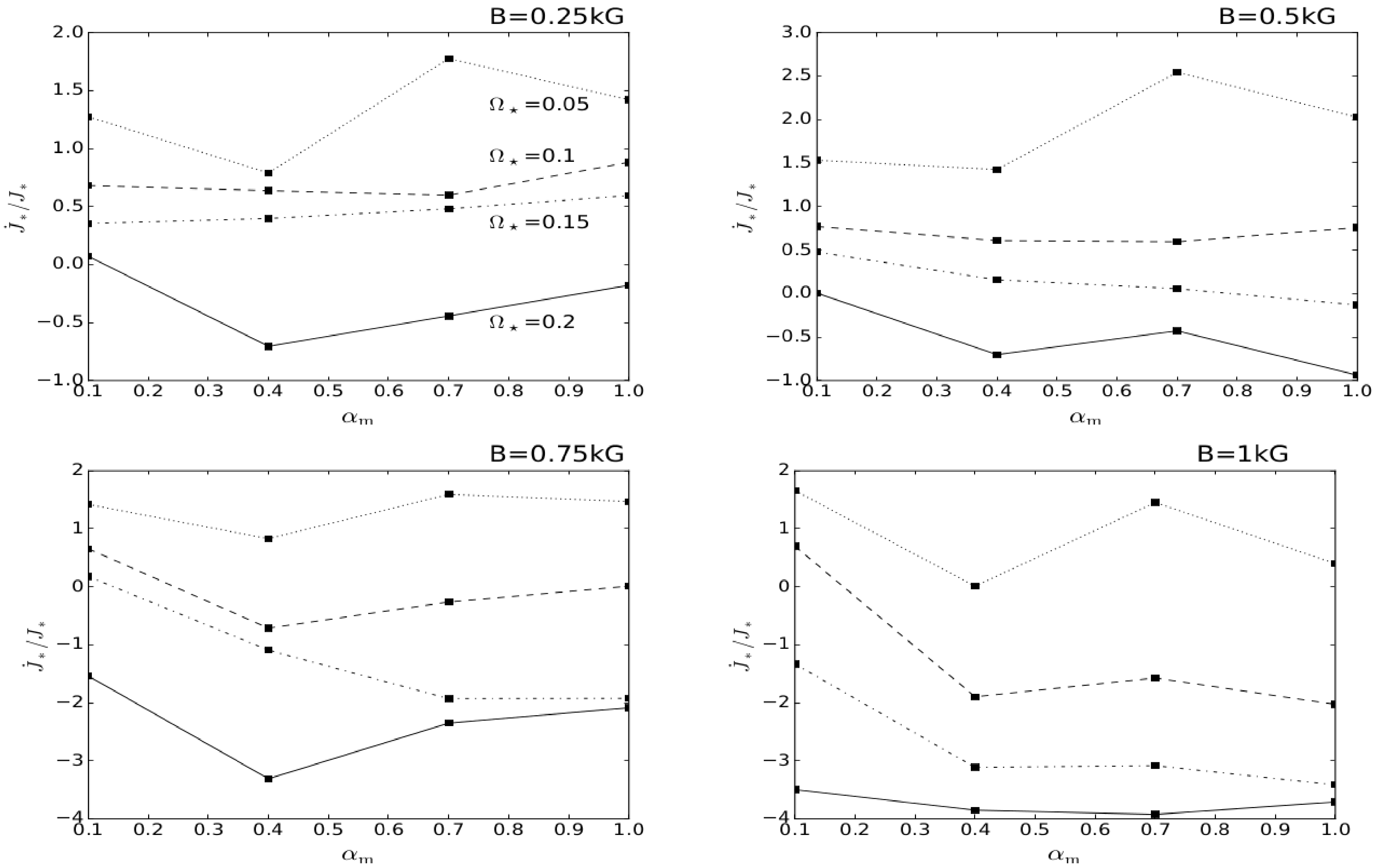
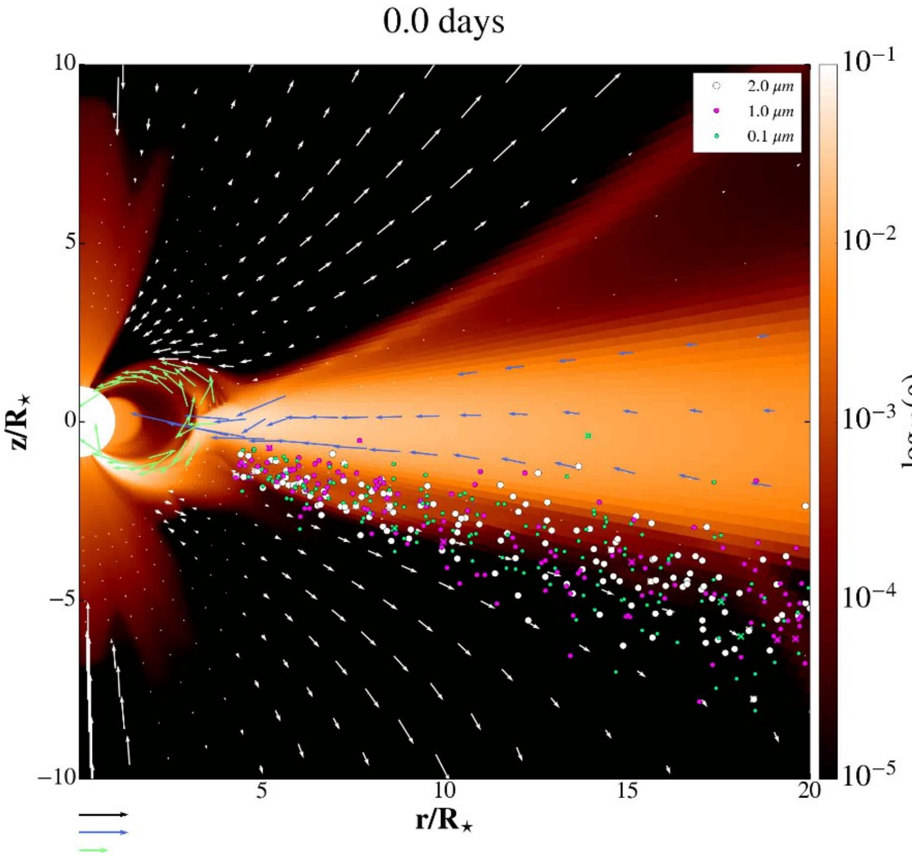
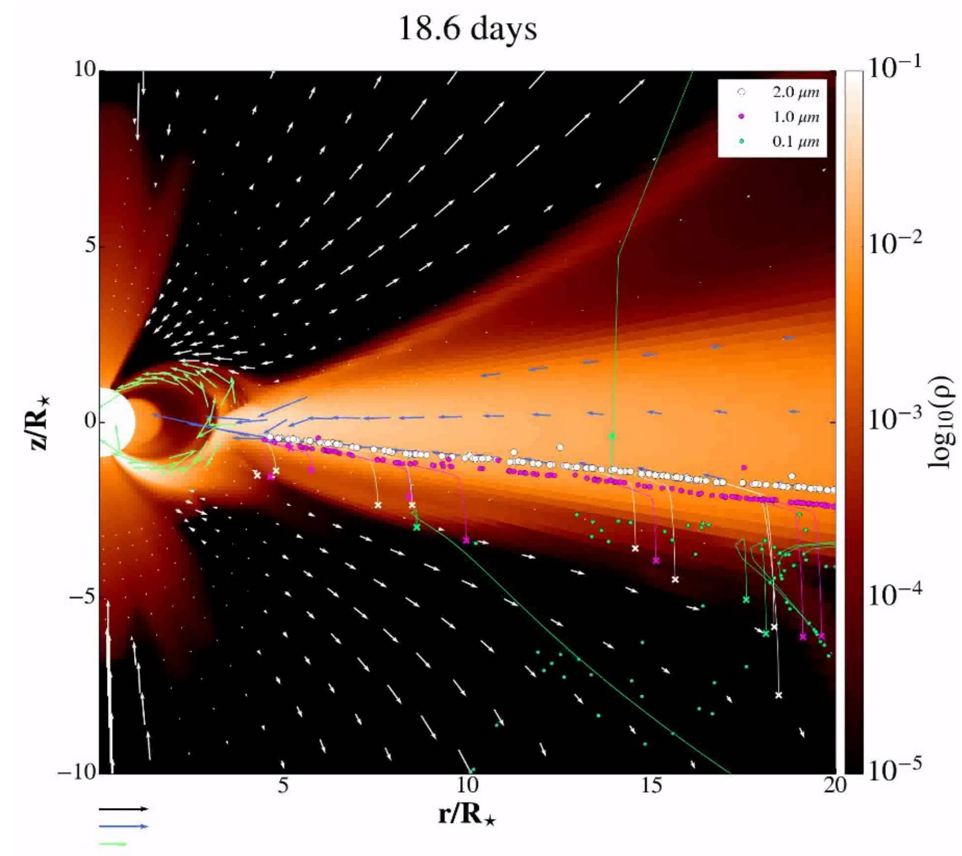


