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 magnetosonic shocks [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 interplanetary/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: \( V_f < |v_n| \),
  - (3) superlow: \( V_s > |v_n| > V_f \),
  - (4) sublow: \( 0 < |v_n| < V_s \).
- Defining the upstream condition \( i \) and downstream condition \( j \), several shocks of the form \( i \to j \) are possible. The transitions relevant for this work are:
  - \( 3 \to 4 \) slow shocks,
  - \( 2 \to 3 \) slow shocks,
  - \( 2 \to 4 \) 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 (PI)P 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:
  \[
  B_x = 0.1 \\
  B_y = -1.0(x > 0), 1.0(x < 0) \\
  \rho_0 = \xi_n \rho_{tot} \\
  \rho_p = \xi_p \rho_{tot} (1 - \xi_n) \rho_{tot} \\
  P_n = \frac{\xi_n + 2\xi_p}{\xi_n + 2\xi_p} \rho_{tot} B_z^2 \\
  P_p = \frac{\xi_p}{\xi_n + 2\xi_p} \rho_{tot} B_z^2 
  \]
- 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 run 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