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RELATIVISTIC RECONNECTION WITH EFFECTIVE RESISTIVITY: A COMPARISON BETWEEN FLUID AND KINETIC MODELS

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Abstract. We present a study that compares, for the first time, results from a typical Particle-In-Cell (PIC) model of relativistic reconnection with those obtained in the resistive relativistic magnetohydrodynamic (ResRMHD) regime with a non-constant effective resistivity, which can capture the local enhancement of magnetic dissipation within the reconnecting current sheet. The dynamical change of the resistivity leads to significant deviations from the standard case of a constant dissipation parameter and a good agreement with fully-kinetic models. The effective resistivity leads to a boost of the reconnection rate even a very modest resolutions, demonstrating how the introduction of kinetic effects can bridge the gap between the PIC and ResRMHD frameworks.

Keywords: magnetic reconnection, magnetohydrodynamics (MHD), relativistic processes, acceleration of particles, numerical methods, plasmas

1 Introduction

Magnetic reconnection is one of the most important physical processes capable of powering many high-energy transient phenomena (such as flares from black hole magnetospheres, blazar jets, and fast radio bursts), as the dissipation of magnetic fields can efficiently accelerate charged particles and thus lead to the production of the observed non-thermal emission. Numerical models adopting a fully-kinetic approach (as in PIC simulations) can self-consistently capture the properties of magnetic dissipation during a reconnection event, but their high computational cost makes the study of the large-scale dynamics of compact objects magnetospheres extremely challenging. On the other hand, fluid models (e.g. relativistic MHD) are instead widely used to describe the accretion/ejection of matter and magnetosphere dynamics on temporal and spatial scales set by a black hole, but they generally can't reproduce a self-consistent dissipation mechanism, being limited by either numerical dissipation (Puzzoni et al. 2021; Berta et al. 2024; Mignone et al. 2024) or an explicit resistivity parameter not constrained by the microphysics (Mattia et al. 2023; Mattia et al. 2024).

We present 2D numerical simulations of reconnecting Harris current sheet performed with the ResRMHD module of the `PLUTO` code (Mignone et al. 2007, 2012) using a recently proposed prescription for an effective resistivity that has been derived from first-principles fully-kinetic PIC simulations (Selvi et al. 2023). We compare our models with PIC simulations performed with the `Zeltron` code (Cerutti et al. 2013; Cerutti & Werner 2019) that use the same numerical box and initial conditions as the fluid models.

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2 Problem setup

Starting from Eq. 2 of Selvi et al. (2023) we manipulate it to express the proposed effective resistivity in terms of quantities available in a standard ResRMHD model (Bugli et al. 2024), i.e.

$$\bar{\eta}_{\rm eff} = \frac{\bar{\delta}_u}{\bar{\rho}} \sqrt{\left(\bar{\delta}_u \partial_{\bar{y}} \bar{v}_y\right)^2 + \bar{e}_z^2}\,, \tag{2.1}$$

where $\bar{\eta}_{\rm eff}$ is the resistivity parameter, $\bar{\rho}$ is the rest mass density, $\bar{v}_y$ is the velocity component transverse to the initial current sheet, $\bar{e}_z$ is the electric field in the fluid comoving frame and $\bar{\delta}_u$ is an *effective skin depth* corresponding to the physical units employed for lengths and mass density by the code. Barred quantities are expressed in dimensionless code units.

We consider a standard 2D Harris current sheet of length $L_0 = 1$ and width $a = 0.01$ with no guide field in pressure balance, where the upstream magnetic field B_0 is derived from the upstream magnetization σ_0 and density ρ_0. We consider an upstream thermal to magnetic pressure ratio $\beta_0 = 0.01$, and effective skin depth $\bar{\delta} = 0.02$ and a numerical box with sizes $[0, 4L_0] \times [-80\sqrt{\sigma_0}a, 80\sqrt{\sigma_0}a]$, to which we impose periodic and reflective boundary conditions along x and y, respectively.

3 Results

Our ResRMHD model with effective resistivity produces a fast onset of reconnection on time scales shorter than those associated to the *ideal tearing mode* (Del Zanna et al. 2016). The associated reconnection rate is $\beta_{\rm rec} \simeq 0.16$, which is in quantitative agreement with the corresponding PIC simulation results and exceed by at least an order of magnitude what is obtained using a constant resistivity across the domain. Fast reconnection is obtained even at modest resolutions ($L_0/\Delta x \sim 100$), as the local increase in resistivity leads to a fragmentation of the current sheet without causing its widening due to strong diffusion. This is in stark contrast with typical fluid models of magnetic reconnection, which require sufficiently low resistivity (hence high resolutions) to capture the onset of the plasmoid instability, the fragmentation of the current sheet, and the formation of multiple X-points. The reconnection dynamics from our effective resistivity models is consistent with the PIC results for a range of magnetizations ($\sigma_0 = \{1, 4, 10\}$), as it can reproduce a similar growth of the reconnected magnetic field, magnetic flux, and reconnection rate. An increase (decrease) in the upstream density produces a decrease (increase) in effective resistivity, which quantitatively impacts the efficiency of the reconnection event.

4 Perspectives

In a future work we will assess the impact of effective resistivity on the acceleration of particles, which depends crucially on the formation of regions with strong resistive electric field. An important application will include the modeling of large-scale accretion flows around compact objects, as a qualitatively different dissipation dynamics is likely to significantly impact how matter is accreted onto the central object along with the properties of the associated jets.

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