Fig. 4. Average angular momentum flux transported onto the stellar surface by the matter in-falling from the disk onto the star through the accretion column. Each panel shows a set of solutions with one stellar magnetic field strength and varying stellar rotation rate and resistivity. Results with $\Omega_\star/\Omega_{\rm br} = 0.05$ (dotted), 0.1 (dashed), 0.15 (dash-dot-dotted), and 0.2 (solid) are shown in units of stellar angular momentum $J_\star = k^2 M_\star R_\star^2 \Omega_\star$ (with $k^2 = 0.2$ for the typical normalized gyration radius of a fully convective star). A positive flux spins the star up, a negative flux slows it down. With the increase in stellar rotation rate, spin-up of the star by the infalling matter decreases and eventually switches to spin-down.

“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”).





Dust settling in the disk

514 *D. Vinković and M. Čemeljić*

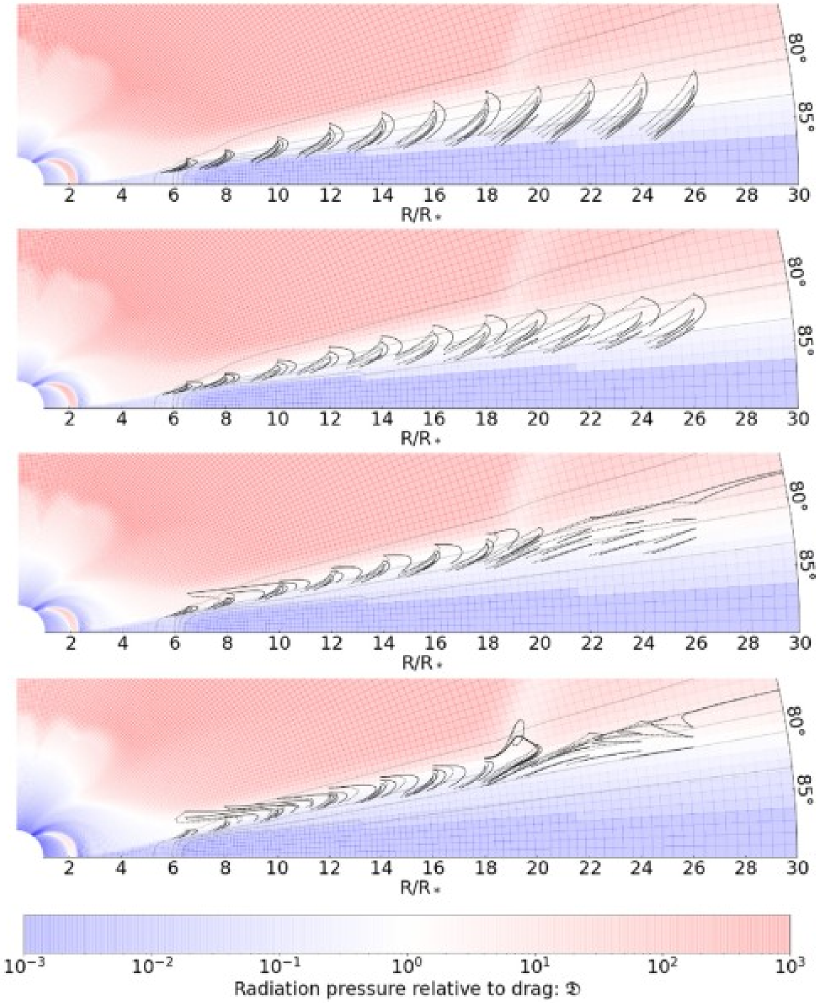


Figure 5. Trajectories of dust grains at different locations over the disc surface in the outflow model A. See Fig. 2 for a view of the gas velocity flow. The colour map shows the strength of radiation pressure relative to the gas drag ($\mathfrak{D}$, equation 34). The thin solid lines are contours of the optical depth attenuation factor ε described by equation (16), with values set to 0.1, 0.4, 0.7, and 0.99 (the maximum is 1.0 in regions without dust). The thick solid lines are paths of dust particles with the radiation pressure force included into the dynamics, while the dotted lines are the same particles with the radiation pressure turned off for comparison. The bulk density of dust grains is 3000 kg m^{-3}, except in the second from the top panel where it is 1000 kg m^{-3}. The grain radius differs between the panels: 2 μm in the top two panels, 0.2 μm in the third panel, and 0.1 μmin the bottom panel. The dust flow is in all cases outward and/or into the disc.

We supply the density, pressure and velocities from our results, and they are used as an input for other code (here "Leluya" by D. Vinković)

- In the proto-planetary disk, it is important to understand how the dust, which is moving inwards, towards the star, is influenced by the radiation pressure from the star-the resulting composition of dust at some radius will depend on the dust properties-here we investigate the dependence on the grain radius.
- Previous models were estimates, without the detailed disk solutions, now we could supply such solutions from our simulations.

Comparison with observations, “hiccups” in light curves

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

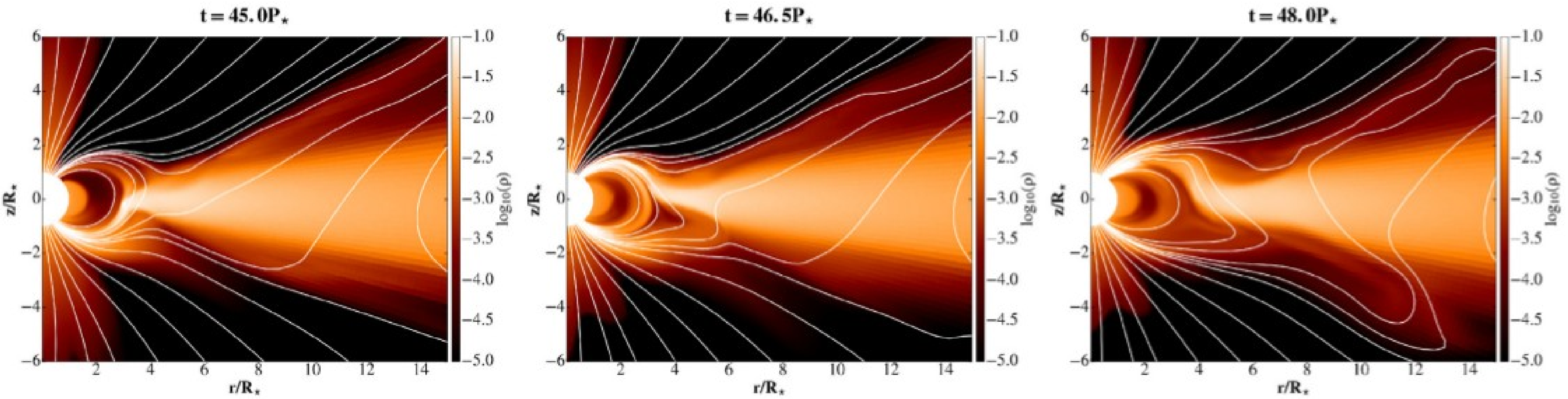


Figure 4. A sequence of snapshots from the results in the interval when switching of the accretion column from the Southern to the Northern hemisphere occurs.

