# Reflection of Alfvén Waves in the Solar Atmosphere

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## 1. Abstract

Alfvén waves have previously been shown to be strongly reflected from the chromosphere and transition region. Most of these studies have focussed on simple magnetic field geometries (uniform or thin flux tube). Observational studies have shown Alfvén waves in the solar atmosphere with sufficient power to heat the solar corona and accelerate the solar wind. We aim to extend the model of propagation and reflection to more general flux tube geometries. With the utilization of a Klein-Gordon equation, the net energy flux can be significantly affected by varying field line geometries.

## 2. Introduction

Alfvén waves can be generated through random motions or magnetic reconnection in the photosphere or chromosphere. Current models conclude that Alfvén waves are strongly reflected at the chromosphere and transition region, primarily at lower frequencies. Higher frequency waves are less reflective, however they steepen rapidly into shocks before reaching the corona. These models are primarily based on thin flux tube approximations, where the tube thickness is small compared to the scale of magnetic field variation. In reality, magnetic field lines are expected to diverge from the photosphere to the corona. We aim to implement these more general geometries into a new model with divergent magnetic field lines. This model will involve the use of a Klein-Gordon equation derived from the induction and momentum equation. If reflection is reduced at lower frequencies, the Alfvén waves can propagate into the corona and contribute to coronal heating and solar wind acceleration, two longstanding mysteries in solar physics.

## 3. Plasma Conditions

A Klein-Gordon equation is used to describe the wave behaviour (velocity and magnetic field perturbations) of Alfvén waves propagating from the chromosphere into the corona. This is derived from the momentum and induction equations in curvilinear coordinates (Taroyan et al. 2021)

Our model splits the solar atmosphere in two, with the chromosphere taken as $s < 0$, and the corona taken as $s > 0$. The transition region is at $s = 0$, this acts as our reflective interface.

We vary the geometry of the flux tube to create three different cases (Figure 1), with the first two being degenerate cases of our Klein-Gordon equation, where cut-off frequencies are set to $0$.

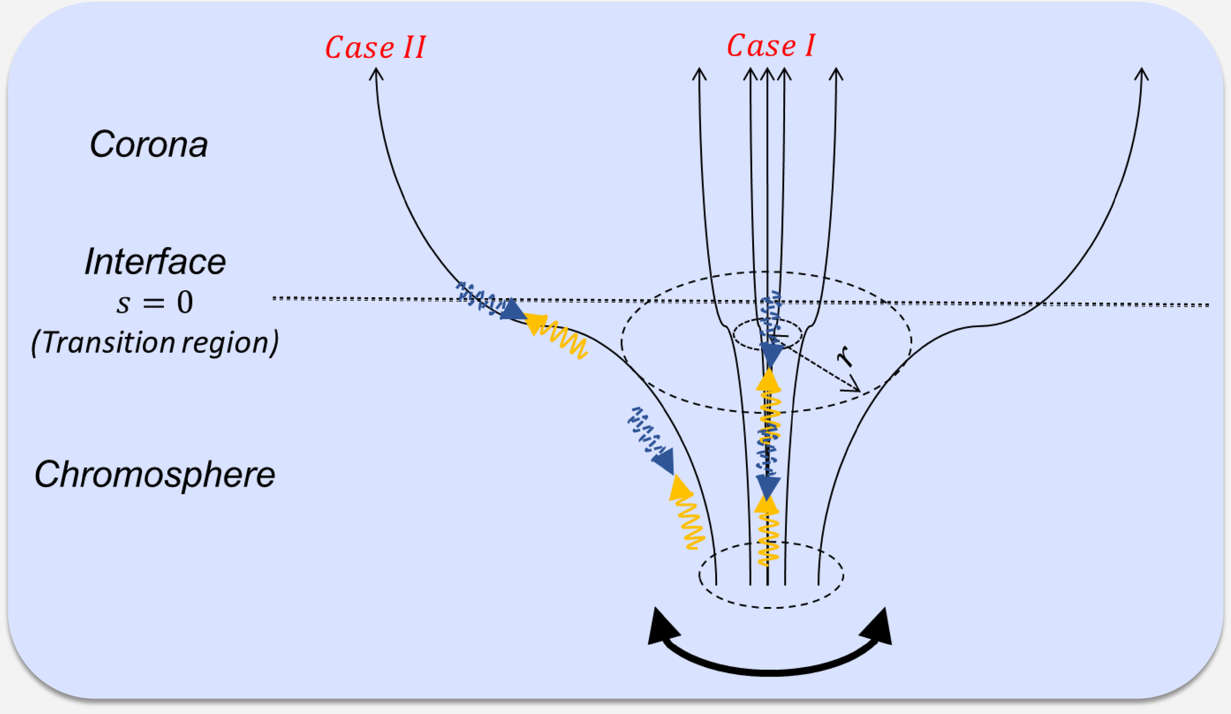



Figure 1: Orientation of different field geometries in the 3 case 2-layer model.

