Accretion disk backflow in resistive MHD simulations

Using PLUTO code

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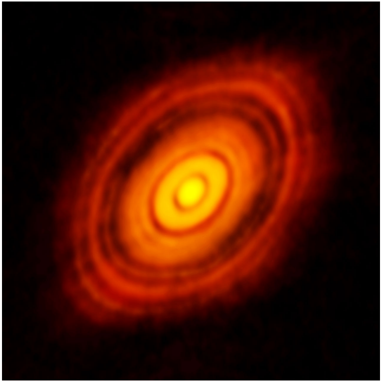
Introduction to accretion disks



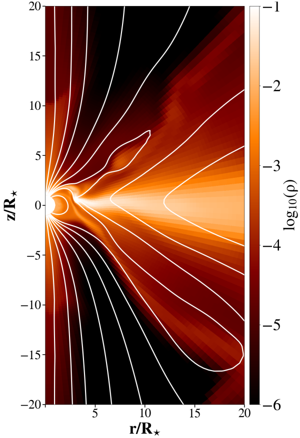
ALMA image of the HL Tau protoplanetary disk

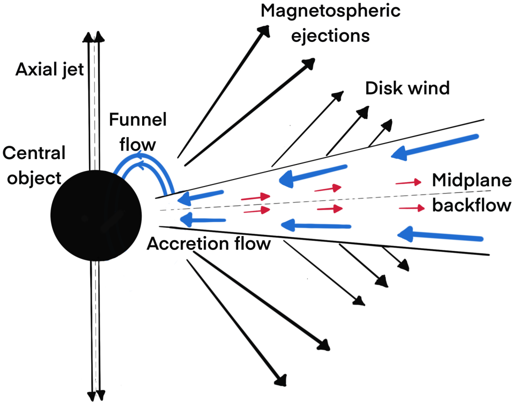
1. Angular momentum is conserved.
2. Matter can not be accreted directly as it has too much angular momentum. This leads to formation of accretion disk.
3. Accretion disks are made of rapidly rotating gas which slowly spirals into the central gravitating object.
4. Example :
    1. Protoplanetary systems
    2. White dwarfs
    3. Black holes and neutron stars
    4. Active galactic nuclei (AGN)

Introduction to accretion disks

1. Accretion process is accompanied by outward angular momentum transfer.
2. In a number of numerical and analytical studies , angular momentum transport results from anomalous alpha viscosity $(\nu \sim \alpha c_{\rm s} H)$ Shakura & Sunyaev (1973). In many scenarios angular momentum transport results by magnetorotational instability MRI Balbus & Hawley (1991).
3. The direction of flow of matter is expected to be inwards but under some conditions a part of the disk flow is found to be in the opposite direction, away from the central object. This is referred to as a **"backflow"** in the accretion disk.
4. Backflow is well established analytically and numerically in alpha disks Urpin (1984), Siemiginowska (1988), Kley & Lin (1992), Różyczka et al. (1994), Kluźniak & Kita (2000), Regev & Gitelman (2002), Igumenshchev et al. (1996), Lee & Ramirez-Ruiz (2002), Takeuchi & Lin (2002) etc .
5. Backflow also appears in numerical simulations in geometrically thick flow driven by magnetorotational instability (MRI) Mishra et al. (2020), global simulations in ideal magneto-hydrodynamics (MHD) by Zhu & Stone (2018) and general-relativistic radiative magneto-hydrodynamics (GRMHD) simulations of radiatively inefficient accretion flows by White et al. (2020).

Different flows in the star-disk system





Backflow : Flow of matter, along the midplane of accretion disk, away from accreting object

Kluźniak-Kita disk

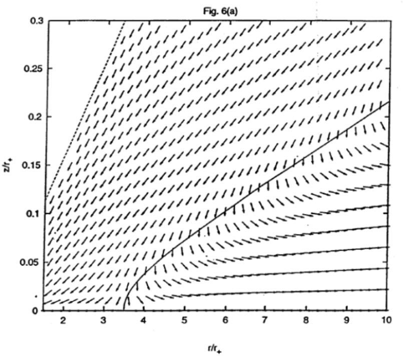
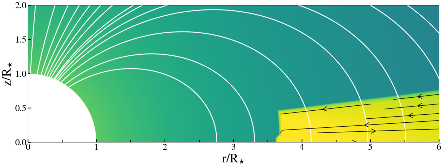
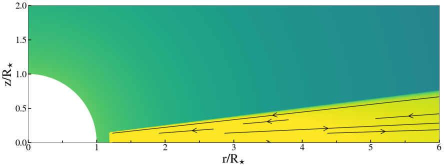


Fig. 6(a).— The unit velocity vector field, i.e. $(\vec{v_r}/|v_r|, \vec{v_z}/|v_z|)$ for $\epsilon = 0.1$ and $\alpha = 0.1$. The dashed curve represents the disk surface and the solid curve the vertical flow surface where $v_r = 0$.