Comparison with observations, “hiccups” in light curves

- Such switching could explain some cases of non-periodicity in the Young Stellar Objects:

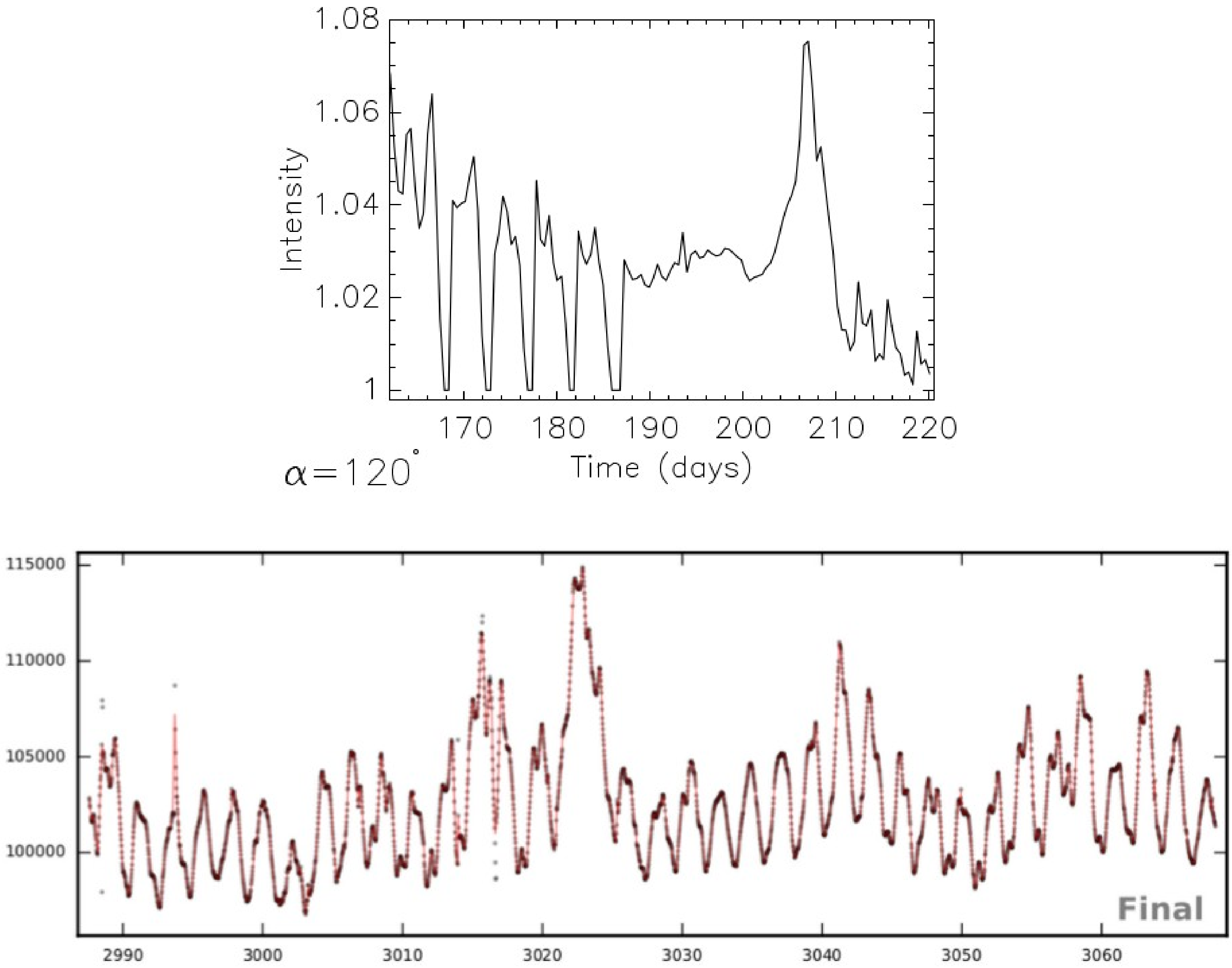
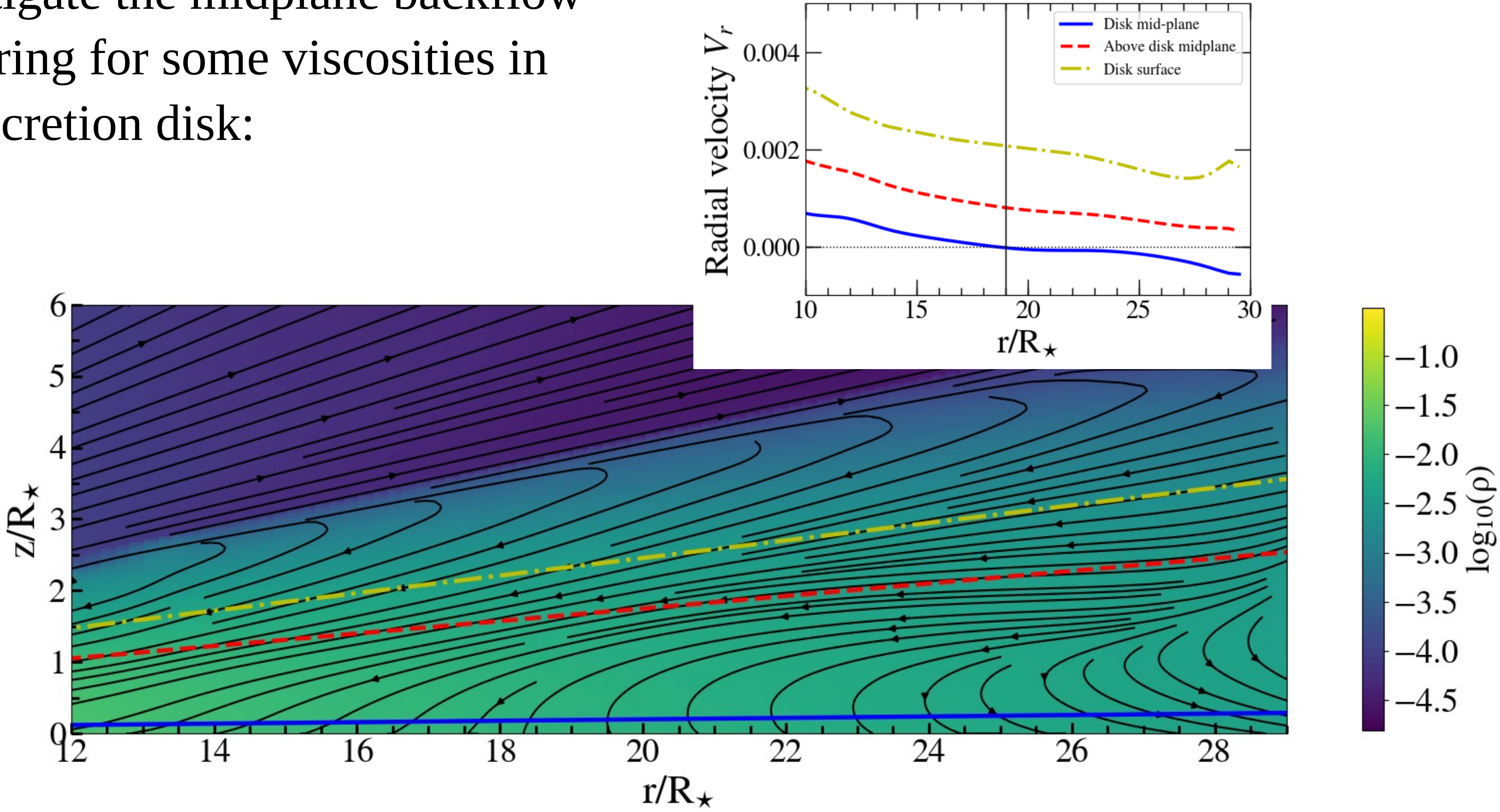


Figure 8. Top panel: intensity in a 3D model made from the longer time sequence than shown in Fig. 7. Shifts in the phase of the observed light (‘hiccups’) occur during the switch of the accretion column from the southern to northern stellar hemisphere between the 190 and 210 d. Bottom panel: light curve 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

