Resistive MHD jet simulations

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We perform axisymmetric resistive MHD simulations for a generalised solution of the radially self-similar type and compare them with the corresponding analytical and numerical ideal-MHD solutions. The magnetic diffusivity could occur in outflows above an accretion disk, being transferred from the underlying disk into the disk corona by MHD turbulence (anomalous turbulent diffusivity), or as a result of ambipolar diffusion in partially ionized flows. We conclude that while the classical magnetic Reynolds number Rm measures the importance of resistive effects in the induction equation, a new introduced number Rb measures the importance of the resistive effects in the energy equation. We find two distinct regimes of solutions in our simulations. One is the low-resistivity regime, in which results do not differ much from ideal-MHD solutions. In the high-resistivity regime, results depart significantly from the ideal-MHD case, and seem to show some periodicity in time-evolution. Whether this departure is caused by numerical or physical reasons is of considerable interest for numerical simulations and theory of such outflows and is currently investigated.

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \boldsymbol{V}) = 0\,, \quad (1)$$

$$\rho\left[\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V}\cdot\nabla)\boldsymbol{V}\right] + \nabla p + \rho\nabla\Phi - \frac{\nabla\times\boldsymbol{B}}{\mu_0}\times\boldsymbol{B} = 0\,, \quad (2)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla\times(\boldsymbol{V}\times\boldsymbol{B} - \eta\nabla\times\boldsymbol{B}) = 0\,, \quad (3)$$

$$\rho\left[\frac{\partial e}{\partial t} + (\boldsymbol{V}\cdot\nabla)e\right] + p(\nabla\cdot\boldsymbol{V}) - \frac{\eta}{\mu_0}(\nabla\times\boldsymbol{B})^2 = 0\,, \quad (4)$$

$$\nabla\cdot\boldsymbol{B} = 0\,, \quad (5)$$

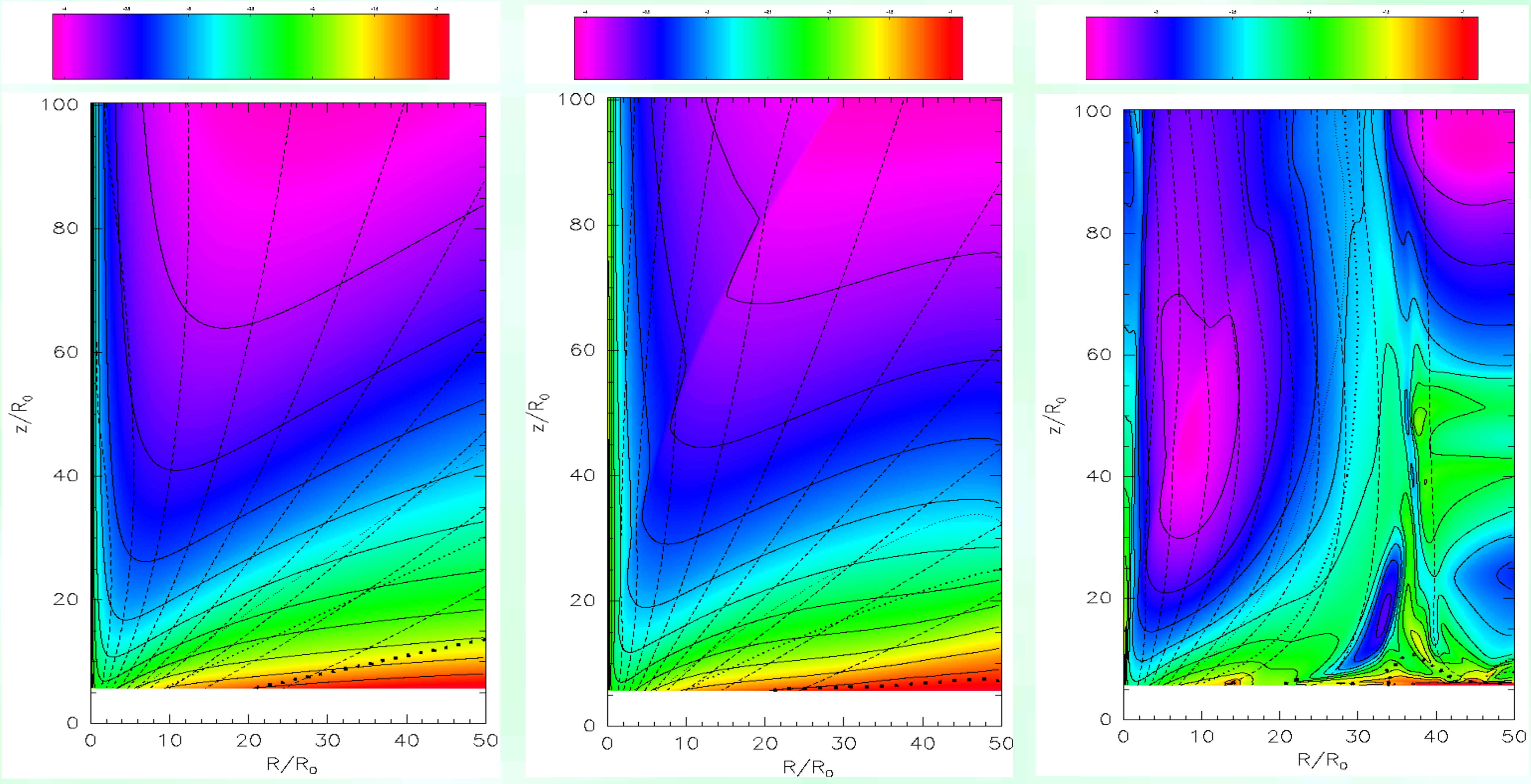
Equations of resistive-MHD in SI units, as solved by NIRVANA code in our simulations. We included finite resistivity both in the induction (Eq.3) and in the energy equations (Eq. 4).

