Title: Understanding Magnetic Dissipation in the Magnetar Magnetosphere Regime

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Collection/Series: Magnetic Fields Around Compact Objects Workshop

Date: March 26, 2025 - 12:20 PM

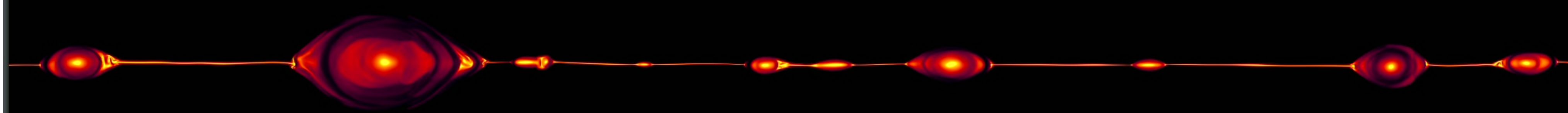
URL: https://pirsa.org/25030134

Abstract:

Magnetars produce the brightest detected outbursts in the X-ray and radio bands, offering unique opportunities to probe extreme plasma physics and exotic quantum electrodynamic processes. Magnetospheric reconnection is a suspected mechanism for generating bursts and giant flares. However, modeling the interplay between small-scale reconnection processes and the global structure of magnetar magnetospheres remains a major theoretical and computational challenge. This is due to the multi-scale nature of the problem: resolving localized reconnection while capturing the global dynamics of the star in a single numerical simulation is computationally prohibitive. Global models have primarily used force-free schemes which are unable to capture dissipation, recent advances have made global ideal magnetohydrodynamic models viable but will still lack the explicit resistivity needed to carefully study the reconnection physics. This motivates the use of local resistive relativistic magnetohydrodynamic simulations which probe the details of reconnection in the magnetospheric regime.
These local simulations allow for the quantification of magnetic energy dissipation and the role it plays in powering emission due to magnetic reconnection inaccessible to force-free models. Furthermore, the use of ideal global models motivates the careful quantification of numerical dissipation in ideal schemes.

We use 1D and 2D tests to quantify the nature of magnetic dissipation in resistive and ideal, relativistic magnetohydrodynamic and force-free-electrodynamic schemes. Our tests, which are agnostic to the form of the effective numerical dissipation operator in ideal schemes, probe both Ohmic dissipation and magnetic reconnection of current structures in the highly magnetized strong guide field regime. These tests characterize exactly how well schemes commonly used to model magnetic dissipation in magnetar and pulsar magnetospheres perform compared to resistive relativistic magnetohydrodynamics. We find Ohmic dissipation in both ideal magnetohydrodynamic and force-free schemes to be subdiffuse, while producing an analogue to the Sweet-Parker regime at low resolutions and an asymptotic reconnection rate at high resolutions. The resistive force-free scheme we test is found to exactly reproduce the Ohmic diffusion and the Sweet-Parker regime, but differs from the full resistive relativistic magnetohydrodynamic result in the asymptotic regime.

Magnetic diffusion and reconnection: a comparison between physical models



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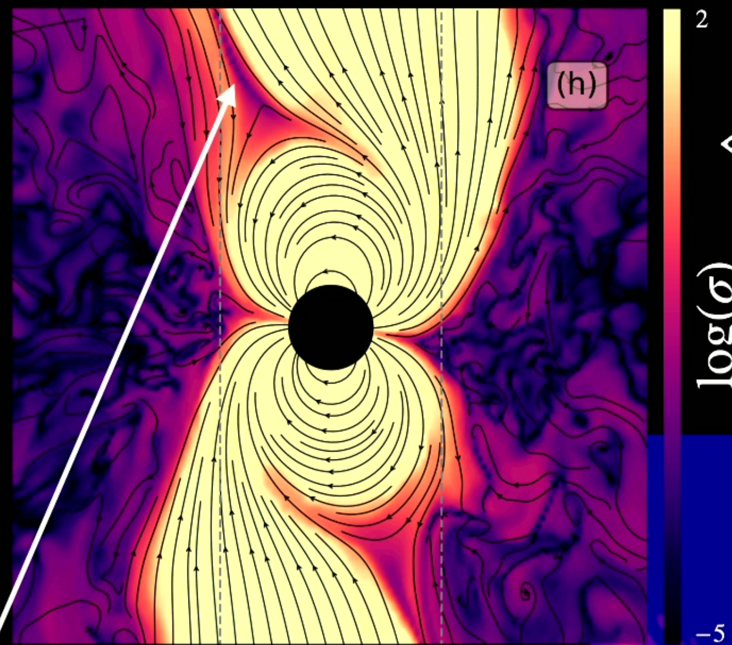
Collaborators: Tanisha Ghosal, James R. Beattie, Bart Ripperda, Oliver Porth, and Fabio Bacchini