***Case I*** – Thin flux tube approximation, based on Hollweg (1984).

***Case II*** – Highly divergent.

***Case III*** – General case, taken as a set of mid-divergent field lines.

Across these three cases, the density, background magnetic field, and Alfvén speed are equal. Below the transition region the density and background magnetic field are exponentially decreasing with height, and the Alfvén speed exponentially increases. The radius of the flux tube is also exponential, with the three cases having different rates of growth. Above the transition region all parameters are taken to be continuous, but constant.

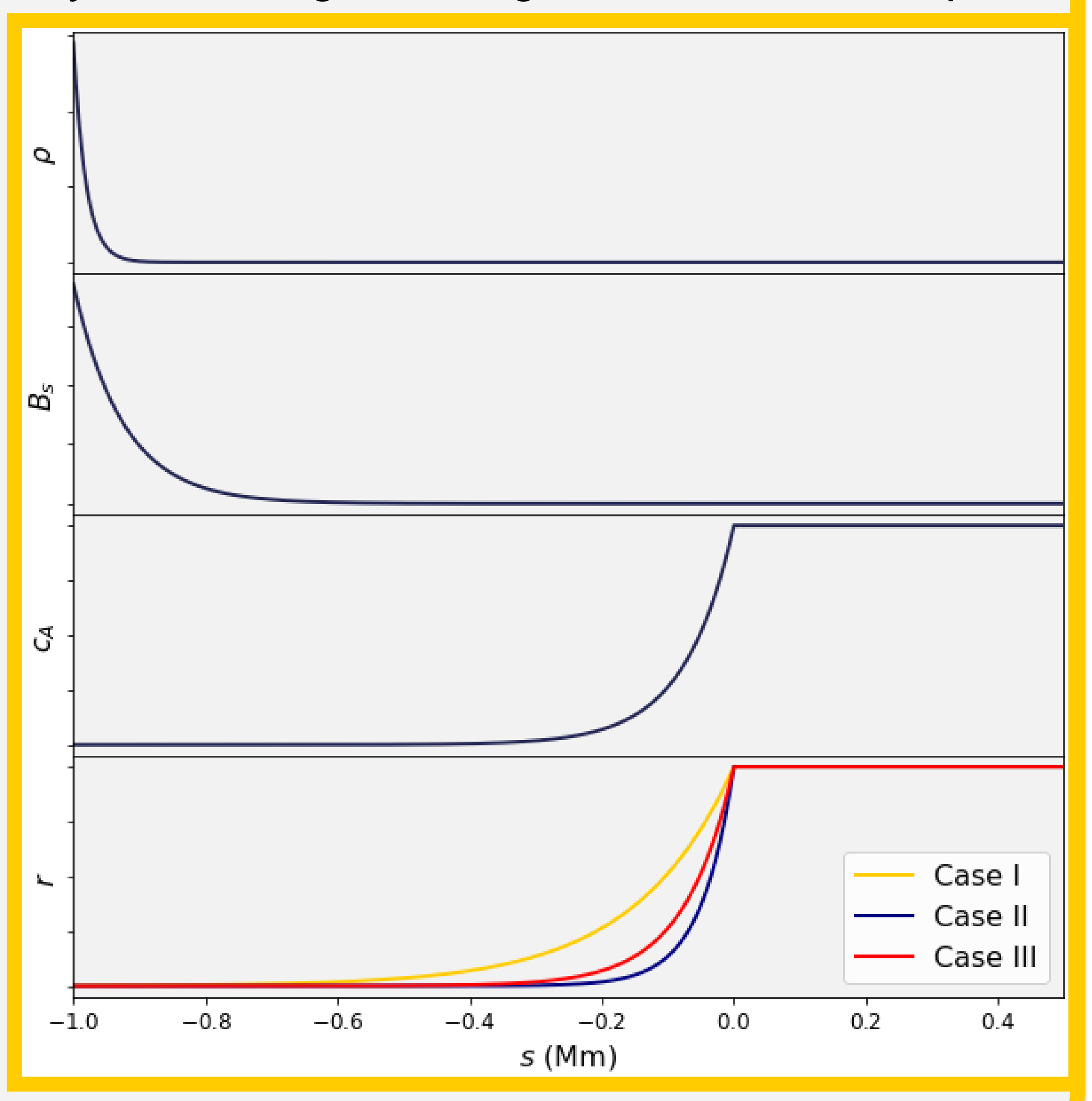



