Towards pseudo-Newtonian black hole jets: comparison of forces

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ABSTRACT: We perform resistive and viscous MHD simulations of axial jet launching from a magnetized thin accretion disk around a supermassive black hole. We compare the forces in our pseudo-Newtonian simulations for the Paczyński-Wiita and Kluźniak-Lee potentials. The results will help to find magnetic field configurations and physical parameters conducive to jet launching.

INTRODUCTION

Accretion onto a supermassive Black Hole in Active Galactic Nuclei is extensively studied both in observations and in numerical simulations. Launching mechanism of outflows and axial jets is still not fully explained. We extend our Newtonian non-ideal MHD simulations with a magnetized accretion disk around a central object to the simulations with a pseudo-Newtonian gravitational potential, to study the jet launching from AGNs.

NUMERICAL SETUP

We use the PLUTO code (Mignone et al. 2007, 2012) to perform 2D-axisymmetric star-disk simulations in the complete $[0, \pi]$ half-plane, in resolution $R \times \theta$=[125×100] grid cells. The physical domain extending from [1-50] R_i, where R_i is set to three Schwarzschild radii $r_S = 2GM/c^2$. The equations we solve with the PLUTO code are the resistive and viscous magneto-hydrodynamic equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(P + \frac{B^2}{8\pi} \right) \tilde{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} - \tilde{\tau} \right] = -\rho \nabla \Psi_g$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{B^2}{8\pi} \right) \mathbf{v} - \frac{(\mathbf{v} \cdot \mathbf{B})\mathbf{B}}{4\pi} \right] = -\rho \nabla \Psi_g \cdot \mathbf{v}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{B} \times \mathbf{v} + \eta_m \mathbf{J}) = 0$$

where ρ, P, v, B, η_m are the density, pressure, velocity, magnetic field and the Ohmic resistivity, respectively. The terms $\tilde{I}$ and $\tilde{\tau}$ are representing the unit tensor and the viscous stress tensor, respectively. In the energy equation, we assumed that all the dissipation (viscous and resistive) heating is radiated away, and removed the corresponding terms in the code. The Paczyński-Wiita and Kluźniak-Lee pseudo-Newtonian gravitational potentials Ψ_g are:

$$\Psi_{PW}(r) = -\frac{GM_{BH}}{r - r_S}, \;\; \Psi_{KL}(r) = -\frac{GM_{BH}}{3r_S}(e^{3r_S/r} - 1).$$

The initial disk is set up with a quasi-stationary result from the purely hydro-dynamical (HD) simulations, which were obtained modifying the setup described in Čemeljić (2019), with the use of pseudo-Newtonian gravitational potentials. The Kluźniak-Kita (2000) analytical solution was used as the initial disk set up for our HD simulations. In the magnetic case, to the relaxed HD disk as an initial condition we add the magnetic field with the vector potential described in Zhu & Stone (2018) and Mishra et al. (2019):

$$A_\phi = \begin{cases} \frac{1}{2} r \sin\theta B_0 (\frac{r_{min}}{R_0})^m & \text{if } r \le r_{min} \\ \frac{B_0}{R_0^m} \frac{(r \sin\theta)^{m+1}}{m+2} + \frac{B_0 r_{min}^{m+2}}{R_0^m r \sin\theta} (\frac{1}{2} - \frac{1}{m+2}) & \text{if } r > r_{min} \end{cases}$$

RESULTS

Snapshots of our preliminary results with Paczyński-Wiita and Kluźniak-Lee potentials are shown in Figs. 1 & 2. Shown are the initial phases of the simulation, before the disk relaxation to the action of magnetic field. To better understand the disk dynamics, we computed the forces in each of those cases (Figs. 3 & 4), projected along the magnetic field lines. The Lorentz force is the strongest force acting on the disk in both cases, pulling it apart from the disk equatorial plane. Such results will guide our further work, search for the combination of physical parameters which would result in the configuration with launching of the axial jet.