1. Kluźniak & Kita (2000) gave a global analytic solutions in 3D for a hydrodynamic steady, thin alpha disc using the polytropic pressure–density relation, and including a zero–torque inner boundary condition.
2. They also modified the alpha prescription by incorporating the z dependence in the kinematic viscosity.
3. Beyond a certain distance along the midplane of the disc there may or may not be backflow, depending on the α parameter.
4. The position where the backflow starts is termed as the "stagnation radius". It is a function of viscosity parameter. As α increases, stagnation radius increases. There is no backflow for $\alpha > \alpha_{cr}$.

Simulation setup





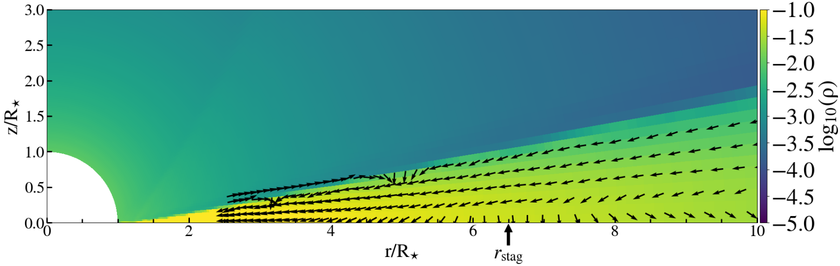
① We use the publicly available PLUTO code (v.4.1) for our simulations.

② In the initial conditions we set a thin, viscous, purely hydrodynamical KK disk around YSO with $M_\star = 0.5M_\odot$ and $R_\star = 2R_\odot$. For the MHD case, we add a stellar dipolar magnetic field and include anomalous Ohmic resistivity in the disk.

③ For most simulations resolution is $r \times \theta = [217 \times 100]$ grid cells, in a quadrant of the meridional plane $(r, \theta) \in (1, 29) \times (0, \pi/2)$.

④ We perform a parameter study by changing the viscosity parameter $\alpha_{\rm v}$ and stellar rotation rate $\Omega_\star$ in HD simulations, and add the variation of the resistivity parameter $\alpha_{\rm m}$ in MHD simulation. Both the viscosity and resistivity parameters are varied from 0 to 1.

HD simulations

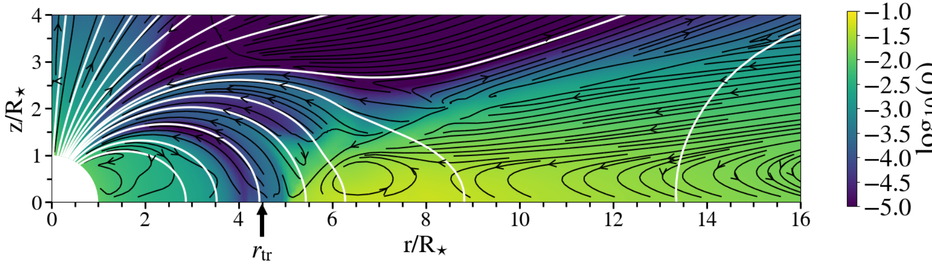


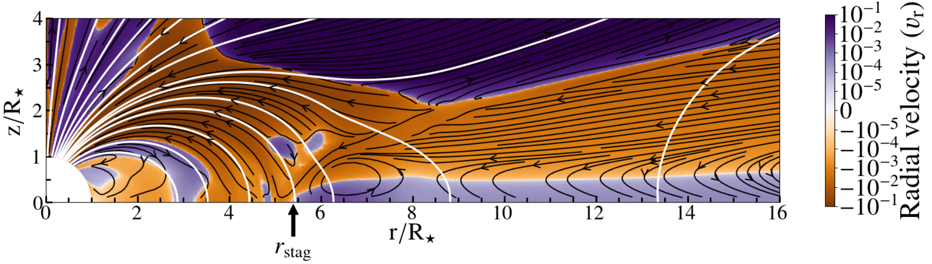
① For the simulations with $\alpha_{\rm v} < 0.6$, after initial relaxation a stable backflow appears close to the equatorial plane of the computational domain.

