Backflow in an accretion disk as a vehicle for outward transport of heavy elements

M. Čemeljić, R. Mishra and W. Kluźniak

Nicolaus Copernicus Astronomical Centre, Warsaw, Poland

Analytical solutions for purely hydrodynamic viscous accretion disk in three dimensions show backflows near the disk midplane, where the flow is directed outwards, away from the accreting star. We obtain such backflows in the simulations of a thin accretion disk in the cases with and without magnetic field. Using the quasi-stationary solutions in our star-disk simulations as a background, we add dust particles of different diameters in post-processing. We study the distribution of the particles in the disk, their exposure to the heat from the central star, and their motion. Entrainment of the dust particles by the backflow could have important implications for the composition of outer planets, as the radial outwards transport opposes radial segregation of elements in the protoplanetary disk.

Introduction:

Solutions of the 3D hydrodynamical model of thin accretion disc were derived analytically using the method of asymptotic approximation in Kluźniak & Kita (2000, hereafter KK00). A magnetic extension of this solution was given in Čemeljić et al. (2018).

Interaction of the flow onto a star with its magnetic field was investigated numerically in the works of Romanova et al. (2002, 2004, 2009, 2010, 2013), and Zanni & Ferreira (2009, 2013). Similar results were obtained in Čemeljić et al. (2017) and Čemeljić (2019), where an extensive parameter study was performed for slowly rotating Young Stellar Objects with different magnetic field strengths and disk resistivities.

We study the movement of the dust grains in the disk in post-processing of the stationary solutions in our numerical solutions for the disk with different physical parameters.

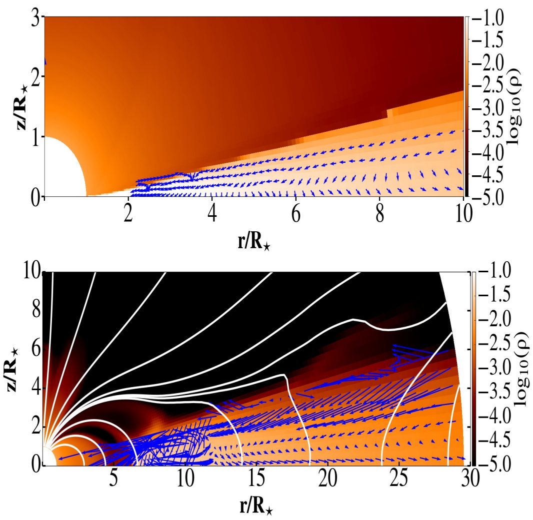

Figure 1: *A zoom in the solutions in our simulations with the PLUTO code with a backflow in the disk. We used those solutions as a background to compute the dust grains motion in the hydrodynamic (top panel) and magnetic case (bottom panel). Density is shown in the logarithmic color grading, and vectors show the poloidal velocity in the disk.*

Simulations and post-processing:

As a background for the post-processing we use our solutions from 2D-axisymmetric viscous and resistive numerical simulations with the PLUTO v.4.1 code (Mignone et al. 2007, 2012). The setup is presented in Čemeljić (2019). As the initial condition we used the KK00 disk solution, with the viscosity and resistivity parametrized by the Shakura-Sunyaev alpha parameter.

For post-processing we developed a Python code STARDUST, in which the dust particles motion is computed with the flow solution for the disk and corona from the output of PLUTO simulation.

To the gravity force and gas drag, we add the radiation pressure on the particles:

$$\ddot{\vec{r}} = -G\frac{M_{star}}{r^3}\vec{r} - \frac{\rho_g}{\rho_s}\frac{c_s}{a}(\dot{\vec{r}} - \vec{v}_g) + \vec{\beta}G\frac{M_{star}}{r^2}$$

$$\beta = 0.4\frac{L_{star}}{L_{sun}}\frac{M_{sun}}{M_{star}}\frac{3000\,{}^{kg}/_{m^3}}{\rho_s}\frac{\mu m}{a}$$

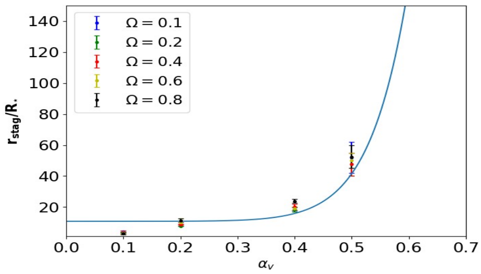

Figure 2: *Stagnation radius in our numerical simulations with different stellar rotation rates and viscosity anomalous coefficient is following the same curve as found in the analytical solutions (solid line). Data points from different simulations are shown with estimated error bars.*