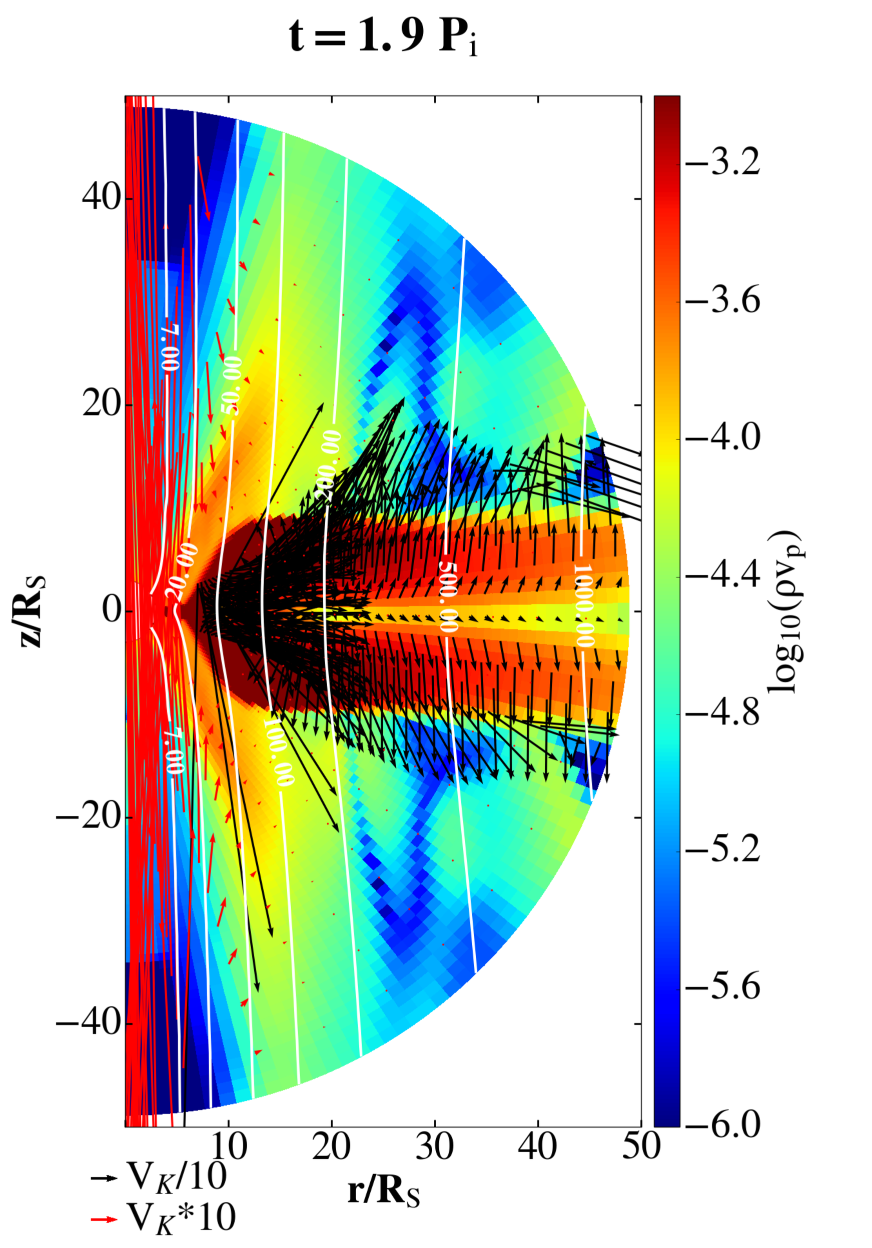

Figure 1: Snapshot in a simulation with Paczyński-Wiita potential. Poloidal momentum flux ρv_p is shown in a logarithmic color grading and a sample of magnetic field lines is shown with solid white lines. Arrows show the poloidal velocity, with the different unit vector lengths in the disk and corona, measured in Keplerian velocity units at R_i, as indicated below the figure.

