Intermediate shock substructures within a slow-mode shock occurring in partially ionised plasma

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Overview

- Partially ionised plasma is capable of supporting several types of stable MHD shocks.
- Slow-mode shocks are important in understanding the heating and dynamics of the solar chromosphere.
- We study numerically the fine substructure within slow-mode shocks in a partially ionised plasma.
- We discover that intermediate (Alfvén) shocks can form within the slow-mode shock under certain parameter regimes.

Introduction

- In MHD, several types of shocks are possible and can be classified based on the velocity transition across the shock.
- Slow-mode shocks are important in understanding fast magnetic reconnection [1], jet formation and heating in the solar atmosphere.
- The atmospheric conditions in the solar chromosphere allow both ionised and neutral particles to exist and interact.
- Fine substructures exist within slow-mode shocks in partially ionised plasma (e.g. chromosphere). This substructure can include the formation of additional shock transitions.
- The combination of MHD, shock formation and partial ionisation has wide applicability in many astrophysical systems, e.g., chromospheric jets and interplanitary/interstellar shocks.

Shock Conditions

- MHD shock transitions can be classified using the relationship between the flow velocity normal to the shock (v_n) and the characteristic speeds:
  - (1) superfast: $V_f < |v_n|$,
  - (2) subfast: $V_A < |v_n||V_f$,
  - (3) superslow: $V_s < |v_n| < V_A$,
  - (4) subslow: $0 < |v_n| < V_s$,
- Defining the upstream condition i and downstream condition j, several shocks of the from $i \rightarrow j$ are possible. The transitions relevant for this work are:
  - $3 \rightarrow 4$ slow shocks,
  - $2 \rightarrow 3, 2 \rightarrow 4$ intermediate shocks.
- Intermediate shocks exceed the Alfvén speed and feature a reversal in the magnetic field across the shock front.

Numerical Model

- Two fluid numerical simulations of slow-mode shocks are performed using the (PIP) code for solving interactions of neutral and ion-electron fluids [2]. The two fluids are coupled via collisional terms.
- Our initial conditions are an extension of the slow-mode shocks formed from reconnection proposed by Petschek [3]. The normalised initial conditions are given by:

$$B_x = 0.1 \quad (1)$$

$$B_y = -1.0(x > 0), 1.0(x < 0) \quad (2)$$

$$\rho_n = \xi_n \rho_{tot} \quad (3)$$

$$\rho_p = \xi_i \rho_{tot}(1 - \xi_n)\rho_{tot} \quad (4)$$

$$P_n = \frac{\xi_n}{\xi_n + 2\xi_i} P_{tot} = \frac{\xi_n}{\xi_n + 2\xi_i} \beta \frac{B_0^2}{2} \quad (5)$$