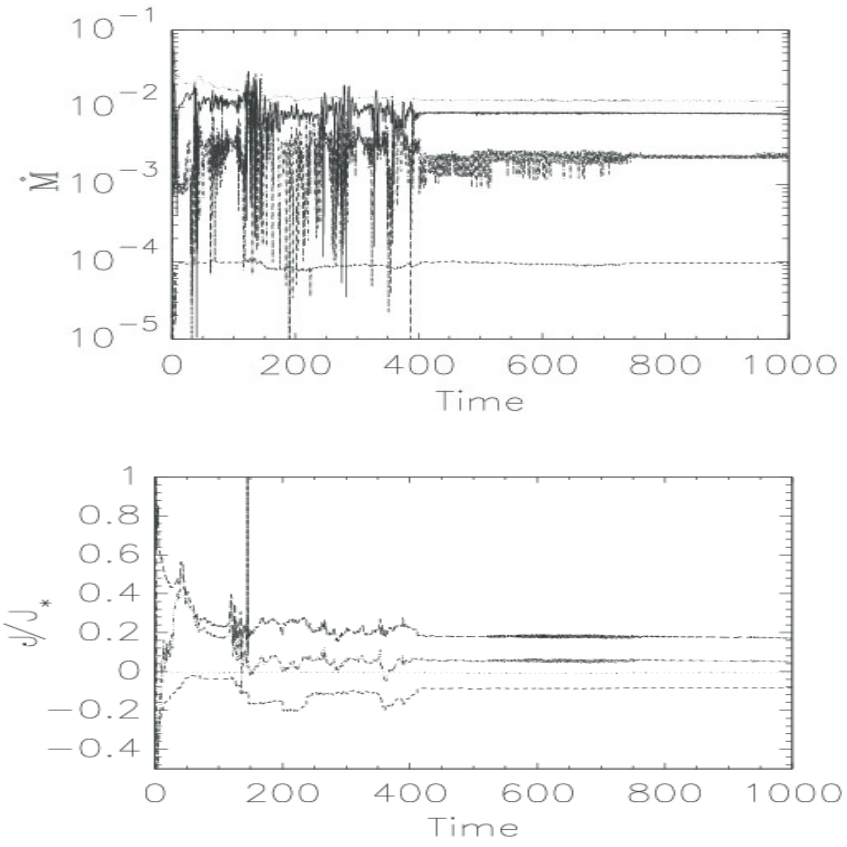
In “Atlas” paper we held the viscosity constant. With PhD student Ruchi Mishra, using similar simulations, but varying the viscosity parameter, we investigate the midplane backflow occurring for some viscosities in the accretion disk:

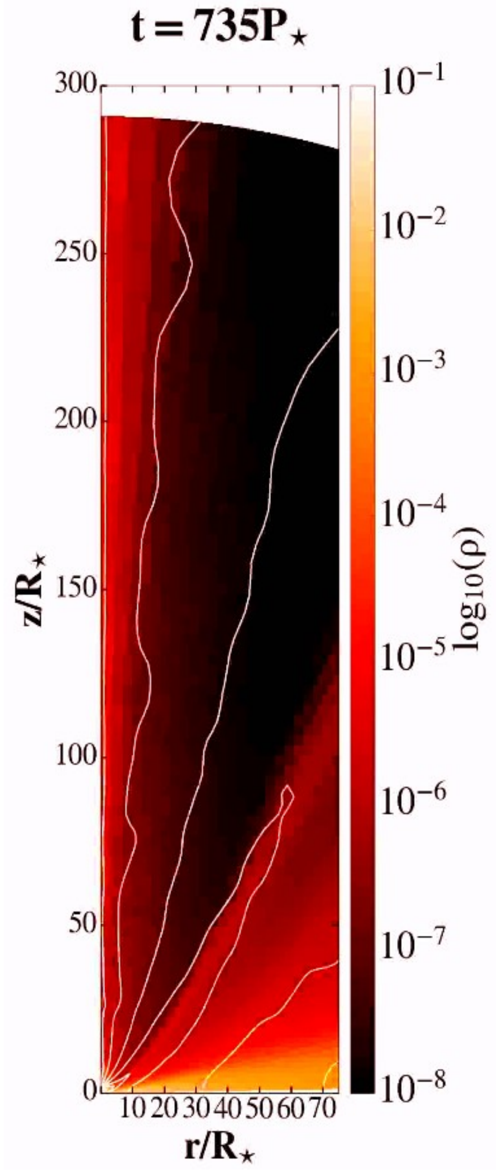


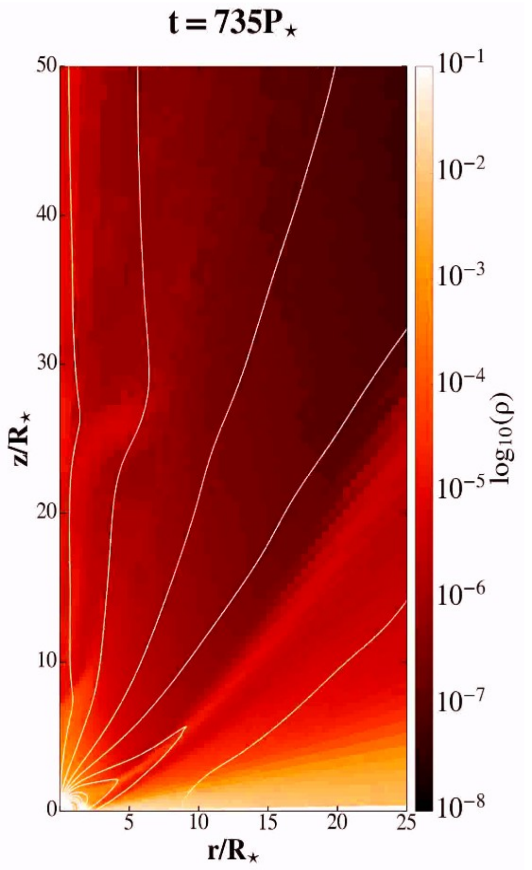
- With PhD student Fatima Kayanikhoo, we compare PLUTO and KORAL results in Orszag-Tang problem in 2D and in 3D, as she already showed you. Ruchi, Fatima and Angelos also work on KORAL simulations, PLUTO was just the starting point for them.

The jet launching

- In a part of the parameter space, there is a continuous launching of axial jet from the star-disk magnetosphere. In my simulations, it showed that one has to wait until few hundreds of rotations of the star. With a summer student Aleksandra Kotek we made initial study.
- 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).



