Self-similar models of resistive relativistic astrophysical jets

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Abstract

Relativistic, magnetized outflows lie at the heart of most high-energy astrophysical phenomena. In the past, numerical works have studied the role of resistivity and Ohmic dissipation of electromagnetic energy in shaping the dynamics of relativistic jets. However, there is a lack of an analytical framework for the construction of models which describe relativistic jets in the context of resistive MHD. We present a novel self-similar formalism based on the angular expansion of the governing equations for the modeling of resistive relativistic spine jets, which enables the inclusion of non-zero electrical resistivity and of a variable adiabatic index equation of state. Our solutions, which describe strongly relativistic spine jets, show that non-zero resistivity leads to the generation of an electric potential gradient along the poloidal magnetic field lines. This electric potential gradient acts as the source of Ohmic dissipation, which affects the acceleration and collimation profiles of these types of outflows. In regions of strong dissipation, the Ohmic heating of the plasma leads to the weakening of the dominant thermal acceleration mechanism. Additionally, the current density along the jet axis is enhanced, resulting in the localized amplification of the toroidal magnetic field and consequently, in slightly stronger jet collimation.

Self-similar Model Construction

Construction of meridionally self-similar jet models in the context of general relativistic resistive magnetohydrodynamics (GR-RMHD):

Equations of GR-RMHD

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Impose $\partial_t = 0$ & $\partial_\phi = 0$

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Prescribe polar angle dependences

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Expand Eqs. w.r.t polar angle

↓

ODEs for radial dependences

- Schwarzschild spacetime: $h_t = \sqrt{1 - \frac{r_S}{r}}$
- Resistivity through GR generalization of Ohm's law [1, 2]
- Resistivity profile: $\eta \sim \theta^2$
- Ryu et al. 2006 EoS [3]

Results

Jet acceleration and collimation:

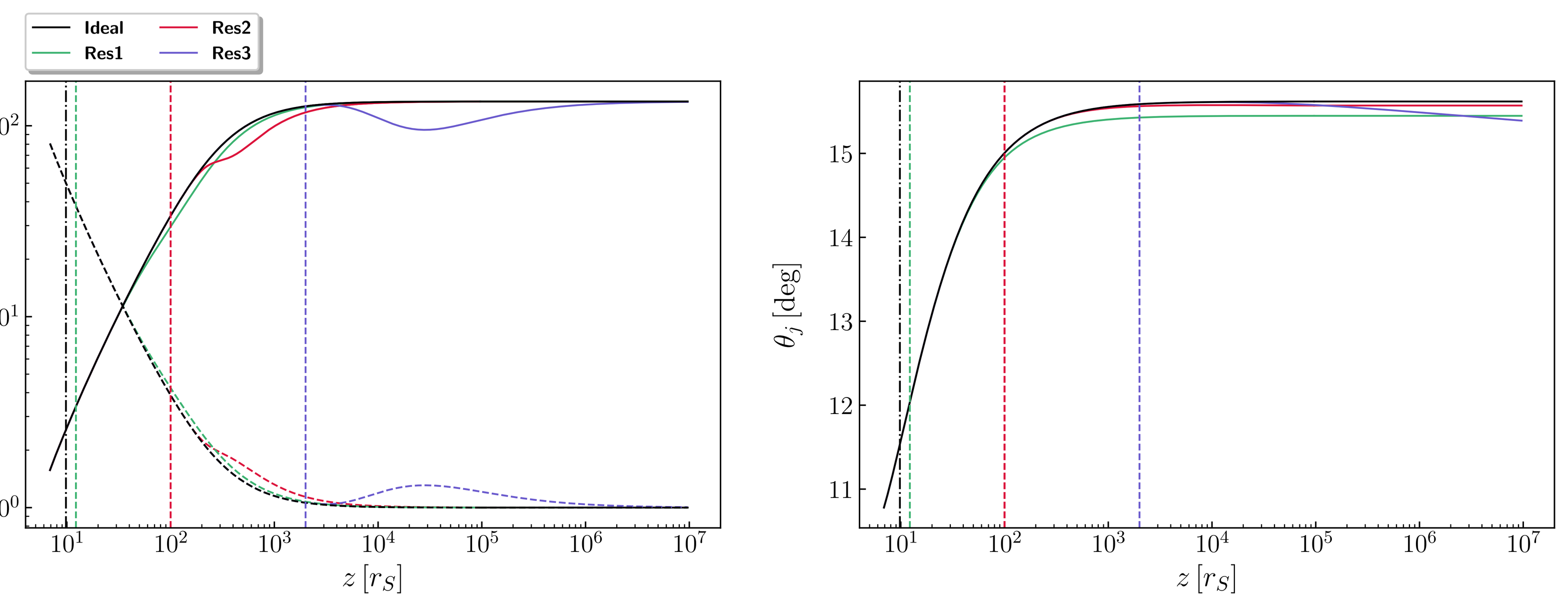

Figure 1. *Left panel*: $-U_t = h_t \Gamma$ (solid lines) and specific enthalpy (dashed lines). *Right panel*: Jet half-opening angle. Colored dashed lines: positions where resistivity is switched on in each resistive jet model. Black dot-dashed line: position of Alfvén surface.