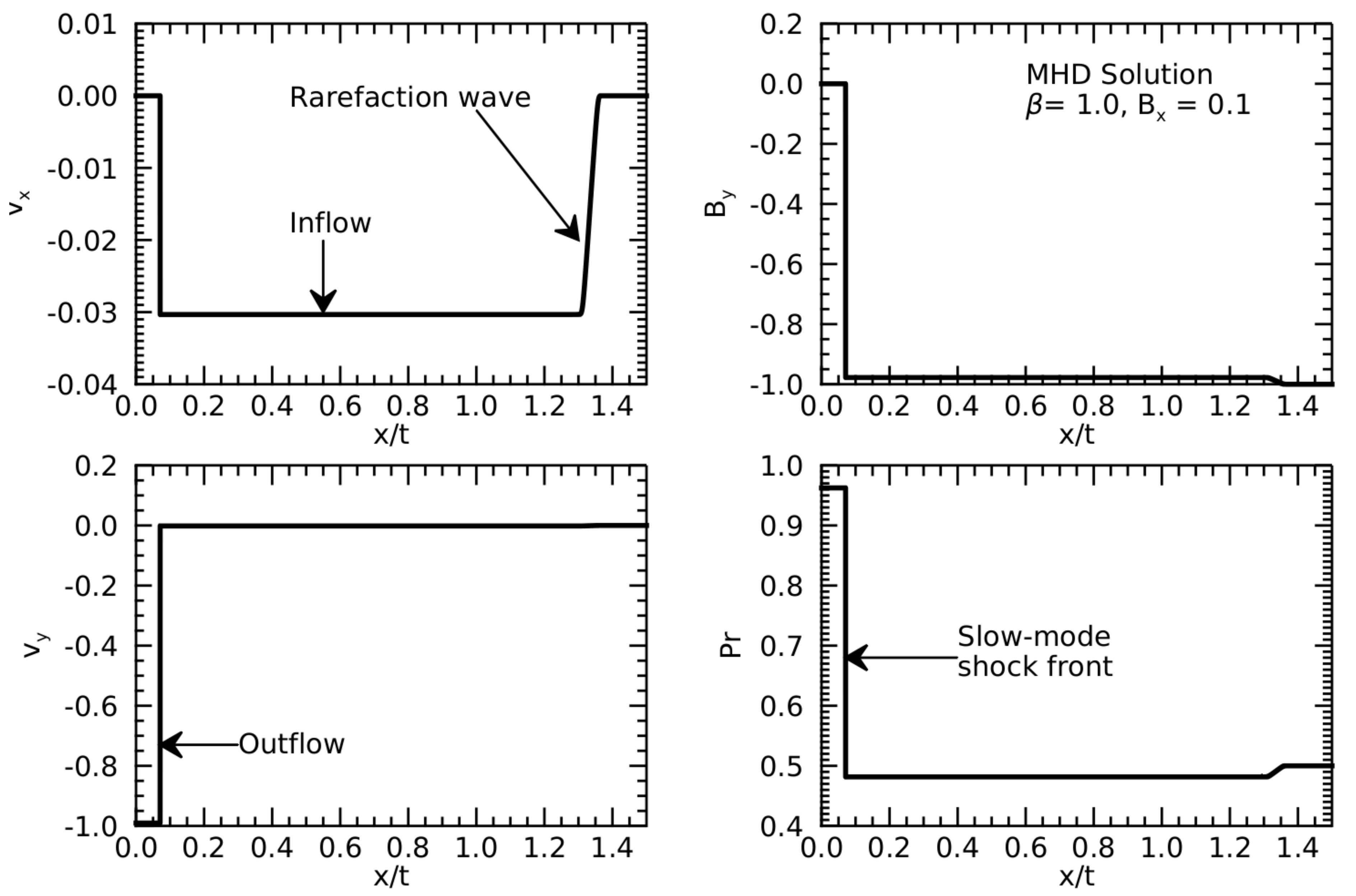
$$P_p = \frac{2\xi_i}{\xi_n + 2\xi_i} P_{tot} = \frac{2\xi_i}{\xi_n + 2\xi_i} \beta \frac{B_0^2}{2} \quad (6)$$

- Previous work [2] has used similar initial conditions to investigate substructure in slow-mode shocks.
- We use a different parameter regime and find intermediate shocks. The results presented here use $\beta = 1$ and $\xi_n = 0.9$.
- 128000 grid cells are used and features are well resolved.