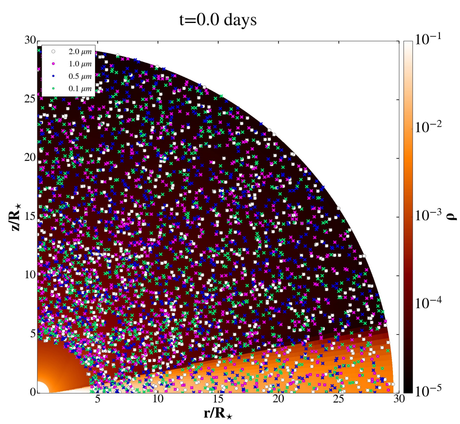

Figure 3: *A zoom into the initial random distribution of the dust grains with four different diameters in the STARDUST code.*

Results:

In numerical simulations we obtain backflow in the disk as predicted by the analytical solutions - see Figs. 1 & 2. Above a critical value of alpha_v=0.685 there is no backflow (Fig.2).

We randomly insert dust particles of four different diameters - see Fig.3, and compute their trajectories in the background of our star-disk solution, including the gas drag and radiation pressure-see Fig. 4. Particles are assumed to melt within some critical distance from the star.

Distribution of the dust grains in a disk with backflow will be different than in the case without it. Fraction of the particles which are heated in the vicinity of the star and later ejected away above the disk will also change, contributing to the change in chemical composition of the circumstellar material in the disk.

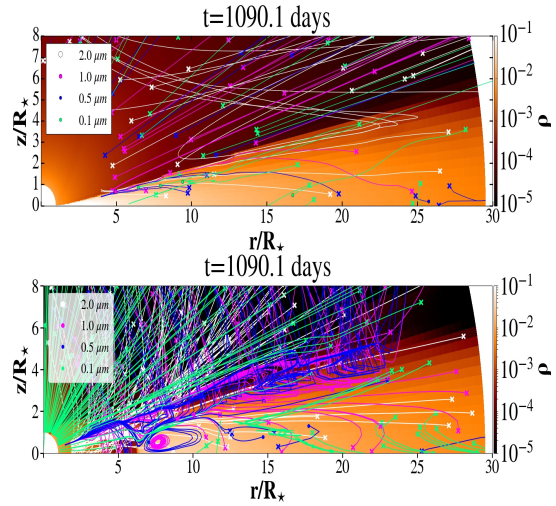

Figure 4: *A zoom in the STARDUST solutions after 1090 days in the hydrodynamic (top panel) and magnetic (bottom panel) cases. A sample of the particle paths is shown with the solid lines - the initial position of a particle is marked with a cross sign.*

Conclusions and future work:

In our numerical simulations with PLUTO code, we verified the analytical prediction for the stagnation radius dependence on the viscous alpha coefficient. We presented preliminary results for the distribution of dust grains of different diameters in a thin accretion disk with backflow. Backflow of the particles in the disk could have implications for the composition of outer planets.

We will perform a parameter study with the dust grains of different diameters in the cases with different stellar rotation rates, viscosity and resistivity coefficients and strength and topology of the magnetic field.

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 development of the STARDUST script was partly under Croatian HRZZ grant IP-2014-09-8656. We thank A. Mignone and his team of contributors for the possibility to use the PLUTO code. C. Turski is thanked for writing the STARDUST Python code, D. Vinković for discussion of the dust dynamics, V. Parthasarathy, F. Bartolić and D.A. Bollimpalli for help with the initial version of the Python script.

References:

Čemeljić, M., Parthasarathy, V. & Kluźniak, W., 2017, JPhCS, 932, 012028

Čemeljić, M., 2019, A&A, 624, A31

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

Lovelace, R. V. E., Romanova, M. M., Ustyugova, G. V. and Koldoba, A. V., 2010, MNRAS, 408, 2083

Mignone, A., Bodo, G., Massaglia, S., et al., 2007, ApJS, 170, 228

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

Romanova, M.M., Ustyugova, G.V., Koldoba, A.V., Lovelace, R.V.E., 2002, ApJ, 578, 420

Romanova, M.M., Ustyugova, G.V., Koldoba, A.V., Lovelace, R.V.E., 2004, ApJ, 610, 920

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

Zanni, C., Ferreira, J., 2013, A&A, 550, A99