- Ohmic dissipation acts as a heat source, decreasing the efficiency of the thermal acceleration mechanism (conversion of internal energy to kinetic along flux lines)
- Decelaration of the bulk flow is possible when the dissipation region lies beyond the acceleration region (solution Res3 shown in Fig. 1)
- Resistive jets experience stronger collimation due to enhanced transfield components of the Lorentz and pressure gradient forces

Jet magnetic field:

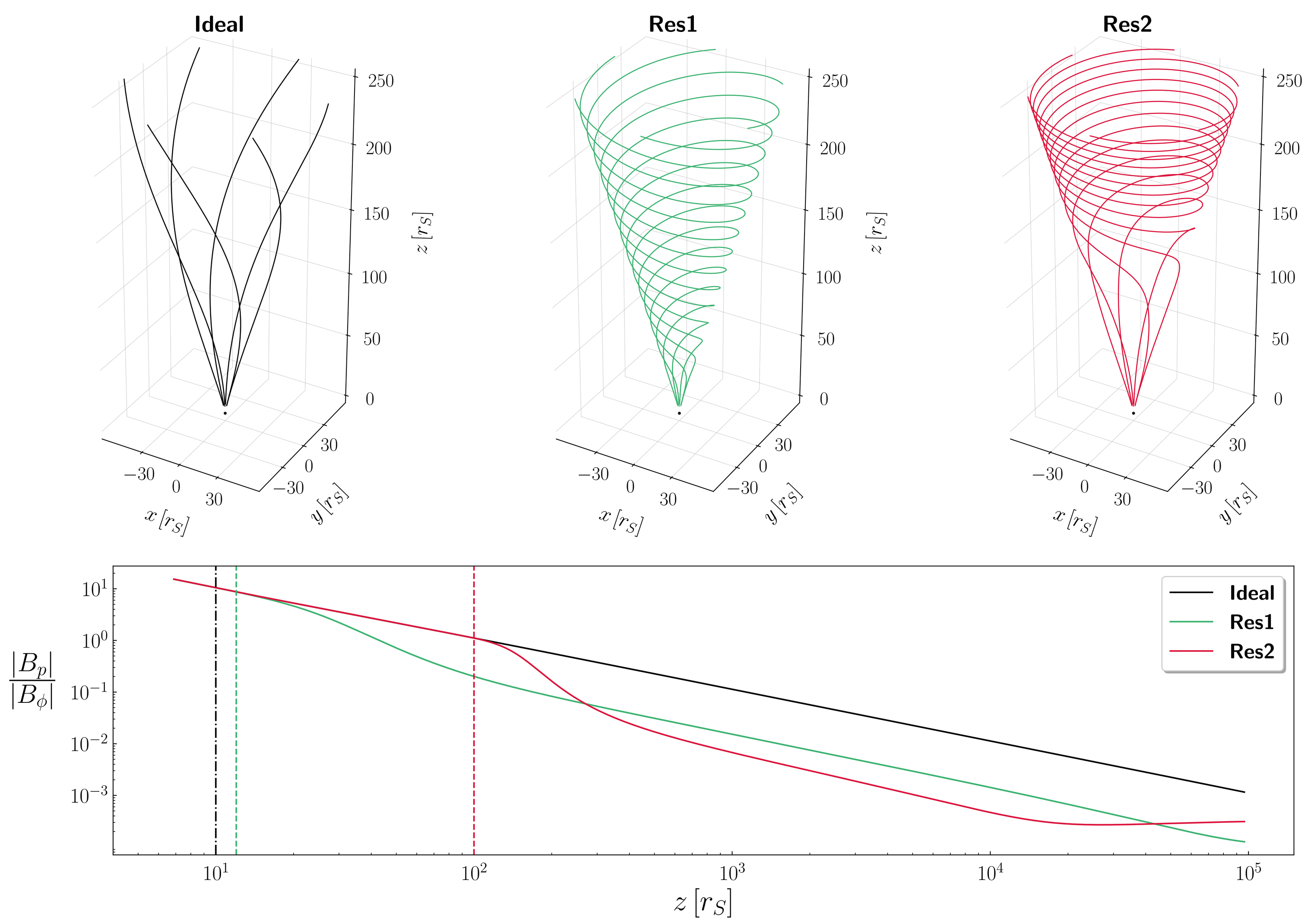

Figure 2. Magnetic field lines and poloidal-to-toroidal field ratio for the **Ideal** MHD solution and for resistive solutions Res1 and Res2.