Figure 2: Variation of plasma properties, density ($\rho$), background magnetic field ($B_s$), Alfvén speed ($c_A$), and flux tube radius ($r$).

## 4. Preliminary Results

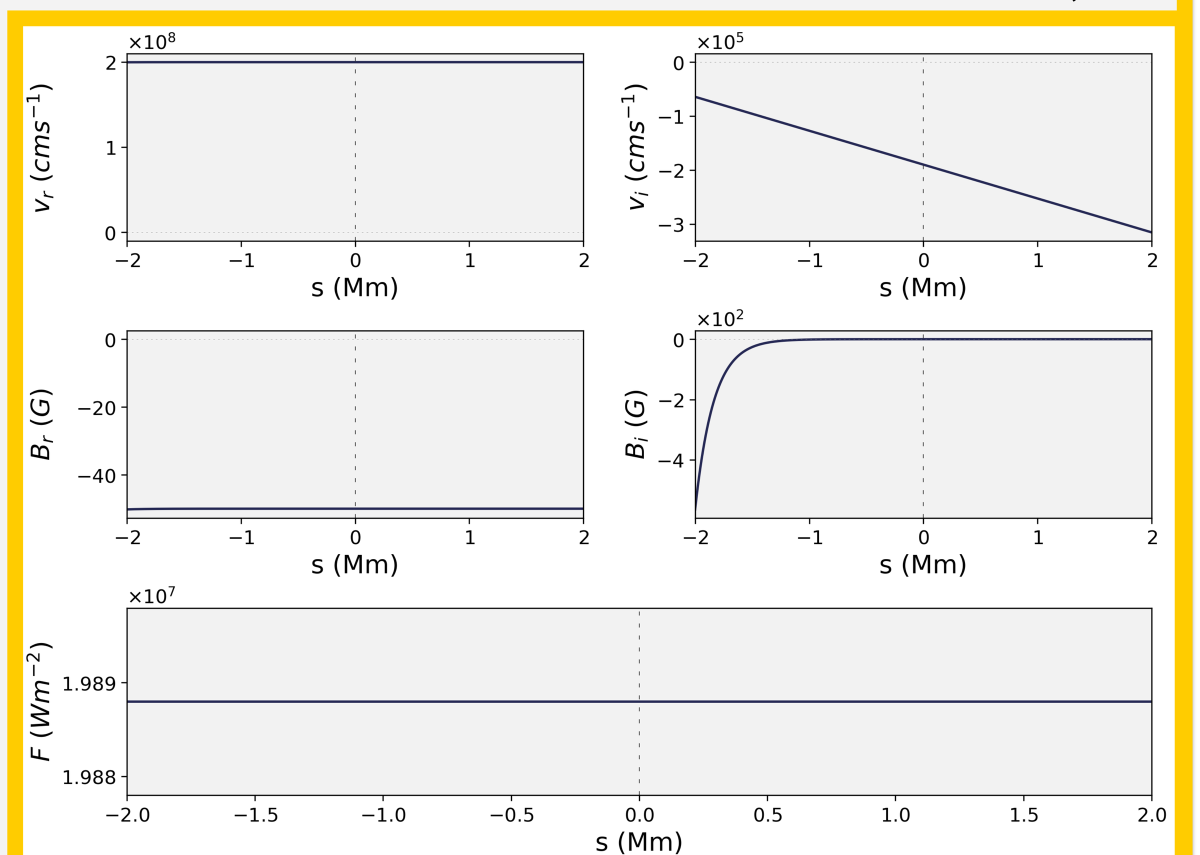
For each of these cases the plasma velocity ($v_\varphi$) and magnetic field perturbations ($B_\varphi$) are calculated, as well as the net energy flux of the waves.

The ratio of the outgoing wave to the ingoing wave can be calculated analytically. This can then be used to calculate the reflection coefficient, as given by Hollweg (1972). Whilst this was originally only applied to the thin flux tube case (case I), it will also be used for case II.

