Stability of shock fronts in the partially-ionised lower solar atmosphere

Ben Snow & Andrew Hillier (University of Exeter, UK) Contact:b.snow@exeter.ac.uk

CLICK FOR FULL PAPER

Context

- Shocks are regularly observed in the lower solar atmosphere, for example, umbral flashes which have average lifetimes of roughly a minute.
- For ideal magnetohydrodynamic (MHD) theory, slow-mode shocks should become unstable to the corrugation instability, triggered by the inhomogeneities in the solar atmosphere, see the schematic in Figure 1(left).
- By contrast, a hydrodynamic (HD) shock is stable to the corrugation instability, Figure 1(right).
- The lower solar atmosphere is partially ionised and consists of both HD and MHD fluids, and the stability of shocks to the corrugation instability is unclear.
- Here I present numerical results to investigate the stability conditions for a partially-ionised slow-mode shock with regards to the corrugation instability.
- The full paper is published as Snow & Hillier, 2021. A&A, in press

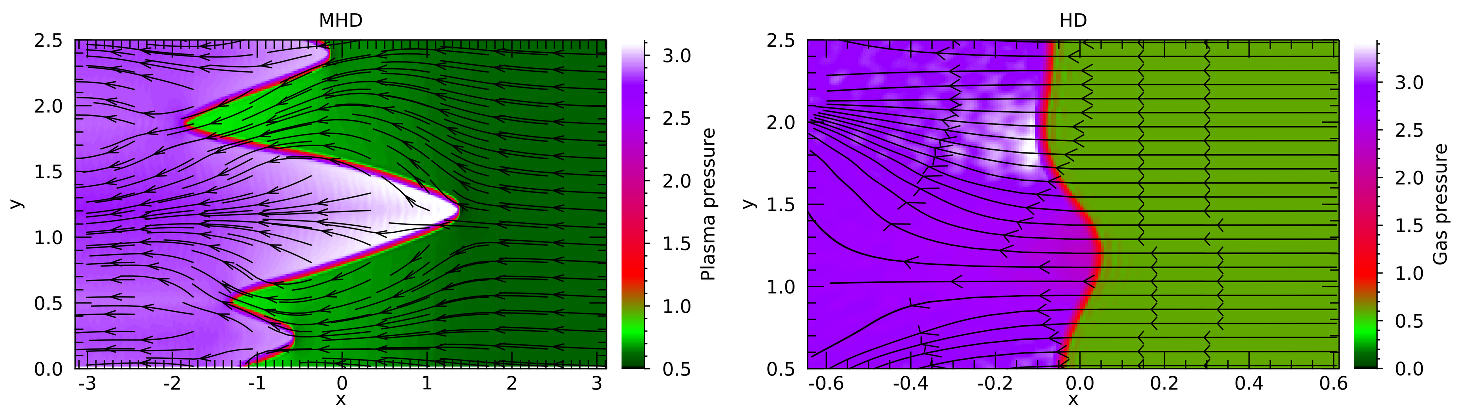

Figure 1: Corrugation instability in MHD (left) and HD (right) shocks.

Numerical model and initial conditions

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

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

We model a parallel slow-mode shock in the shock frame and place a small density perturbation in the upstream medium.