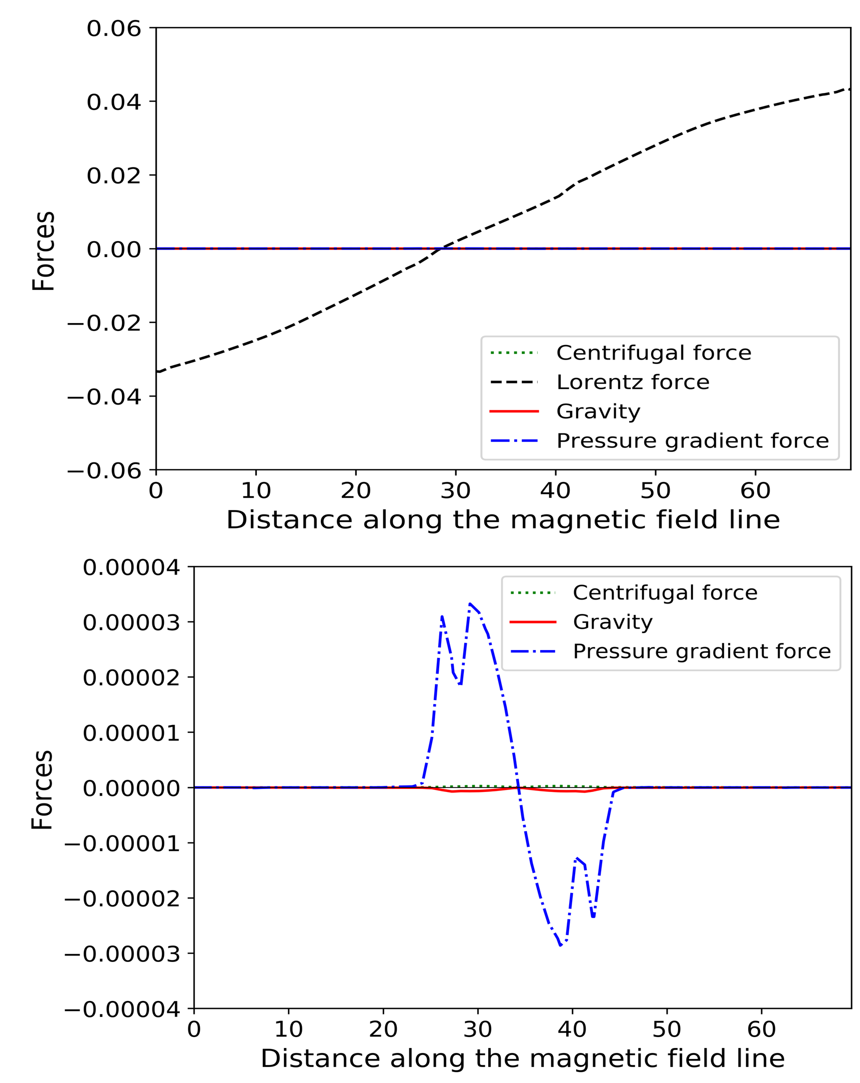

Figure 3: Forces projected along a field line Ψ=500 for Paczyński-Wiita potential calculated from the bottom to the top. *Top panel*: Lorentz force (black dashed line). *Bottom panel*: centrifugal force (green dotted line), gravity (red solid line), thermal pressure gradient (blue dot-dashed line).