② The radial velocity component in the disk points away from the star from the stagnation radius, where the velocities turn away from the star, to the end of the computational domain.

③ When $\alpha_{\rm v} > 0.7$ there is no backflow in the disk, hence the radial velocity vectors point towards the star across the entire height of the disk.

MHD Simulations

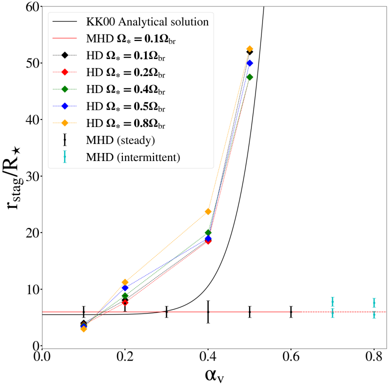




Simulation	$\alpha_{\rm v}$	$\alpha_{\rm m}$	$P_{\rm m}$	Backflow	$r_{\rm tr}$	$r_{\rm stag}$	Type
S1	0.1	1.0	0.06	Yes	4.5 ± 0.5	6 ± 1	steady
S2	0.2	1.0	0.13	Yes	6 ± 1	7.5 ± 1.5	steady
S3	0.3	1.0	0.20	Yes	4.5 ± 0.5	6 ± 1	steady
S4	0.2	0.6	0.22	Yes	4.5 ± 0.5	6 ± 1	steady
S5	0.4	1.0	0.26	Yes	4.5 ± 0.5	6 ± 2	steady
S6	0.5	1.0	0.30	Yes	4.5 ± 0.5	6 ± 1	steady
S7	0.6	1.0	0.40	Yes	4.5 ± 0.5	6 ± 1	steady
S8	0.4	0.6	0.44	Yes	4.5 ± 0.5	6 ± 1	steady
S9	0.7	1.0	0.46	Yes	3 to 5^*	$\approx r_{\rm tr} + 1.5$	intermittent*
S10	0.8	1.0	0.53	Yes	3 to 5^*	$\approx r_{\rm tr} + 1.5$	intermittent*
S11	0.1	0.1	0.66	No	-	–	–
S12	0.4	0.4	0.66	No	-	–	–
S13	1.0	1.0	0.66	No	-	–	–
S14	1.0	0.4	1.65	No	-	–	–
S15	0.4	0.1	2.64	No	-	–	–
S16	1.0	0.1	6.60	No	-	–	–

1. Backflow can be of two categories: a steady flow or an intermittent flow.
2. The presence of backflow depends on magnetic Prandtl number $P_{\rm m} = 2\alpha_{\rm v}/3\alpha_{\rm m}$. Above a critical value of magnetic Prandtl number, which is about $P_{\rm m}^{\rm crit} \sim 0.6$, there is no backflow in the disk in our simulation.

Stagnation radius



1. We present the position of the stagnation radius in HD and MHD simulations with the different viscosity coefficients.
2. In HD the curves increase with viscosity in qualitative agreement with the analytic Kluzniak Kita solution.
3. In MHD we find the stagnation point to have a fixed value regardless of the viscosity parameter

Conclusion

1. We present resistive MHD simulation of thin α-disks in accretion onto magnetized and non-magnetized rotating stars for different values of α_{v} and α_{m} parameters.
2. For purely HD simulations of the thin α-disk ($\alpha_{\mathrm{m}} = 0$) we find backflow in the midplane of the accretion disk for $\alpha_{\mathrm{v}} < \alpha_{\mathrm{cr}} \approx 0.7$. The stagnation radius in the midplane follows the dependence on α_{v} predicted by the KK analytical model.
3. We find that the character of backflow (steady or not, present or absent) in the resistive MHD simulations depends on the magnetic Prandtl number, P_{m}. When $P_{\mathrm{m}} < 0.6$ there is a backflow. As the critical value of P_{m} is approached the backflow in the disk becomes intermittent.
4. In the presence of strong magnetic field and high resistivity (so that P_{m} is below its critical value), we obtain backflow in MHD disk for even higher values of viscous parameter than critical α_{v} in the purely HD case.
5. In contrast with the HD case, where the stagnation radius is strongly dependent on α_{v}, in the MHD case the stagnation radius has the same value for all values of the viscous and diffusion coefficients, as long as $P_{\mathrm{m}} < 0.45$

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Thank you!