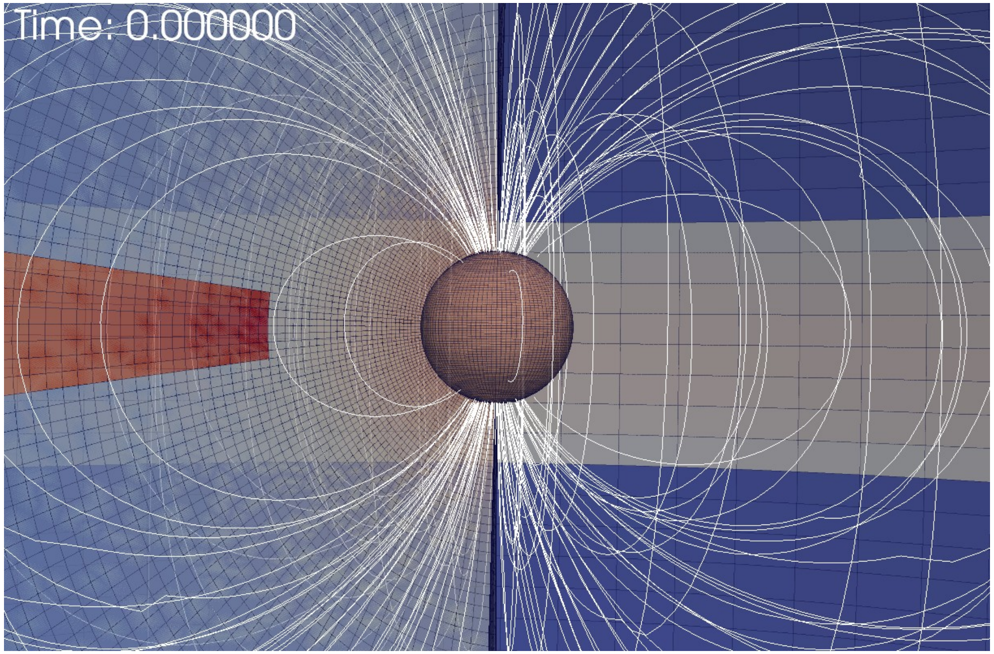


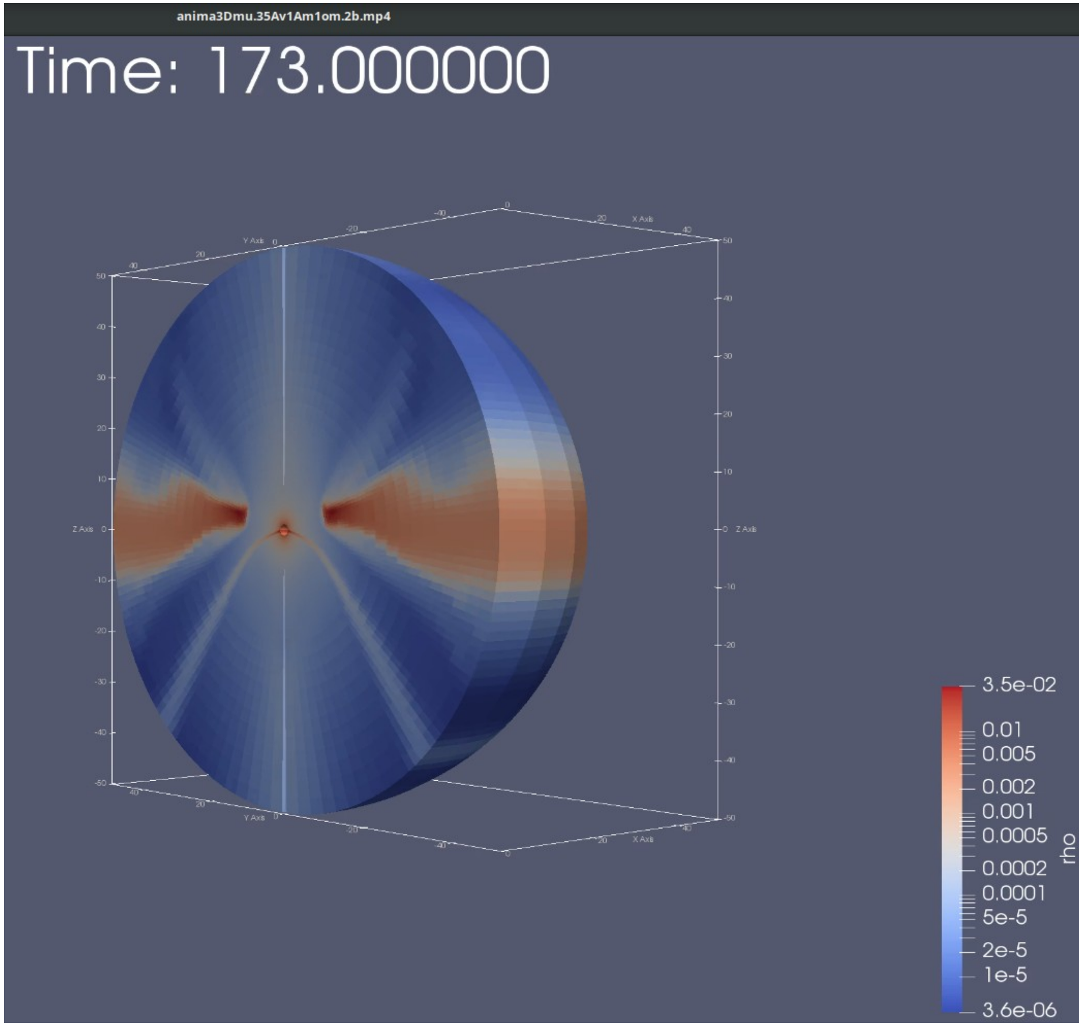


Zoom into the launching region.

3D simulations, case with magnetic field aligned with rotation

- The first step here is to perform the axisymmetric 3D simulation. I use the spherical grid. The magnetic field in this case is aligned with the rotation axis.
- Zoom into the vicinity of the star=inner boundary condition at T=0 and at T=173





Athena++ code, GRMHD simulations, initial conditions

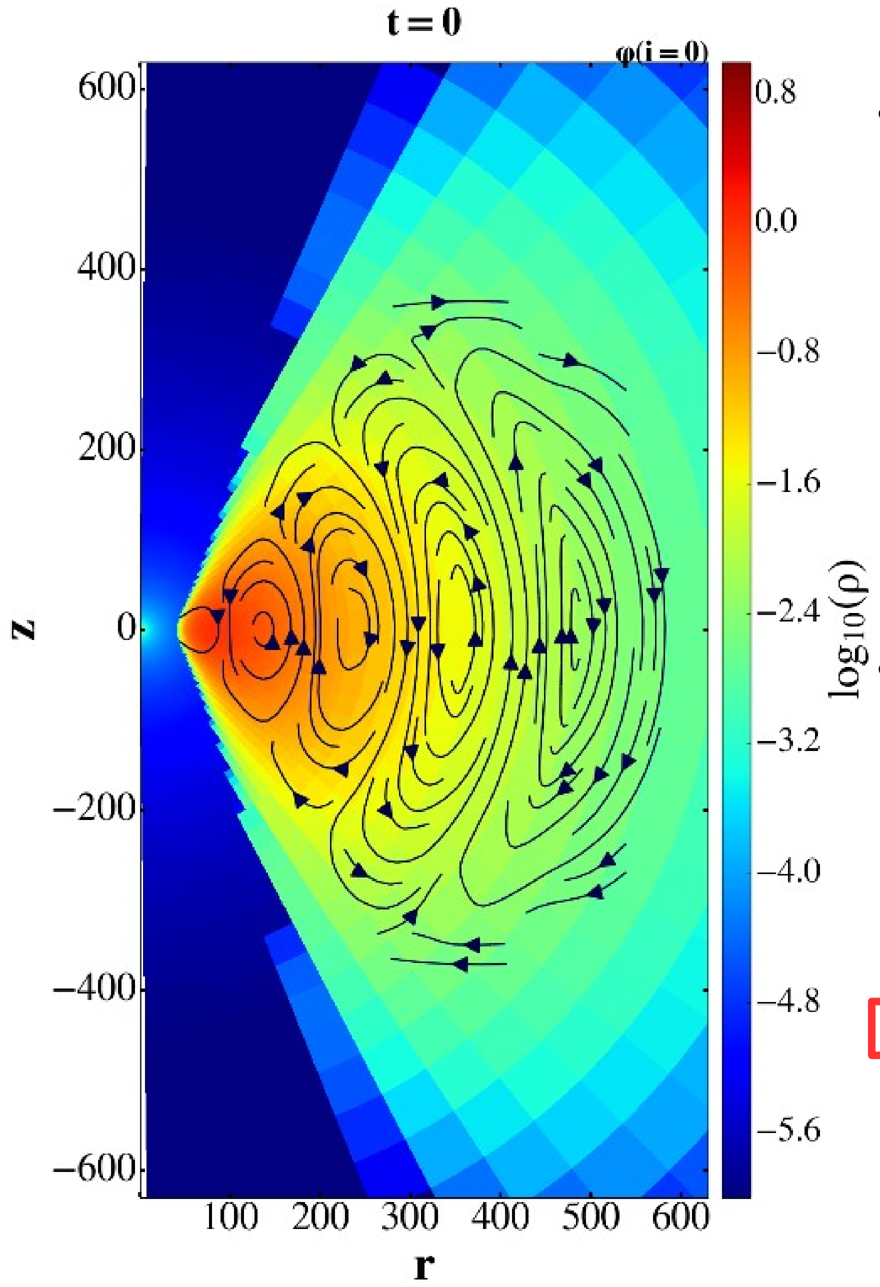


Fig. 1. Density in a logarithmic colour grading and a poloidal magnetic field contained inside the torus around a black hole in our SANE setup. Loops of poloidal magnetic field are shown with solid lines, with arrows showing the clockwise and counter-clockwise direction of the initial loops of magnetic field.