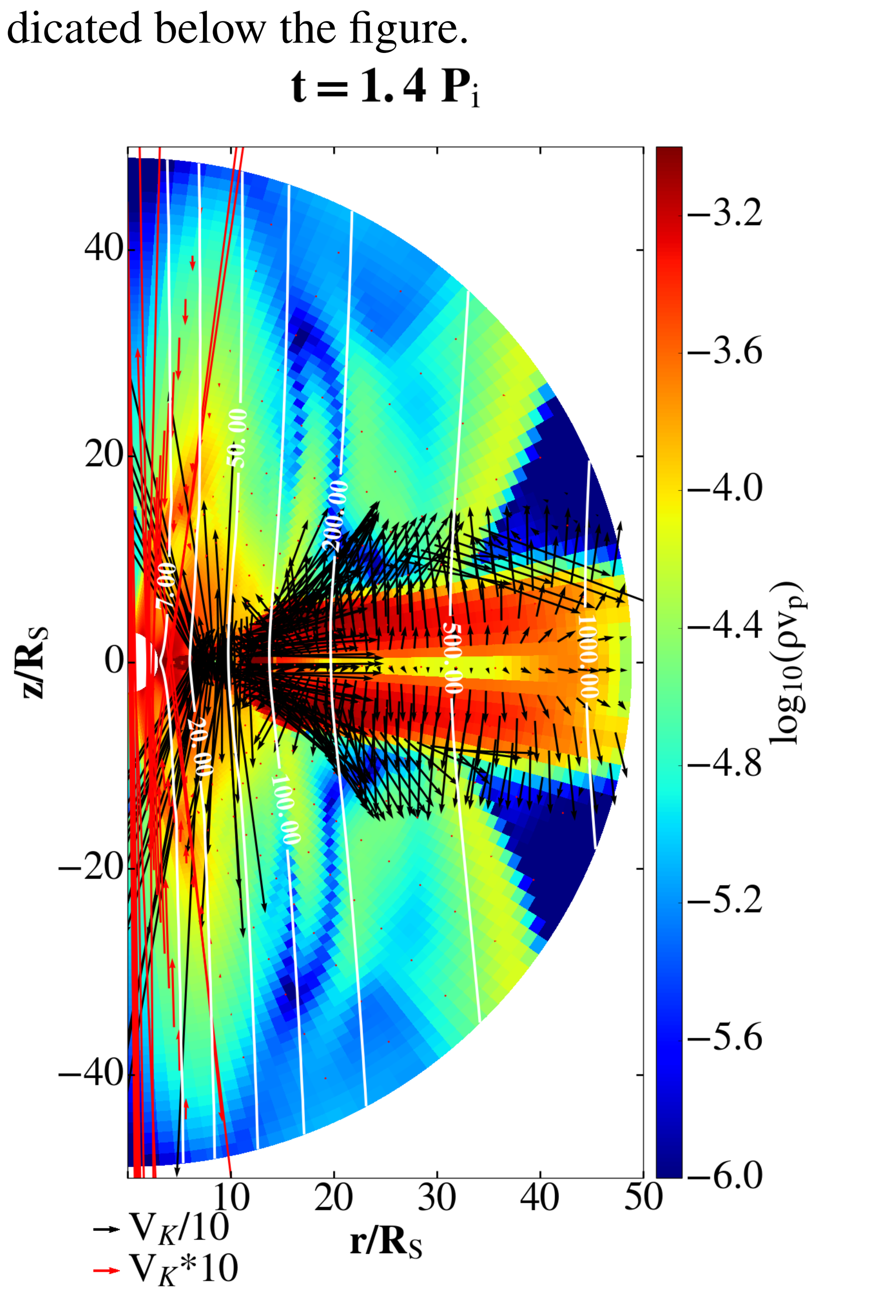

Figure 2: Snapshot in a simulation with Kluźniak-Lee potential.

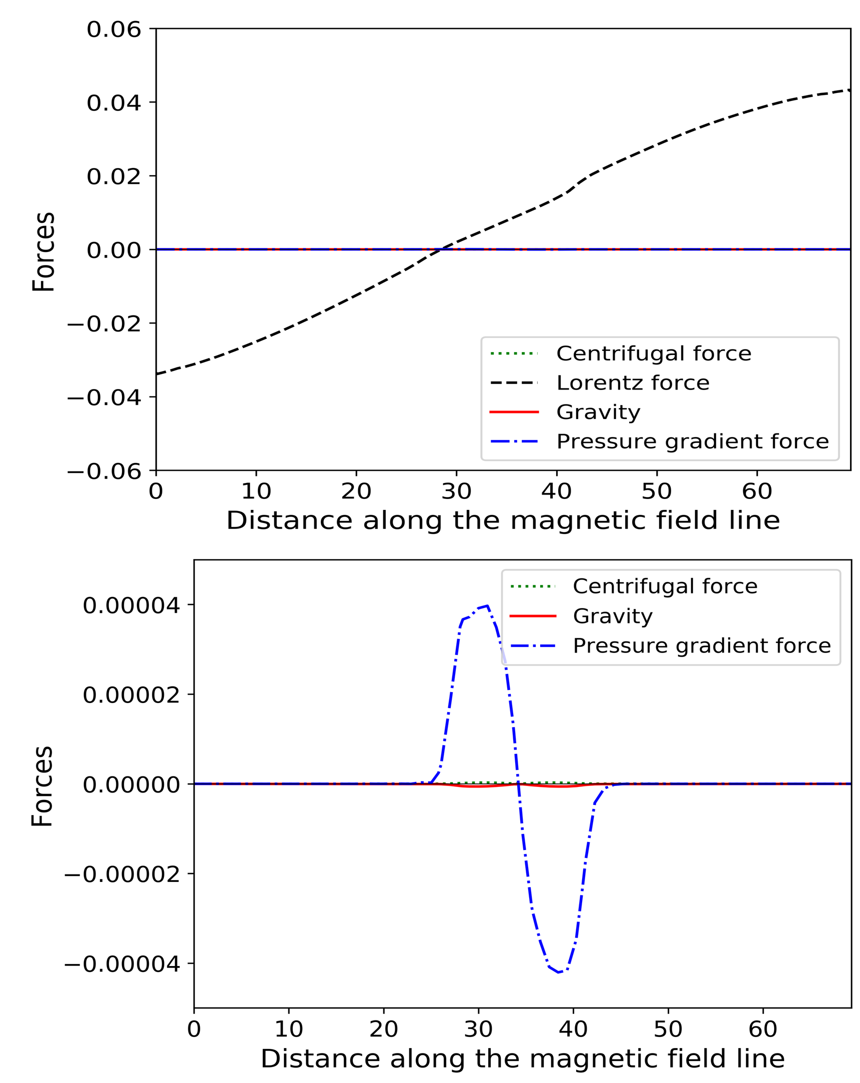

Figure 4: Forces projected along a field line Ψ=500 for Kluźniak-Lee potential.

CONCLUSIONS

In our simulations with pseudo-Newtonian gravitational potentials, we are investigating configurations of the magnetic field from which jets could be launched from the vicinity of a supermassive black hole. Starting from the relaxed HD numerical solution, we study forces on the material in the disk and its corona, searching for the configuration facilitating the launching of outflows.

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