Initial and boundary conditions

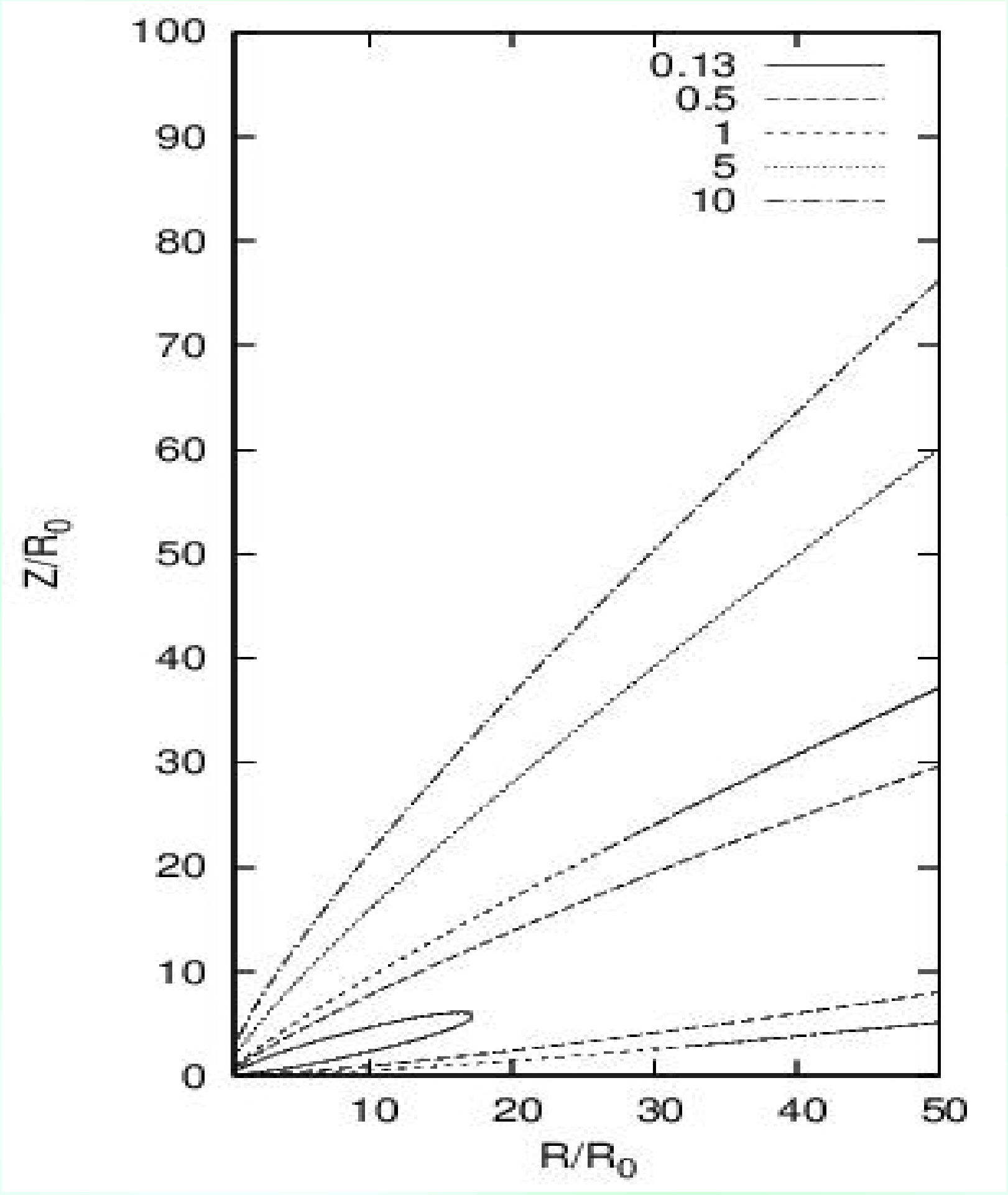
In Vlahakis & Tsinganos (1998) general classes of self-consistent ideal-MHD solutions have been constructed. In Vlahakis et al. (2000) Blandford & Payne (1982) model was analysed, and the problem with the terminal wind solution (which was not causally disconnected from the disk) has been solved. The common deficiency of all radially self-similar models, a cut-off of the solution at small cylindrical radii and also at some finite height above the disk because of a strong Lorentz force close to the system's axis has been corrected numerically. A search in the numerical simulations for solutions at larger distances from the disk has been performed in Gracia et al. (2006) with NIRVANA code (version 2.0, Ziegler, 1998), and similar results were obtained also using the PLUTO code by Mignone et al. (2007) in Matsakos et al. (2008). Extension in the resistive-MHD has been investigated in Cemeljic et al. (2008) using the NIRVANA code and some of results we present here.