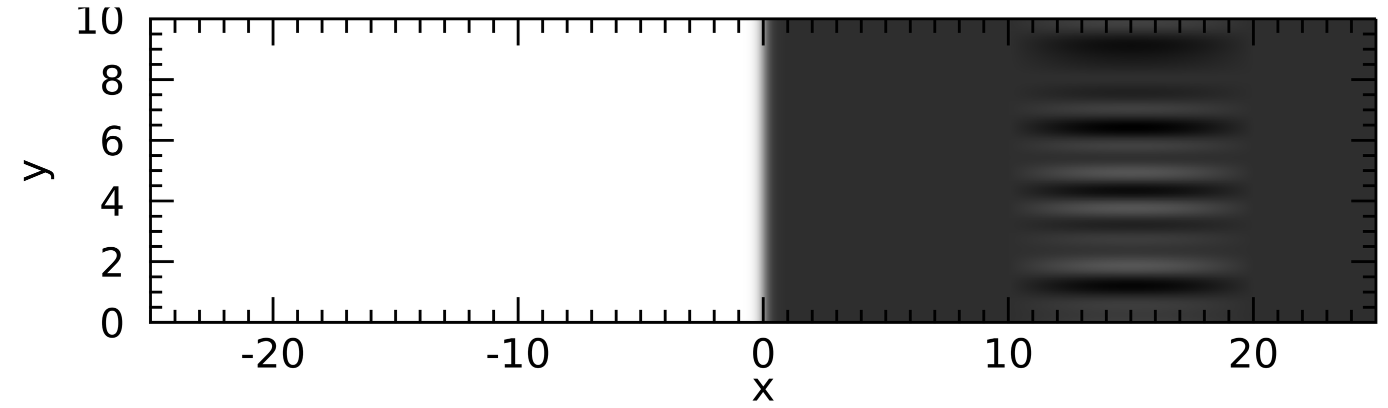

Figure 2: Initial density profile

The two-fluid case is designed such that the bulk (plasma+neutral) fluid is the same as the MHD simulation. The initial shock front has a Mach number of $M = 2$ and the downstream conditions are calculated analytically based on the upstream values.

Shock front evolution at different coupling

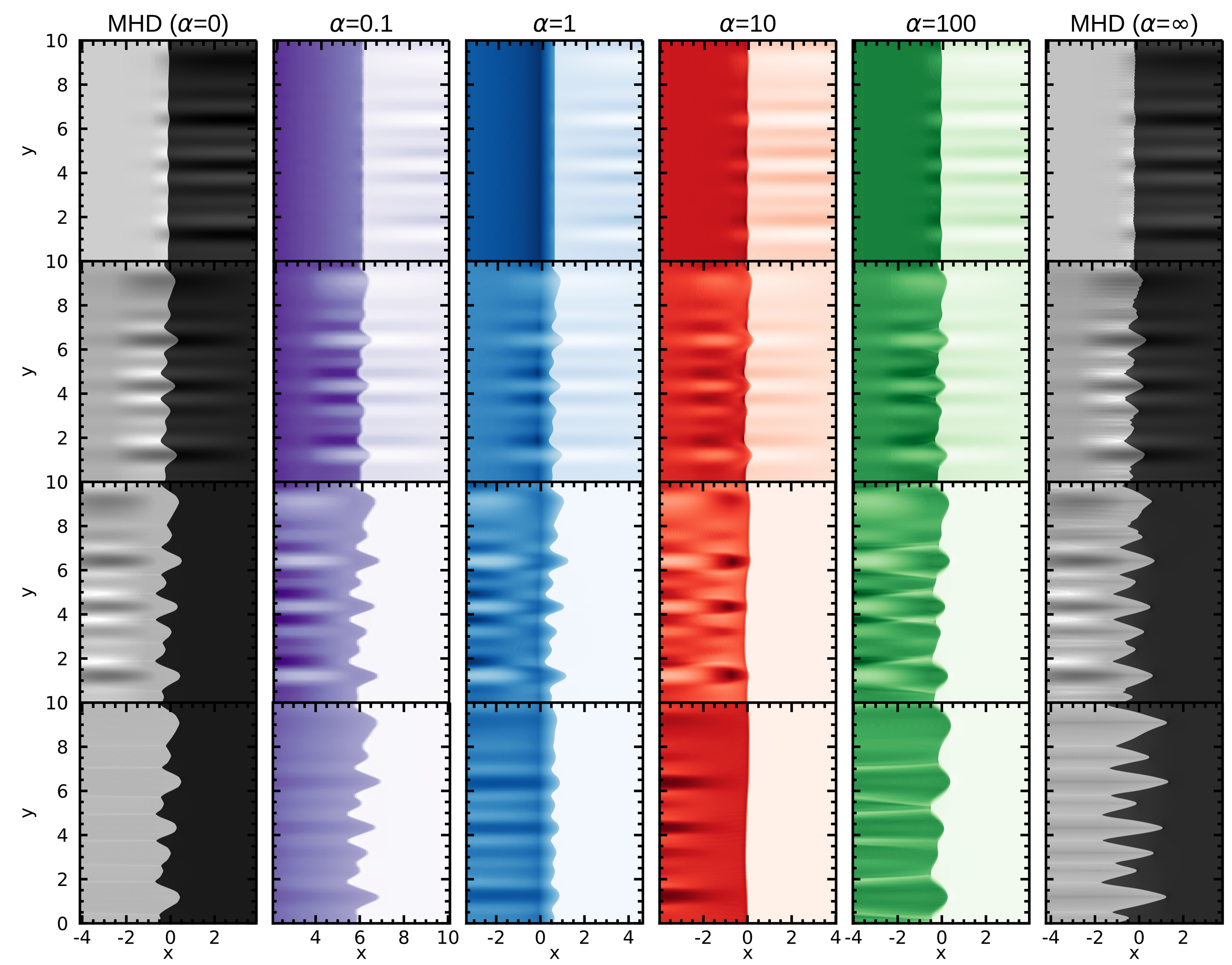

Figure 3: Timeseries of the corrugation instability for different levels of collisional coupling

