Integrating Data-Driven and Physics-Based Modelling of Magnetosheath Dynamics

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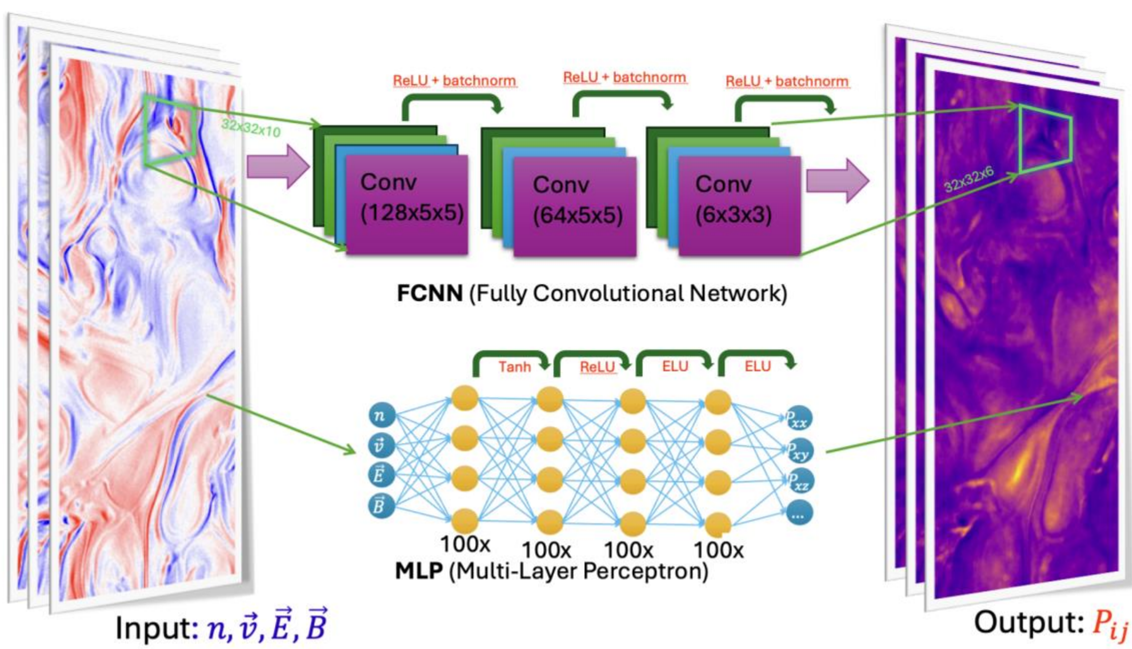
Understanding how the solar wind couples to Earth's magnetosphere remains one of the central challenges of space weather research. The turbulent magnetosheath - the plasma region between the bow shock and magnetopause - plays a critical role in controlling this coupling. However, modeling this system is inherently difficult. Fully kinetic Particle-in-Cell (PIC) simulations provide high fidelity but are computationally prohibitive for modelling global evolution. Hybrid fluid models are efficient but oversimplify electron physics by assuming a polytropic or isothermal equation of state. A gap remains between accuracy and efficiency, which limits understanding of space weather events.



We present a new hybrid physics–AI framework that bridges this gap by coupling physics-based kinetic ion models and neural network surrogates for the electron pressure tensor

- We train a Fully Convolutional Neural Network (FCNN) on outputs from ECsim (energy-conserving semi-implicit PIC simulations) of a magnetosheath decaying turbulence simulation.
- The learned surrogate provides a non-local electron closure that captures the pressure response to lower-order fluid moments. This nonlocal model significantly outperforms a local model (Multi-Layer Perceptron or MLP) and a baseline double-adiabatic model.
- This pressure tensor is coupled through Ohm's law with the electric field.
- This surrogate model is implemented in Menura, a GPU-accelerated hybrid PIC code, enabling online (a posteriori) coupling and testing with kinetic ions.

This is the first demonstration of hybrid PIC–AI integration for turbulent magnetosheath plasmas.