Our case III is derived to involve a geometry that experiences no reflection.

Initially work was focussed on case I, in this case reflection reaches 100% at low frequencies. Different frequencies behave very differently, as seen in Figures 3 and 4.

Preliminary results from case II and III show that the change in divergences greatly affect the net flux propagating through the flux tube.



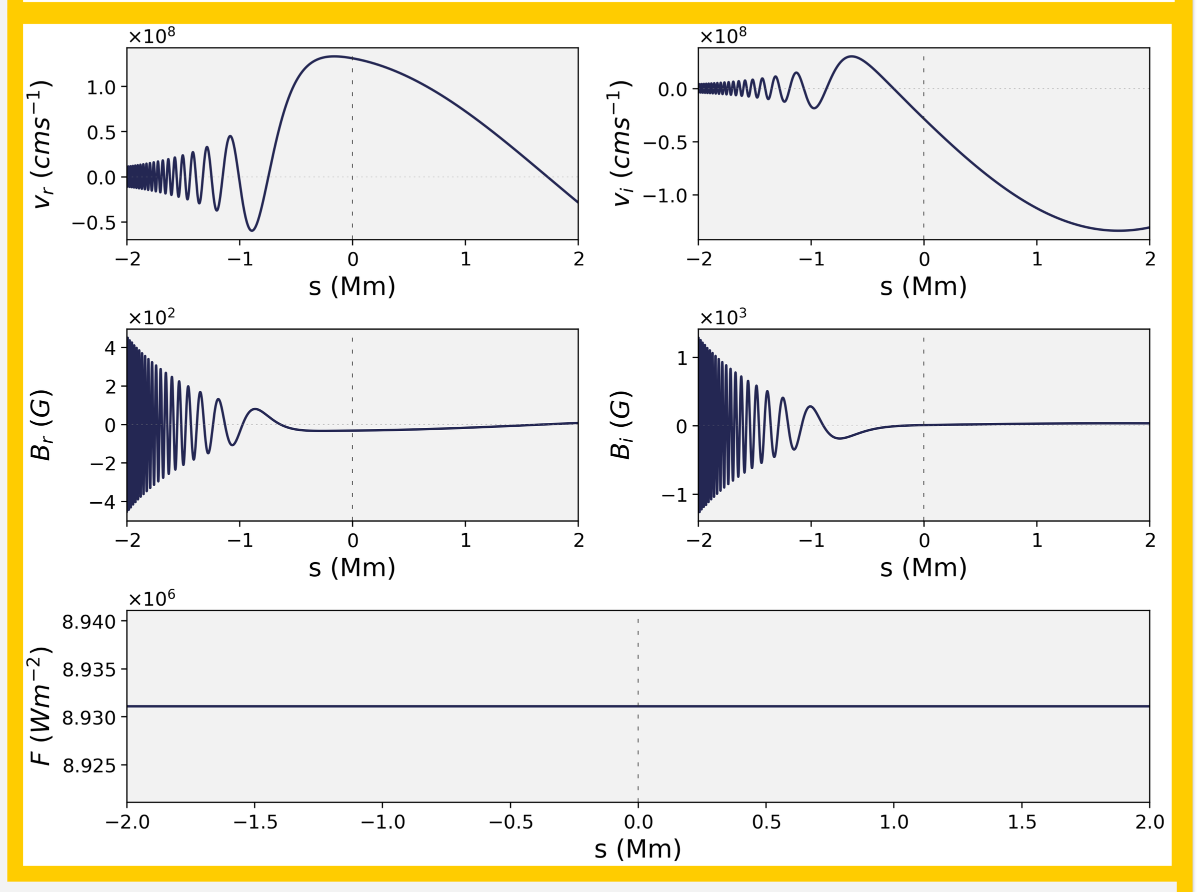




Figure 3 (top): Low frequency ( $\sim 6.3\times10^{-4}$ rad s$^{-1}$) wave propagating in case I – reflection is $\sim 1.0$ at $s = 0$.

Figure 4 (bottom): High frequency ( $\sim 1.6$ rad s$^{-1}$) wave propagating in case I – reflection is $\sim 0.15$.

## 5. Conclusion

Preliminary results show that certain geometries (such as the thin flux tube) show total reflection at low frequencies, however other geometries may display no reflection. This could greatly affect the Alfvén wave energy that reaches the upper solar atmosphere.

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