Introduction

Motivation

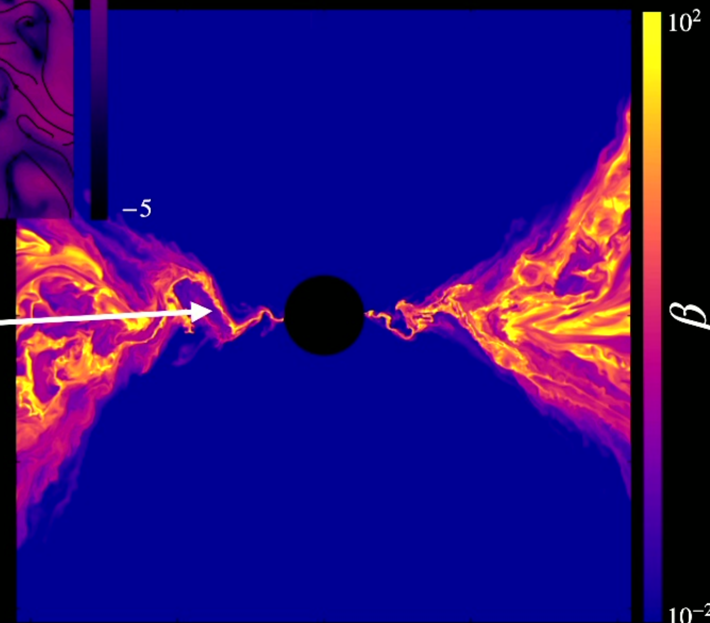
- Global simulations commonly use ideal models
- Assumed that numerical diffusion acts as an effective resistivity
- Includes simulations with reconnection



⇐ Accreting NS

(Das et al. 2023)

Accreting BH ⇒



(Ripperda et al. 2022)

Introduction

Overview

- Ran in BHAC (Porth et al. 2017, Olivares et al. 2019, Ripperda, Bacchini et al. 2019), total of 80+ simulations

Four Physical Models:

(1) Resistive MHD

(2) Ideal MHD

(3) ~~Magnetodynamics~~

(4) Resistive FFE
(Alic et al. 2012)

Two Tests:

(1) ~~1D Ohmic diffusion~~

(2) 2D magnetic reconnection

$$J = q\frac{E \times B}{B^2} + \frac{1}{\eta}\left[(E \cdot B)\frac{B}{B^2} + \Theta(E^2 - B^2)\frac{E}{B^2}\right]$$

