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# 部分電離・重力成層大気における衝撃波の性質

# Properties of shocks in a stratified and partially ionized plasma

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We investigate the properties of shocks in a stratified and partially ionized plasma using 1D hydrodynamical numerical simulations. The fluid studied here consists of two distinct components: plasma (electrons and ions) and neutral gas. These different fluids interact with each other through collisional processes. If the coupling is strong, they move together, therefore they behaves as a single fluid. Conversely, if the coupling is weak, these fluids can move separately. We focus on how this coupling effects the properties of a shock wave propagating through a stratified atmosphere. An important result is, as expected, that when a shock wave enters the lower density regions of the atmosphere where the collisional coupling timescale is comparable to or larger than a dynamical timescale, the shock front splits into two, i.e. the plasma shock and the neutral gas shock start to propagate separately. We discuss the effects of this process on shocks, considering the effects of collisions, ionisation and recombination.

## 1. Introduction

Shocks play an essential role in many astrophysical systems. Plasma behind shocks obtains a large amount of the thermal and kinetic energies in a dynamical timescale. Therefore shocks are believed to be important for many rapid acceleration and heating processes, like collimated plasma flows in the solar atmosphere [1] and supernovae.

Let us consider a typical a gravitationally stratified atmosphere, like a stellar atmosphere. It can be shown that in such an atmosphere, the amplitude of waves propagating upward become large due to the law of conservation of energy, which is a direct result of the effect of the stratification. This means that small disturbances in a low atmosphere can lead to the formation of shocks. For example, it is observationally suggested that many collimated plasma flows in the solar atmosphere (spicules) are accelerated by shocks growing during propagation. Therefore, in order to understand dynamical processes in such an atmosphere, we need a detailed understanding of the physics of shocks.

How shocks grow in a one-dimensional (1D) stratified and pure-hydrodynamic atmosphere is well investigated by many authors. Considering the conservation laws, Ôno et al. [2] showed that the velocity amplitude of a strong shock $v$ is proportional to $\rho^{0.236}$, where $\rho$ is the density in front of the shock. Shibata et al. [3] studied the properties of collimated plasma flows in the solar atmosphere using this analytical relation, and they could account for some important observational features.

If the temperature of a gas is comparable to or below an ionisation temperature, the gas is partially ionized. The solar chromosphere and ionosphere of the earth are examples of the partially ionized plasma. In the solar chromosphere, electrons and ions are strongly coupled by collisions and they move together. Now we also have neutrals, which do not feel the Lorentz force but couple with ions by collisions. Therefore we can consider the chromospheric plasma as the two fluid gas which consists of the plasma gas (electrons and ions) and the neutral gas. These two fluids exchange their energy and momentum through the collisional processes.

The behaviour of the two fluid gas depends on the strength of the ion-neutral collisional coupling. If the ion-neutral collisional timescale is smaller than the dynamical timescale (i.e. high density), we can approximate the partially ionized plasma as the one-fluid plasma. However, if the ion-neutral collisional timescale is longer than a dynamical timescale (i.e. low density), the two fluids are weakly coupled and they can move separately, therefore we must track the motions of the two fluids separately.

We can show that if the temperatures of plasma and neutrals are the same (say, $T$), the sound speeds of the two gases are not identical, considering the equations of state. The pressures of the plasma and neutrals can be expressed as $P_p = n_e k_B T + n_i k_B T \simeq 2 n_i k_B T = 2\rho_i R_g T$ and $P_n = \rho_n R_g T$, respectively. Thus the sound speeds become $C_{sp} = \sqrt{2R_g T}$ and $C_{sn} = \sqrt{R_g T}$, respectively. Here $P$, $n$, $\rho$, $k_B$, $R_g$ and $C_s$ denote the pressure, number density, mass density, Boltzmann constant, gas constant and sound speed, respectively. The subscript $p$ and $n$ denote plasma and neutrals, respectively. Considering this fact, sound waves in the two gases can propagate separately if the collisional coupling is weak.