- Over the dissipation region an electric potential gradient emerges along the magnetic flux lines
- This amplifies the jets' charge density and consequently their axial current density (Fig. 3)
- The amplified current density strengthens the resistive jets' toroidal magnetic field

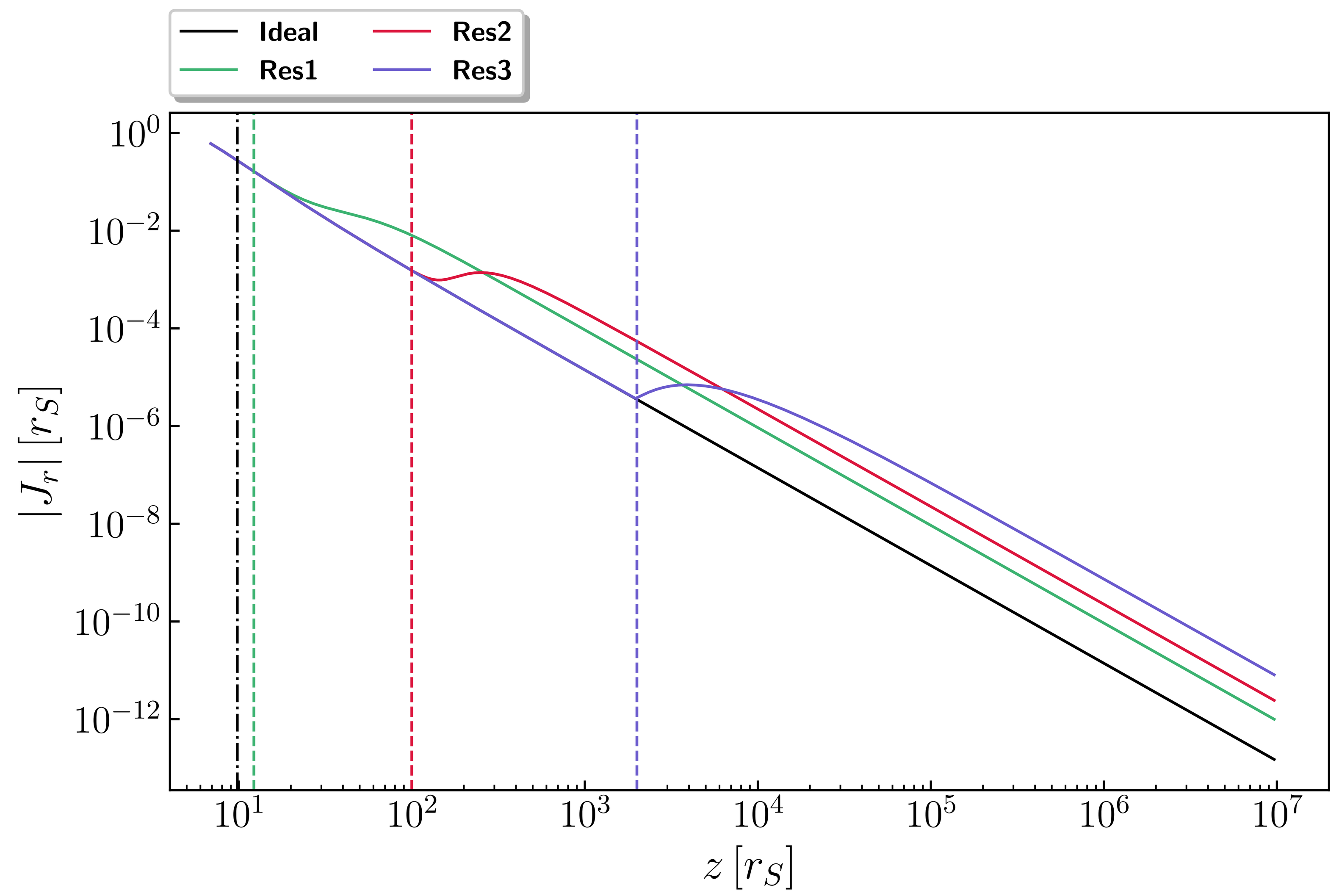

Figure 3. Current density along the jet axis.

Find the paper here:

Loules & Vlahakis (2025), A&A, forthcoming article

References

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[2] B. Ripperda, F. Bacchini, O. Porth, E. R. Most, H. Olivares, A. Nathanail, L. Rezzolla, J. Teunissen, and R. Keppens. General-relativistic Resistive Magnetohydrodynamics with Robust Primitive-variable Recovery for Accretion Disk Simulations. *ApJS*, 244(1):10, 2019.

[3] D. Ryu, I. Chattopadhyay, and E. Choi. Equation of State in Numerical Relativistic Hydrodynamics. *ApJS*, 166(1):410–420, 2006.