For single-fluid MHD models, we consider two cases that mimic a fully coupled and a fully decoupled case. For the PIP simulations, we consider a range of coupling coefficients to study weakly coupled, finitely coupled, and strongly coupled cases. Figure 3 shows the time series for different levels of coupling. For the MHD cases, the shock front is unstable, however, in the finitely coupled regime the shock stabilises.

For our partially ionised simulation, the plasma shock front is ahead of the neutral shock front and hence encounters the perturbation first. This results in the plasma shock front being corrugated first, leading to a small initial instability. The flow entering the neutral shock is then stabilised. A schematic of the slow patterns in the two-fluid model is shown in Figure 4. In this simulation, the neutral fraction is 0.9 hence the medium is mostly neutral and the stabilisation provided by the neutrals is larger than the rate at which the plasma shock front is going unstable. One would expect that for different neutral fraction or finite shock widths, the stability conditions could be different.

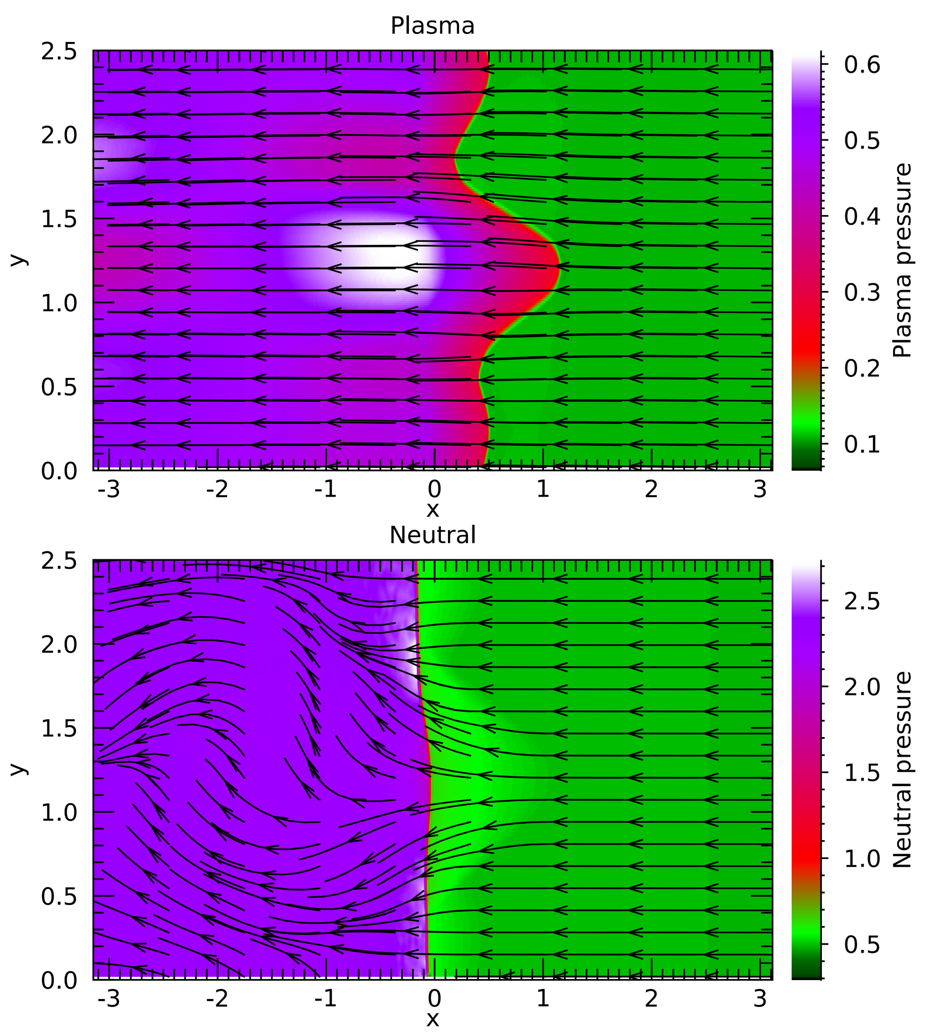

Figure 4: Schematic for two-fluid corrugation

Growth rate

The integrated enstrophy around the shock is shown in Figure 5(left) where the time zero corresponds to the shock encountering the perturbation. The corresponding time derivative at time $\tau = 10$ is shown in Figure 5(right). One can see that at the extremes of weakly coupled and strongly coupled, the shock front is unstable and the corrugation is growing, as expected. In the finitely coupled regime however, the neutral response is sufficient to stabilise the shock front. Overplotted on Figure 5(right) is the theoretical stability range which pairs well with the numerical result.