- In Shanghai Observatory in 2020 I worked, during the scholarship obtained from the Chinese Academy of Sciences, with the results their group had from the Athena++ code simulations in ideal MHD in General Relativity. We investigated the disk around a supermassive black hole—one initial setup is shown in the left Figure.
- In CAMK, we do similar simulations with KORAL code, with which we can introduce the radiative transfer in the simulations.

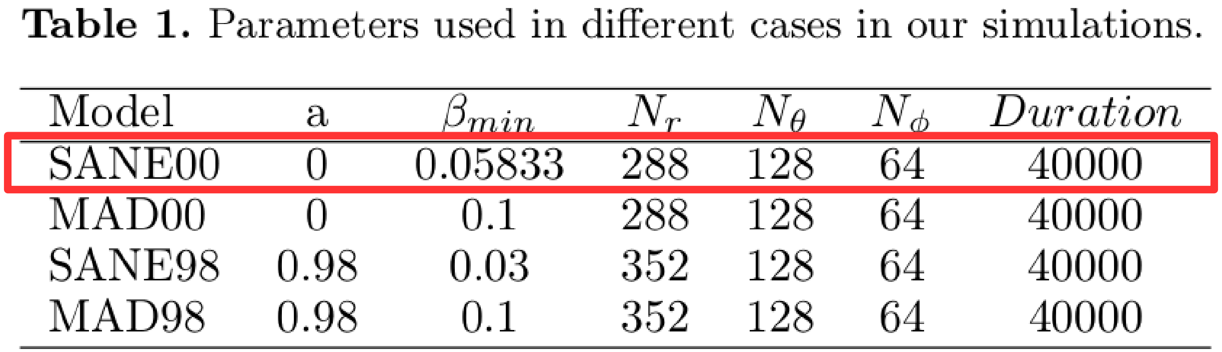
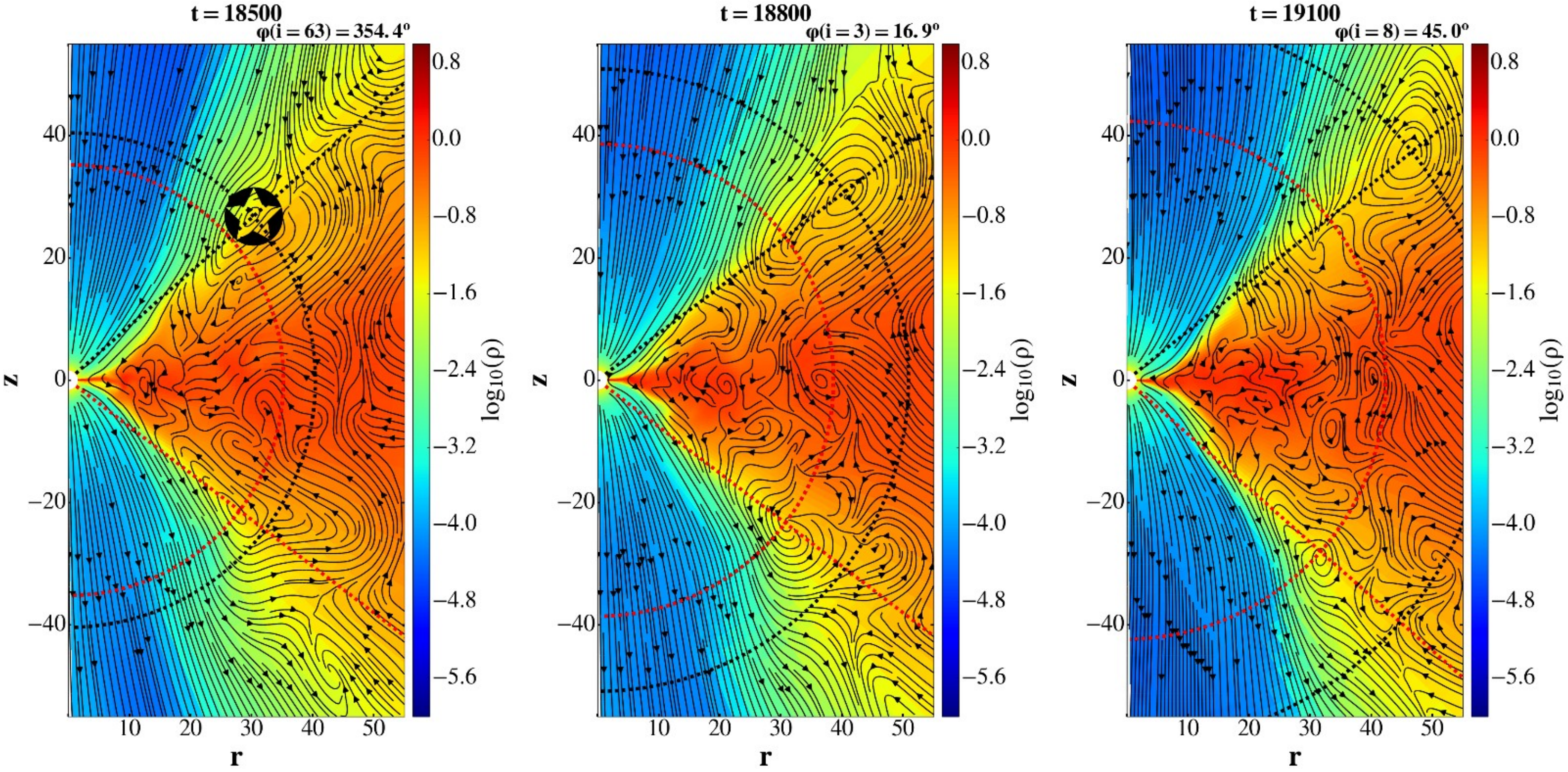
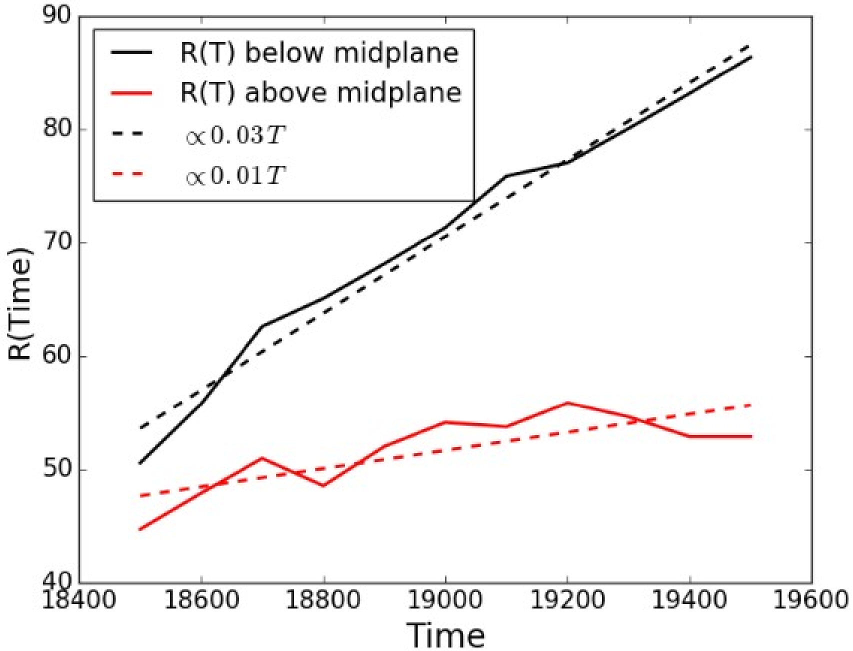


Table 1. Parameters used in different cases in our simulations.

Model	a	β_{min}	N_r	N_θ	N_ϕ	*Duration*
SANE00	0	0.05833	288	128	64	40000
MAD00	0	0.1	288	128	64	40000
SANE98	0.98	0.03	352	128	64	40000
MAD98	0.98	0.1	352	128	64	40000

Athena++, motion of magnetic islands in SANE00 case





-Snapshots at three different times in our simulation, showing density in logarithmic colour grading, overplot with poloidal magnetic field lines, with arrows showing the direction of the poloidal magnetic field. We describe the magnetic islands motion by tracing the positions of their centres. A star mark in the left panel denotes a magnetic island above the equatorial plane.