Results

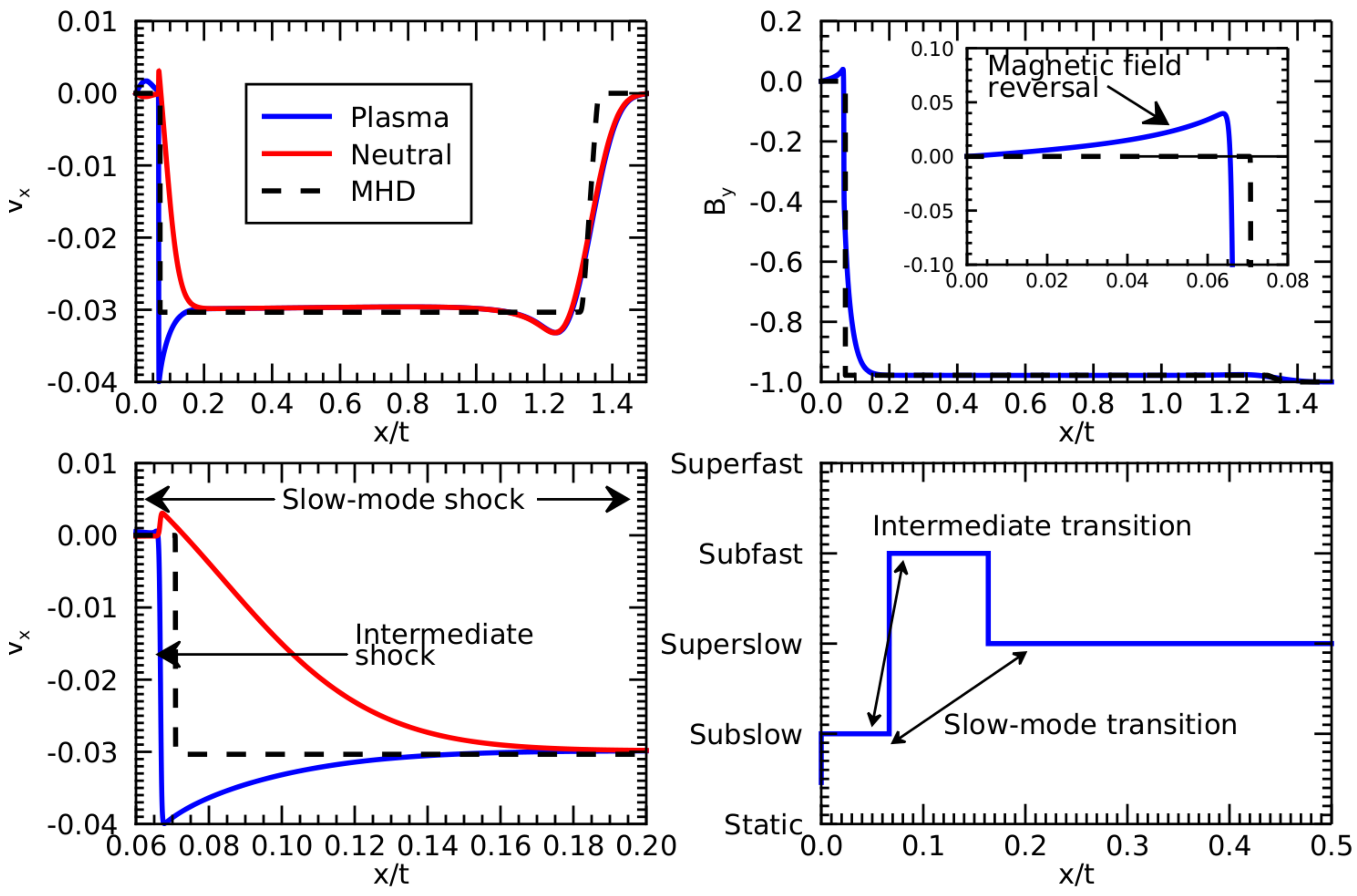
- An MHD simulation using the same initial parameters was performed as a reference case and used to calculate the shock velocity.
- PIP simulation is ran until it approaches a steady-state solution.
- Reversal in magnetic field observed across the shock front in PIP simulation but not in MHD simulation, indicating an intermediate shock formed due to partially ionised effects.

Reference MHD solution



- Magnetic field expansion produces a fast-mode rarefaction wave and a slow-mode shock.
- Rarefaction wave drives inflow towards the shock front.

PIP Solution



- Far more substructure forms in the PIP solution than in the MHD solution.
- PIP solution has a finite shock width due to decoupling and recoupling of species.
- Collisional terms allow a stable intermediate shock to exist within the slow-mode shock characterised by a reversal in the magnetic field across the shock front.

Conclusion

- Partially ionised plasma results in interesting shock substructures forming.
- We discover that stable intermediate shocks (featuring a reversal in magnetic field) can form due to the collisional terms, leading to additional heating.
- Additional diffusion mechanisms (e.g., resistivity, viscosity) may add further heating.

References

[1] T. Shibayama, K. Kusano, T. Miyoshi, T. Nakabou, and G. Vekstein *Physics of Plasmas*, vol. 22, p. 100706, Oct. 2015.
[2] A. Hillier, S. Takasao, and N. Nakamura *A&A*, vol. 591, p. A112, June 2016.
[3] H. E. Petschek *NASA Special Publication*, vol. 50, p. 425, 1964.