Mode conversion of two-fluid shocks in a partially-ionised, isothermal, stratified atmosphere

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Context

- A wave propagating upwards in the solar atmosphere can naturally form a shock as the density decreases due to gravitational stratification.
- If the magnetic field is inclined, the shock undergoes mode conversion, where the shock separates into its fast and slow components.
- Mode conversion occurs where the sound and Alfvén speeds of the system are equal.
- The mode conversion height can be in the lower solar atmosphere which is partially ionised, i.e., both ionised (magnetohydrodynamic MHD) and neutral (hydrodynamic HD) species exist.
- The ionised and neutral species have different characteristic wave speeds and can support different types of shocks; the neutral species can only support sound waves, whereas the plasma species supports the full range of MHD modes.
- Here we study propagating shocks in a two-fluid medium and analyse the interactions between ion and neutral species, and potential observational consequences of two-fluid interactions.
- The full paper is published as Snow & Hillier, 2020. A&A, 637, A97

Numerical model

Numerical simulations are performed using the (PIP) code that evolves two-fluid (neutral, ion+electron) equations for a stratified medium using non-dimensional form. The species are thermally coupled with the coupling coefficients calculated using the average temperature and a free parameter α_0:

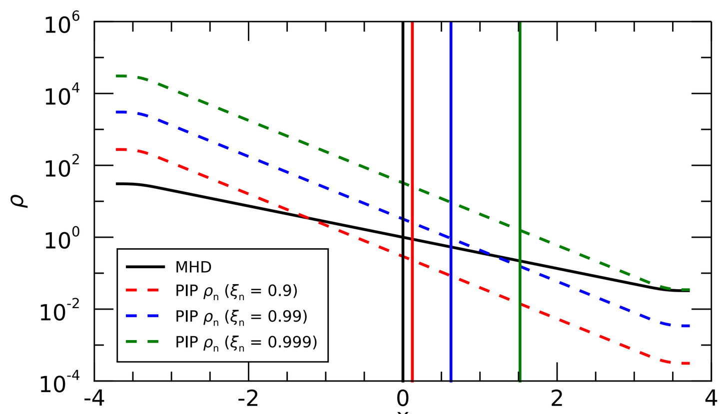
$$\alpha_c = \alpha_0 \sqrt{\frac{T_n + T_p}{2}}.$$

The isothermal atmosphere is defined using the pressure scale heights of the two species and integrating. Since the average mass of the neutral and plasma (ion+electron) species are different, the pressure scale heights are different by a factor of 2.

$$P_{p;n}(x) = P_{p;n}(0) \exp\left(- \int_{g_1}^{x} \frac{1}{\Lambda_{p;n}} dx' \right),$$

$$\Lambda_n = \frac{T_n}{\gamma g_x},$$

$$\Lambda_p = \frac{2T_p}{\gamma g_x}.$$



The mode conversion height for the MHD simulations is located at $x = 0$, denoted in Figure 1 by the black vertical line. In the two-fluid case, there are two potential mode conversion heights: for the decoupled plasma, mode conversion point is at $x = 0$, as with the MHD simulation due to the normalisation employed. The mode conversion height can also be calculated using the bulk (neutral+ion) species, marked in Figure 1 as the coloured vertical lines. Increasing the neutral fraction increases the bulk mode conversion height. In this poster, we use the case where the neutral fraction at the base of the domain is set to $\xi_n = 0.999$ (green lines).

