Waves in Partially Ionized Solar Atmosphere
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Abstract

The partially ionized part of the solar atmosphere is investigated, in order to study the wave propagation, within the framework of a single-fluid MHD description including the non-ideal effects such as the Hall and the ambipolar diffusion in the generalized Ohm’s law.

MHD Equations

Momentum eq. for electron, ion & neutral

\[
\begin{align*}
\frac{\partial V_e}{\partial t} + (V_e \cdot \nabla) V_e &= -e n_e \left[ E + \frac{V_e \times B}{c} \right] - \gamma_{en} \rho_e (V_e - V_n) - \gamma_{ne} \rho_e (V_e - V_i) \\
\frac{\partial V_i}{\partial t} + (V_i \cdot \nabla) V_i &= e n_i \left[ E + \frac{V_i \times B}{c} \right] - \gamma_{in} \rho_i (V_i - V_n) - \gamma_{ni} \rho_i (V_i - V_e) \\
\frac{\partial V_n}{\partial t} + (V_n \cdot \nabla) V_n &= -\gamma_{ni} \rho_n (V_n - V_i) - \gamma_{ne} \rho_n (V_n - V_e)
\end{align*}
\]

The electrons are inertialess (i.e. \( m_e = 0 \)). For \( \delta < 1 \), the ion dynamics can be ignored. This gives Ohm’s Law in the electron’s case as

\[
E = -\frac{V_e \times B}{c} - \gamma_{en} \rho_e (V_e - V_n) - \gamma_{ne} \rho_e (V_e - V_i)
\]

The ion force balance equation now becomes

\[
0 = e n_i \left[ E + \frac{V_i \times B}{c} \right] - \gamma_{in} \rho_i (V_i - V_n) - \gamma_{ni} \rho_i (V_i - V_e)
\]

These equations ultimately lead to

\[
\rho_n \left[ \frac{\partial V_n}{\partial t} + (V_n \cdot \nabla) V_n \right] = \frac{J \times B}{c}
\]

and an induction equation

\[
\frac{\partial B}{\partial t} = \nabla \times \left[ V_n \times B - \frac{J \times B}{e n_e c} - \frac{(J \times B) \times B}{c \gamma_{in} \rho_i} - \eta (\nabla \times B) \right]
\]
Mixed Modes: a more general case

Including the compression term \(-\nabla p_n\) and the oblique propagation, we show that the modes are mixed.

The pressure-perturbation term is \(p_n = C_s^2 \rho_{in}\) and the sound speed is \(C_s = \sqrt{\gamma \frac{p_{in}}{\rho_{in}}}\).

From the continuity equation, we have \(\rho_{in} = \frac{(k \cdot V_{in})}{\omega} \rho_{0n}\).

Using the continuity equation, momentum equation for the neutrals and the induction equation for a partially ionized plasma, a determinant \(D(\omega)\) is given by:

\[
D(\omega) = [\omega^2 - (V_{Ai}^2 \delta + i \eta_A \omega) k_z^2 - i \eta k^2 \omega][\omega^4 - i(\eta_A + \eta) k^2 \omega^3 - (V_{Ai}^2 \delta + C_s^2) k^2 \omega^2 + i(\eta_A + \eta) C_s^2 k^2 \omega^2 - \eta_H^2 k_z^2 \omega^3 (\omega^2 - k^2 C_s^2)]
\]

It can be seen that the magnetoacoustic and Alfvén-like modes are mixed.
The damping of Alfvén-like mode in a weakly ionized part of the solar atmosphere is mainly caused by the electron-neutral collisions and the ion-neutral collisions (through Cowling diffusivity).

Cowling diffusivity is dominant beyond the height 175 km above the solar surface for the solar model given by Cox (2000) and chosen magnetic field.

The Hall effect introduces a strong dispersion to the Alfvén-like mode in a partially ionized solar atmosphere. It has been shown clearly that the symmetry between co- and counter-propagating wave modes breaks at the length scale approaching the Hall length scale.

In the presence of Hall effect the Alfvén-like mode is circularly polarized whereas in the absence of it, the Alfvén-like mode is linearly polarized. The Hall effect facilitates propagation of short-wavelength modes required for the heating of the solar plasma.

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The ratio of ion to neutral density is shown (log axis) as a function of height (in units of $10^5$ cm) in the solar atmosphere.

The lines $\omega_{RH\pm}$ are the dispersion curves for co- and counter-propagating Hall Alfvén waves.

The lines $\omega_{RAM\pm}$ are the dispersion curves for Alfvén waves including ambipolar diffusion.

The lines $\omega_{RH\pm}$ are the dispersion curves for Alfvén waves including both the Hall and ambipolar diffusion.

Dispersion of wave modes at $h = 600$ km

Damping of wave modes at $h = 600$ km