-Time dependence of the positions of the magnetic islands above (red) and below (black) the equatorial plane of the accretion flow shown above. The dashed lines are least square fits, slopes of which are velocities.

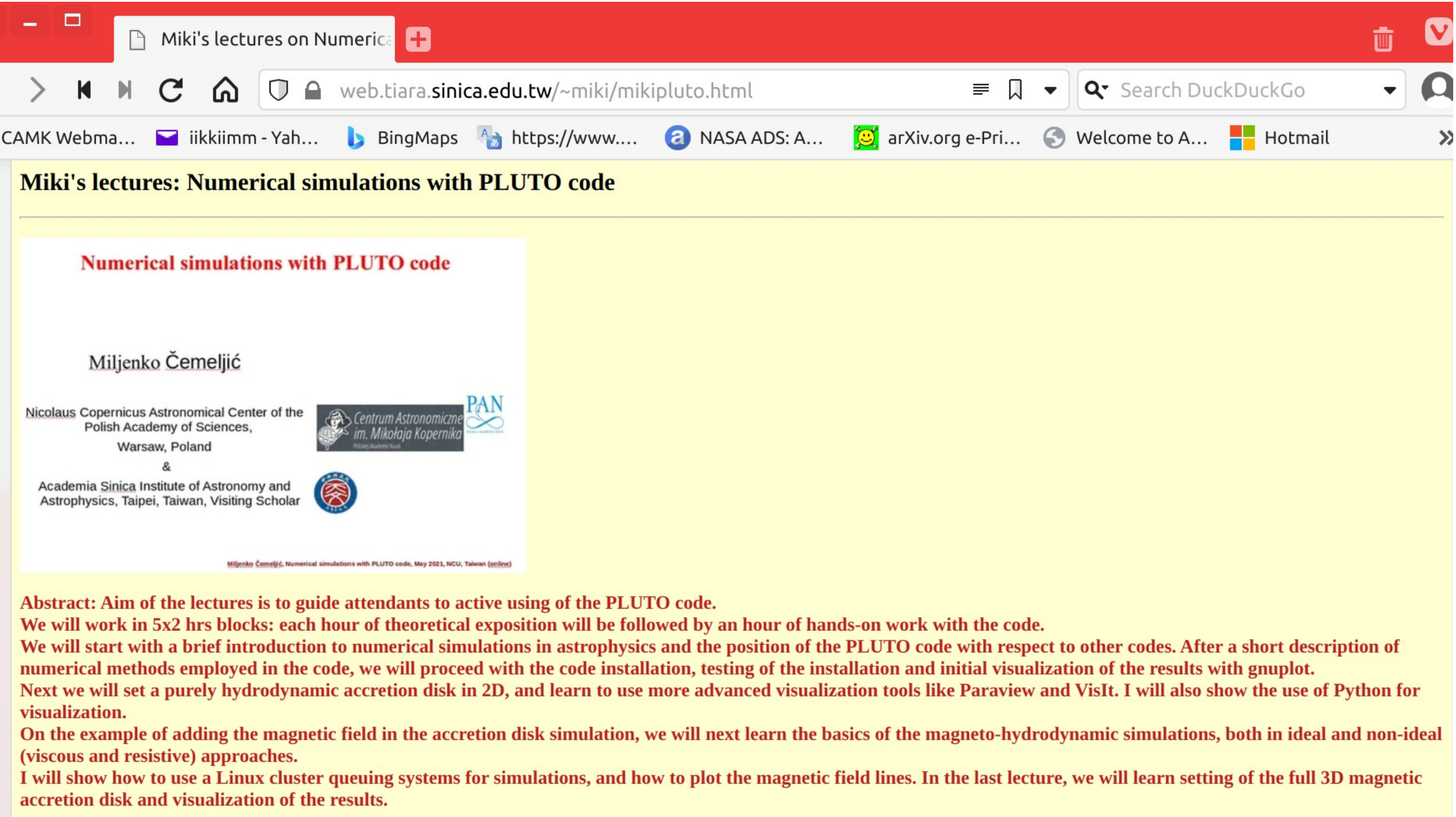
Summer students in our group

- I worked with more than 10 Summer students during the last decade in Taipei and Warsaw.
- Projects were mostly based on a work with PLUTO code, to give the starting experience in MHD numerical simulations. Last year projects with PLUTO:
  – magnetospheric star-disk interaction with non-dipolar stellar magnetic fields
  – thin accretion disk around a black hole
  – thick SANE disk simulations
- In addition to this, our PhD student Fatima Kayanikhoo supervised two Summer students, one from Warsaw University and other from UJ in Cracow on her project, on strange stars with Lorene package.

- 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. There was even one Journal of Plasma Physics publication on comparison of reconnection in 2D and 3D (Rui-Yang was then a Master student in electrical engineering, later he went on to a successful career in industry).

Lectures “Introduction to PLUTO code”

To ease the work for students, I prepared lectures to introduce students to simulations-from scratch. PLUTO is well documented and public, it is a good starting point. In 5x2 hrs lectures, 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

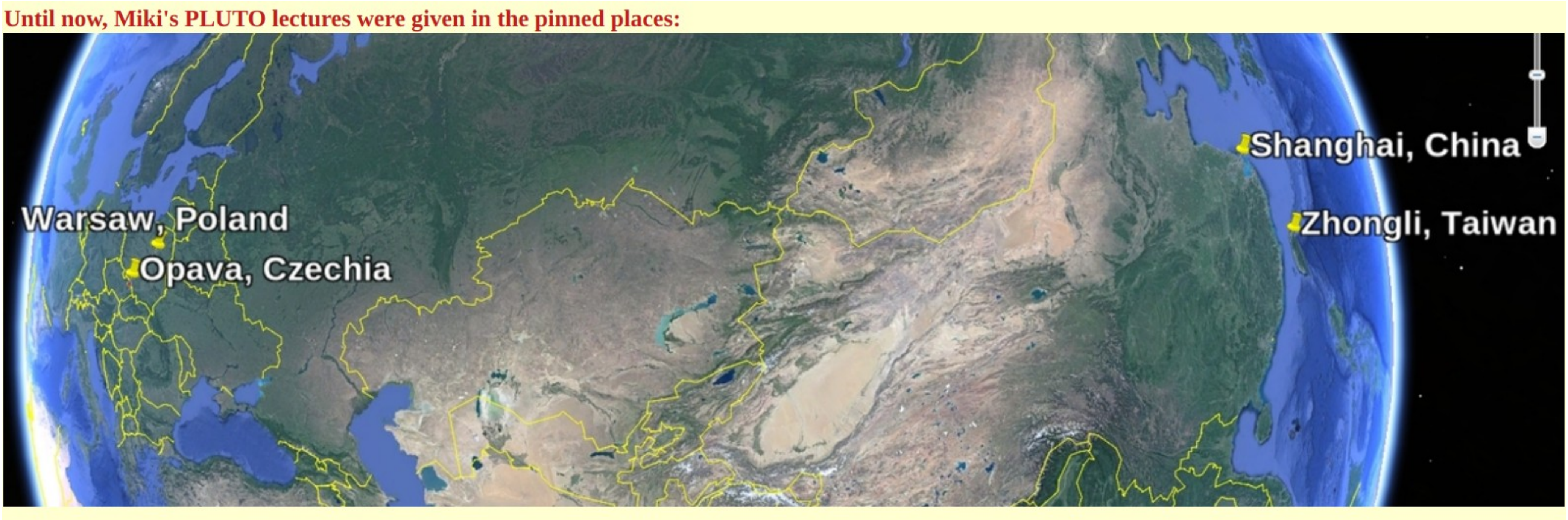
Miljenko Čemeljić

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

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

-I will continue providing such lectures where people would find it useful.

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

Non-dipolar stelar fields

Work with summer students in 2021 was unfortunately during the COVID-19 restrictions, so everything went in the online mode, but collaboration was, anyway, very lively.