Changing the collisional coefficient

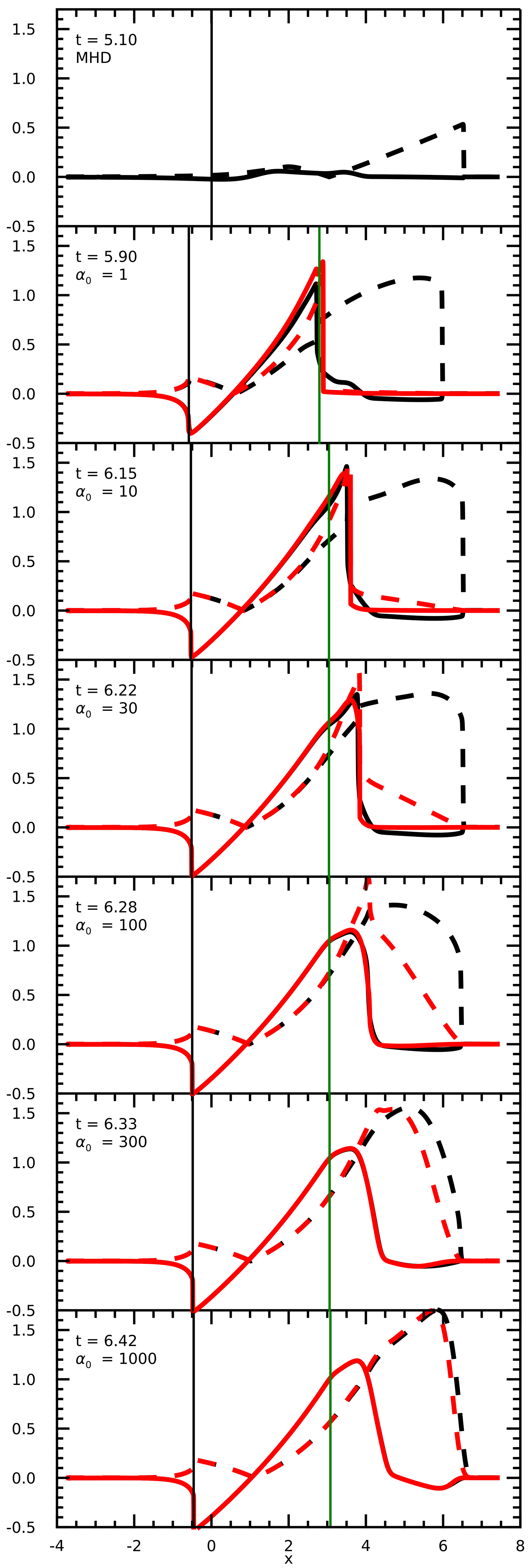
A key parameter is the collisional coupling α_c that governs the interactions between the ion and neutral species. Figure 2 shows the fast (dashed) and slow (solid) components of the system for the plasma (black) and neutral (red) species.

MHD For the MHD simulation, the shock separates into slow (solid) and fast (dashed) components at the mode conversion height. The fast shock remains sharp, whereas the slow component smooths and no longer satisfies a shock transition.

Weak coupling For the two-fluid cases with weak coupling ($\alpha_0 = 1, 10$) the neutrals (red) respond and interact with the slow component of the plasma velocity. Similar structure exists in but neutral and plasma species for the slow-component. The plasma fast component (black dashed) is mostly decoupled from the neutral species.

Moderate coupling As the species become more coupled ($\alpha_0 = 30, 100$), there is a slight response of the neutral species to the fast-mode shock, shown by the red dashed line. The fast-mode shock also demonstrated a slight change in structure as the neutrals provide a drag that increases the width of the shock.

Strong coupling As the coupling increases further ($\alpha_0 = 300, 1000$), the system tends towards an MHD system with the medium acting as a bulk fluid. There is a strong response in the fast-mode shock due to the neutral species and similar structure exists. The width of the shock has started to reduce as the system begins to act like a bulk fluid.



Shock Width

The amount of drag exerted on the fast mode shock by the neutral species depends on the collisional coefficient α_c. At infinite or zero coupling, the system is MHD-like. In the finitely-coupled regime, the fast-mode shock has a finite-width due to ion-neutral interactions that can exceed the pressure scale height.