Simulations

The initial condition in our simulations is modified analytical solution of Vlahakis et al. (2000), from which the solutions with small diffusivity ($\eta<0.15$) do not departure much. η is given in units R_0V_0, where R_0 is the characteristic scale of the YSO, and V_0 is half of the Keplerian velocity at R_0. These two solutions are shown in the left and middle panel here. The only difference is the shock close to the axis, and slight bending of the critical surfaces. The integrals of motion and fluxes along the similar lines in the flow for these solutions can be directly compared. They show smooth trends for increasing diffusivity, until some critical value is reached. The right panel shows simulation with large $\eta=1.5$, which is a super-critical value in our setup. It does not reach a steady state, but remains highly time-variable, with a "wing" showing some periodicity in time evolution. Further investigation of this regime of resistive-MHD simulations is under way, here we present one typical case. The diffusivity in our simulations is treated as an "effective diffusivity", without discussing its physical origin.



The initial condition, which is a modified analytical solution, is shown in the left panel. The low resistivity (η=0.03) and high (super-critical) resistivity (η=1.5) simulations results are shown in the middle and right panels, respectively. The low resistivity case does not differ much from the initial condition, and is a stationary solution. The super-critical solution does not reach stationary state, and shows some periodicity in time evolution. Density is shown in the colour grading and solid isocontour lines, dashed lines depict poloidal magnetic field lines, and dotted lines depict the fast magnetosonic, Alfven and slow magnetosonic critical surfaces, top to bottom, respectively.



Value of $\beta/2$ (VR/V_0R_0) for the analytical solution from Vlahakis et al. (2000). This quantity gives the critical value of magnetic diffusivity η that corresponds to Rb=1. We find that it matches the critical diffusivity in our numerical simulations (Cemeljic et al., 2008).

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New characteristic number

Except the magnetic Reynolds number $Rm=VR/\eta$, which describes influence of the magnetic diffusivity η in the induction equation (3), we introduced a new number, describing such influence on the energy transport in Eq.(4). This new dimensionless number can be written in terms of Rm and plasma beta as $Rb=Rm\beta/2$. It is the ratio of the pressure term over the Joule heating term in the energy equation. Energy dissipation is important when Rb is smaller or close to unity, which can happen even when Rm is much larger than unity, defining one additional mode of resistive-MHD solutions. It becomes a useful parameter when searching for conditions for onset of super-critical regime.

Results

The resistive MHD jets are similar to ideal-MHD solutions for a finite range of magnetic diffusivity, in which they reach a well defined stationary state. Departure from the ideal-MHD regime occurs for larger values of magnetic diffusivity, above some critical value. We show the existence of the distinct super-critical regime in magnetic diffusivity for the outflows initialised with a self-similar analytical solutions, in our setup.

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