- 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 will be his first publication. I show some of his results:

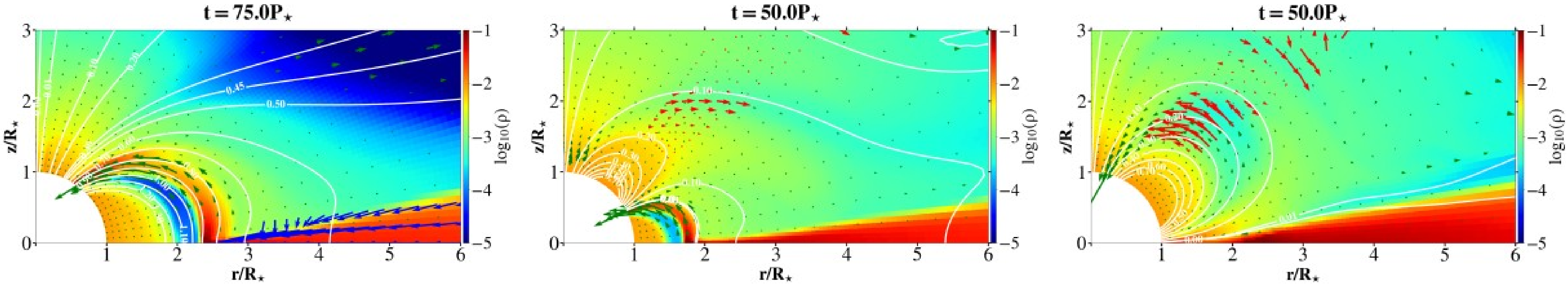


Fig. 1: Zoom into the vicinity of the star in quasi-stationary results in our simulations in the dipole, octupole and quadrupole field cases, left to right, respectively, with time

Non-dipolar stellar fields-torques in the system

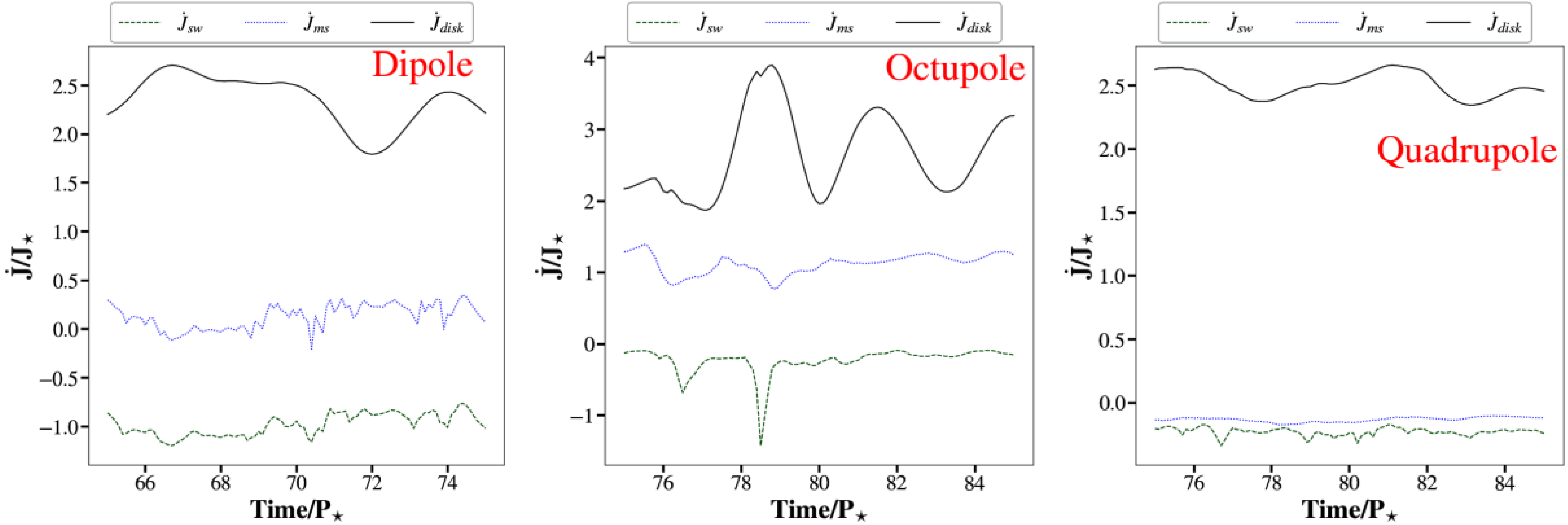
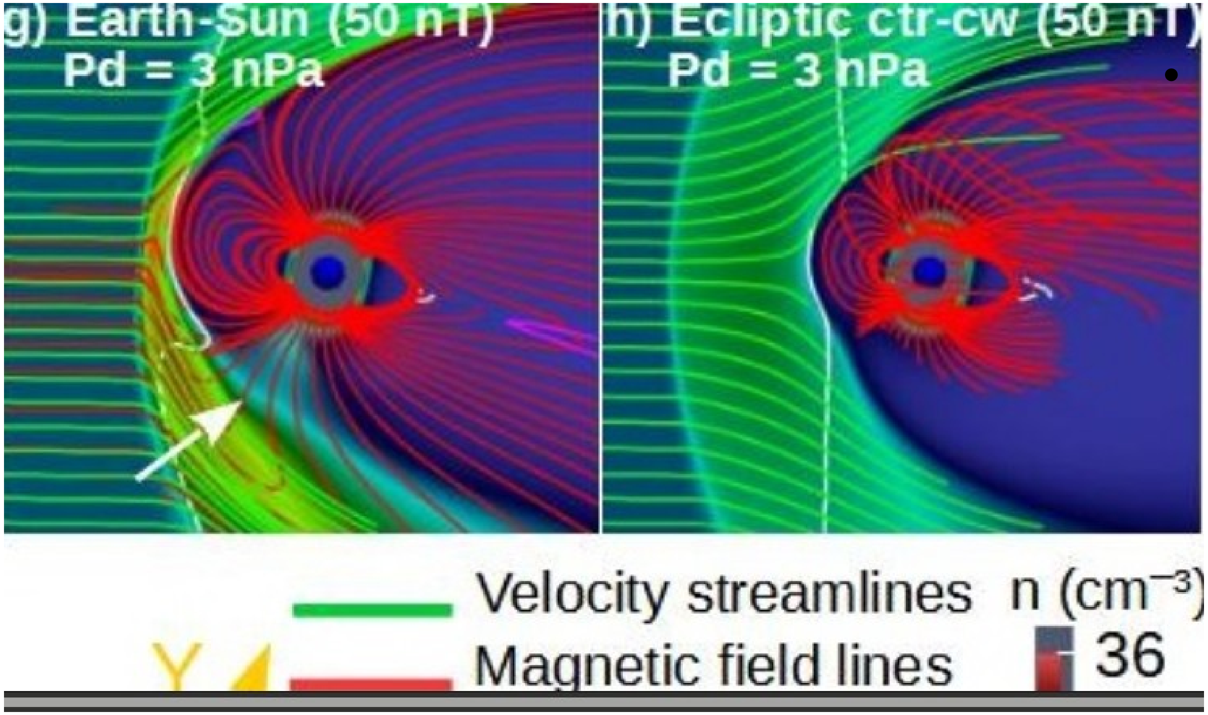


Fig. 3: Angular momentum flux during the quasi-stationary interval in our simulations computed in the "stellar wind" above the disk, $\dot{J}_{sw}$ (dashed green line) and accross the disk $\dot{J}_{disk}$ (solid black line) are computed at the half of the computational box $R = 15R_\star$. The "magnetospheric" angular momentum flux $\dot{J}_{ms}$ (dotted blue line) we compute above the disk, at the distance $R = 1.5R_\star$, at which in all the three geometries the initial field is the same.

Future projects

With members of our group and collaborators in Germany and France (who are actively working in the EHT team), we recently applied for a grant by the Polish NCN to work on accretion simulations for the Event Horizon Telescope-we would like to see how a choice of the space-time metric influences black hole shadows.

In the case of awarding, we would employ PhD students, to work with both PLUTO and KORAL on the state-of-the-art numerical simulations, stay tuned!



- For the Summer 2022 we plan at least one project, PLUTO simulations of magnetosphere interaction of a (neutron or ordinary) star and a planet, in collaboration with a Spanish colleague, J. Varela. Join us if interested.

Thank you!