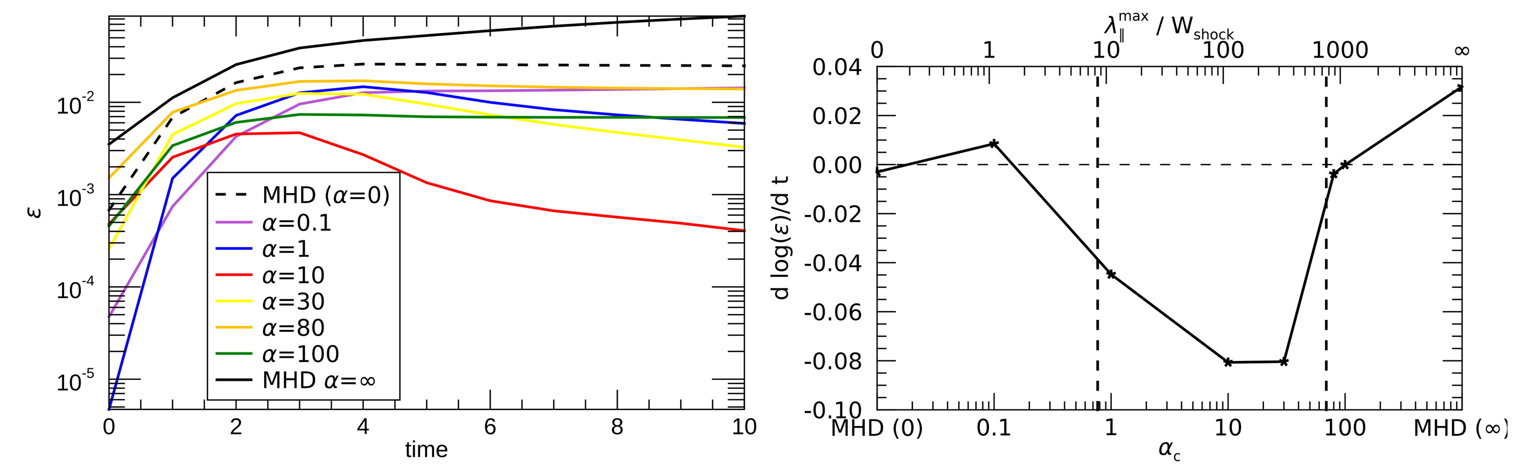

Figure 5: (left) Integrated enstrophy for different levels of coupling. (right) Time gradient of integrated enstrophy at time t=10.

Observable consequences

The theoretical stability range for partially ionised shocks can be expressed determined from the atmospheric coupling, the Mach number of the shock, and the local upstream sound speed:

$$\alpha_{c,\min}\rho_n^u = \frac{2\pi c_s^u}{\lambda_\parallel^{\max}}\frac{2(M^2-1)}{M(\gamma-1)}, \alpha_{c,\max}\rho_p^u = \frac{2\pi c_s^u}{\lambda_\parallel^{\min}}\frac{2(M^2-1)}{M(\gamma-1)}, \quad (1)$$

Applying this to umbral flashes, which have Mach numbers between $M = 1$ and $M = 1.7$ (Anan+2019) and using the coupling frequencies in the upper chromosphere (Popescu+2019) of $\nu_{in} = 3 \times 10^2, \nu_{ni} = 3\ s^{-1}$ with a typical sound speed of $c_s = 8$ km/s gives a stable range of wavelengths between approximately 0.6 and 56 km (for M=1.7).

Key results

- Partially ionised shocks fronts can be stable to the corrugation instability in the finitely coupled regime, whereas the weakly and strongly decoupled regimes are unstable.
- The theoretical stability range developed here can be used to estimate the expected behaviour of shocks in the solar atmosphere
- This may have consequences for observational targets in the lower solar atmosphere.
- The full paper is published as Snow & Hillier, 2021. A&A, in press