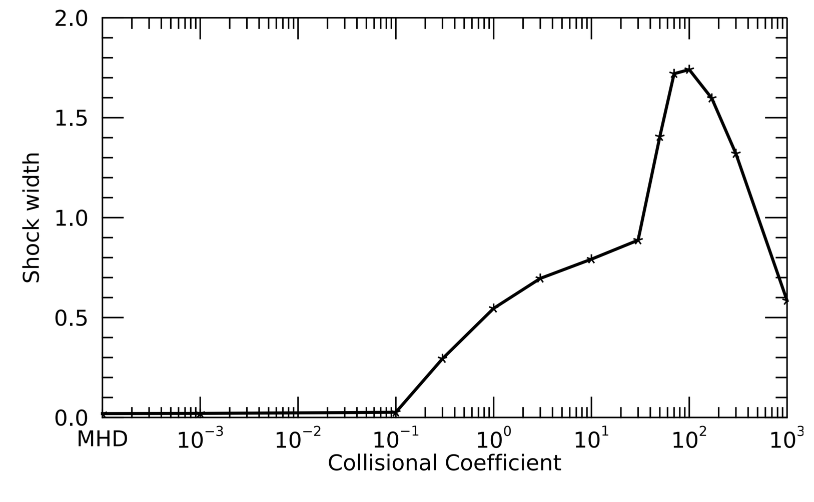
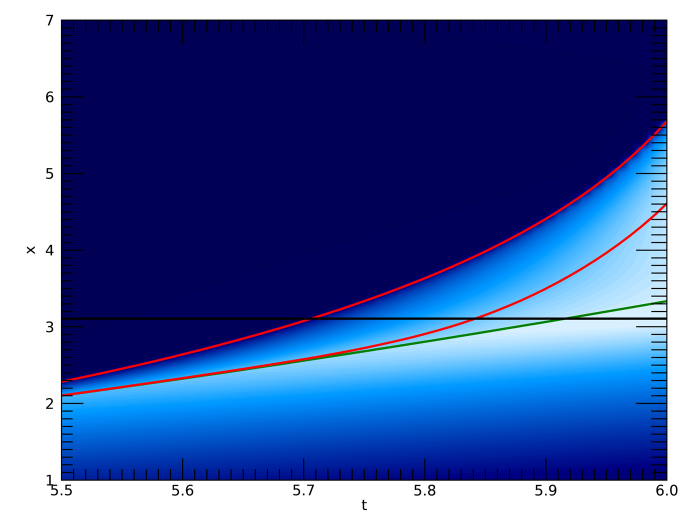
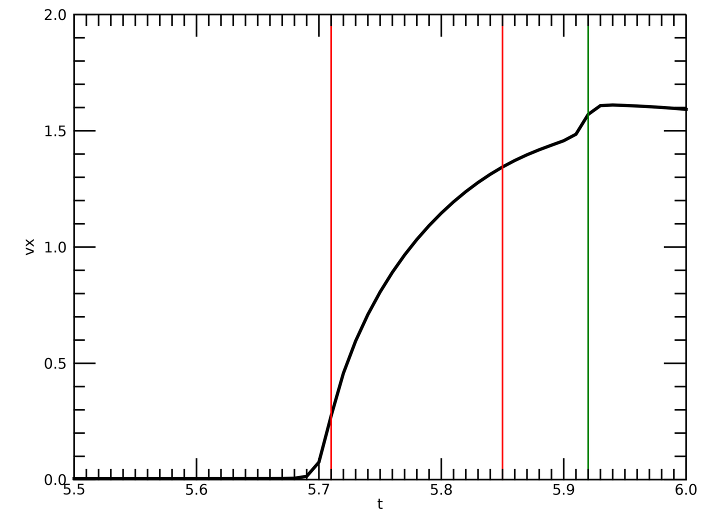


Figure 3: Shock width in pressure scale heights

Potential Observable

A potential observable of two-fluid effects in the solar atmosphere is the relatively large finite width of the fast-mode shock. Figure 4a shows a contour of the vertical velocity through time, with the fast-mode shock outlined in red. Sampling the vertical velocity at a given height gives an estimate of the observable Doppler velocity, as shown in Figure 4b. The observational signature of the fast-mode shock is therefore a gradual rise in the Doppler velocity.





In dimensional units, the fast-mode shock should manifest as a gradual rise of Doppler velocity over approximately 6 seconds.

Summary

- Propagating waves naturally steepen into shocks in the solar atmosphere and undergo mode conversion, separating into slow and fast components.
- When two-fluid effects are important the interplay between neutral and ionised species produces a finite-width in shocks.
- In the finitely coupled regime, the neutral drag results in a large finite-width for the fast-mode shock, exceeding a pressure scale height for a range of collisional coefficients.
- A potential observable of two fluid effects is estimated as a gradual rise in Doppler velocity over approximately 6 seconds for fast-mode shocks.
- The full paper is published as Snow & Hillier, 2020. A&A, 637, A97