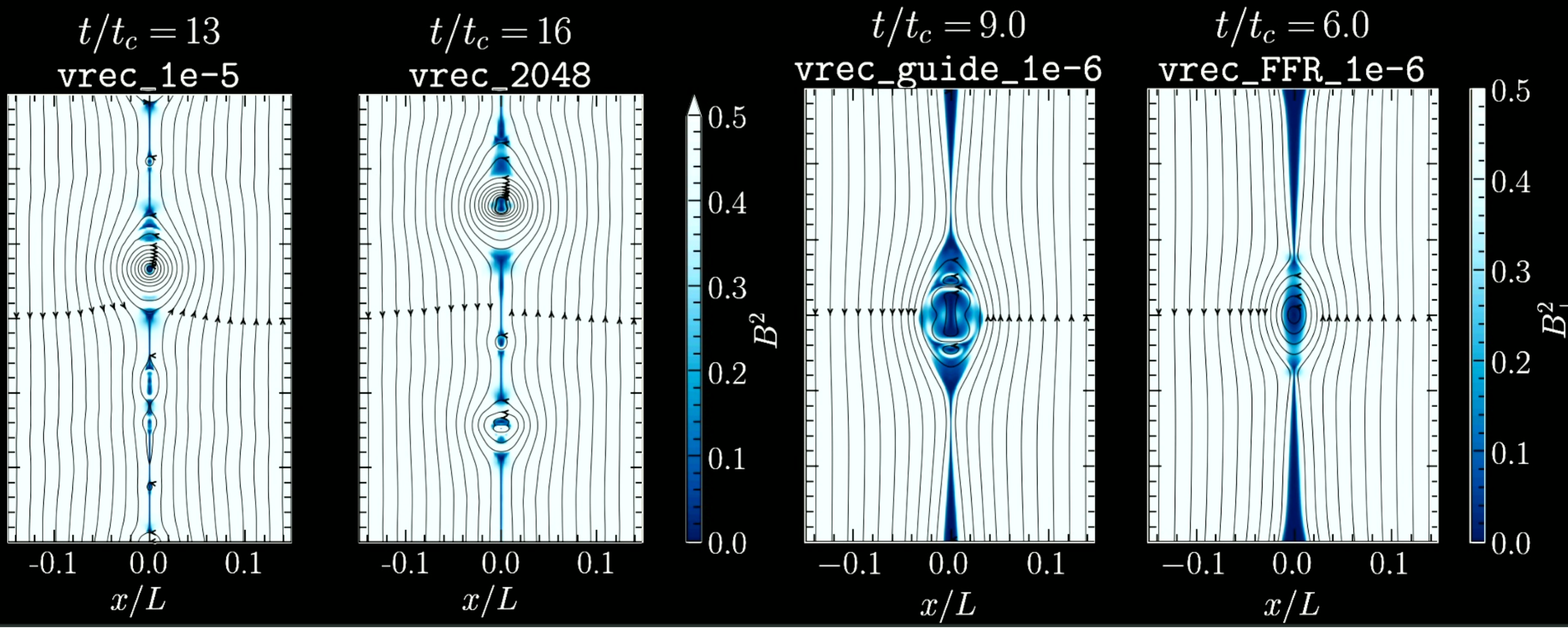
Magnetic Reconnection

Pressure balanced sheet

Resistive MHD vs Ideal MHD

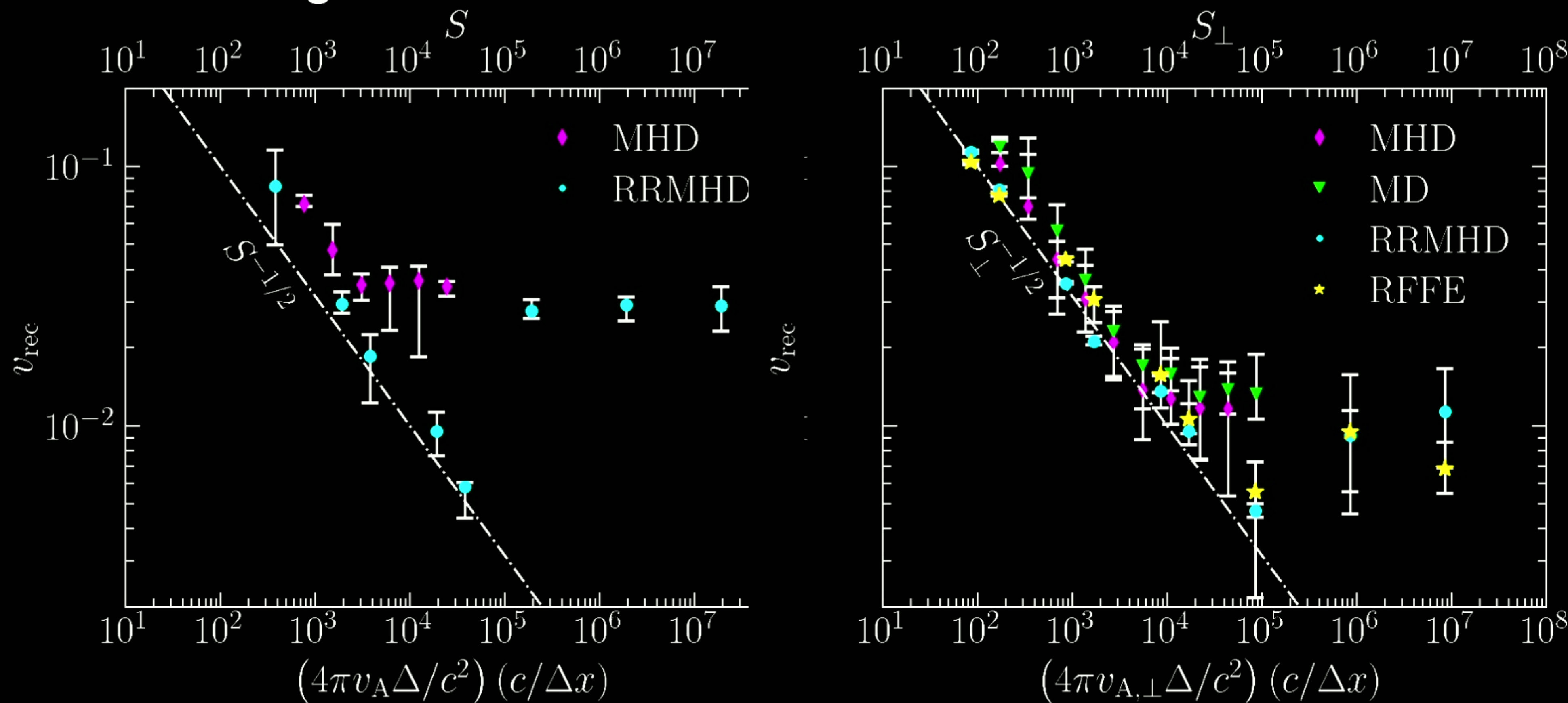
Guide Field balanced sheet

Resistive MHD vs Resistive FFE



Magnetic Reconnection

Time averaged reconnection rates



Magnetic Reconnection

Conclusion

- Discretization does a good job of mimicking reconnection rate, both SP and asymptotic regime

RECONNECTION ONLY: $$S_{\rm num} \simeq \frac{4\pi v_{\rm A}\Delta}{c\Delta x} \Rightarrow \eta_{\rm num} \simeq \frac{\Delta x}{c}$$

- Resistive FFE has the right reconnection rate, matches in SP differs in onset time in asymptotic regime
- Unclear whether the 2D understanding of asymptotic reconnection, and hence our conclusions, translate to 3D systems