Let us consider the propagation of a shock wave in a stratified and partially ionized plasma. When the shock is propagating in a low atmosphere (high density region and therefore the collisional timescale is shorter than the dynamical timescale), the behaviour of the shock will be identical to the behaviour of a shock in a single fluid where the plasma and the neutral fluid move together. This means that the shock fronts in the plasma and the neutral fluid coincide. However, as the shock propagates to the upper atmosphere, where the density is low and the collisional timescale is longer than a dynamical timescale, the plasma shock will propagate faster than the neutral fluid shock because of the difference in the sound speed.

Here we study the basic properties of shocks in a stratified and partially ionized plasma using 1D hydrodynamical numerical simulations. We investigated how the properties of shocks in the two-fluid gas differ from that in the one-fluid gas. We found

## 2. Numerical Method

### 2.1 Basic Equations

In our model, the collisional, ionisation and recombination interactions are considered. The model is purely one-dimensional and no magnetic field is introduced. The continuity equations are

$$
\begin{aligned}
\frac{\partial \rho_n}{\partial t} + \frac{\partial(\rho_n v_n)}{\partial z} &= \Gamma_n^{rec} + \Gamma_n^{ion} & (1)\\
\frac{\partial \rho_p}{\partial t} + \frac{\partial(\rho_p v_p)}{\partial z} &= \Gamma_i^{rec} + \Gamma_i^{ion}, & (2)
\end{aligned}
$$

the momentum equations are given as

$$
\begin{aligned}
&\frac{\partial \rho_n v_n}{\partial t} + \frac{\partial}{\partial z}[\rho_n v_n^2 + P_n] & (3)\\
&= -\alpha_c \rho_p \rho_n (v_n - v_p) + \Gamma_n^{rec} m_i v_i - \Gamma_i^{ion} m_i v_n \\
&\frac{\partial \rho_p v_p}{\partial t} + \frac{\partial}{\partial z}[\rho_p v_p^2 + P_p] & (4)\\
&= +\alpha_c \rho_p \rho_n (v_n - v_p) - \Gamma_n^{rec} m_i v_i + \Gamma_i^{ion} m_i v_n,
\end{aligned}
$$

and the energy equations are given as

$$
\begin{aligned}
&\frac{\partial e_n}{\partial t} + \frac{\partial}{\partial z}[(e_n + P_n) v_n] = & (5)\\
&-v_n \cdot \alpha_c \rho_p \rho_n (v_n - v_p) + 0.5 \alpha_c \rho_p \rho_n (v_n - v_p)^2 \\
&-3 \alpha_c \rho_p \rho_n R_g (T_n - T_p) \\
&-\Gamma_i^{ion} \frac{1}{2} m_i v_n^2 + \Gamma_n^{rec} \frac{1}{2} m_i v_p^2 \\
&\frac{\partial e_p}{\partial t} + \frac{\partial}{\partial z}[(e_p + P_p) v_p] = & (6)\\
&+v_p \cdot \alpha_c \rho_p \rho_n (v_n - v_p) + 0.5 \alpha_c \rho_p \rho_n (v_n - v_p)^2 \\
&+3 \alpha_c \rho_p \rho_n R_g (T_n - T_p) \\
&+\Gamma_i^{ion} \frac{1}{2} m_i v_n^2 - \Gamma_n^{rec} \frac{1}{2} m_i v_p^2,
\end{aligned}
$$

where $e_n = P_n/(\gamma-1) + 0.5 \rho_n v_n^2$ and $e_p = P_p/(\gamma-1) + 0.5 \rho_p v_p^2$, and $\gamma$ is the specific heat ratio. The equations of state are

$$
\begin{aligned}
P_n &= \rho_n R_g T_n & (7)\\
P_p &= 2 \rho_p R_g T_p. & (8)
\end{aligned}
$$

Here we assume that the electron temperature and ion temperature and the electron number density and ion number density are identical. The recombination reaction rate for ions is given as

$$
\Gamma_i^{rec} = -n_p \nu^{rec}, \tag{9}
$$

where from [4,5] the recombination frequency is as follows

$$
\nu^{rec} = 7.2 \times 10^{-11} n_p \frac{1}{\sqrt{T}} \quad [sec] \tag{10}
$$

The ionisation reaction rate for neutrals is defined as

$$
\Gamma_n^{ion} = -n_n \nu^{ion}, \tag{11}
$$

where from [4] the ionization frequency is as follows

$$
\nu^{ion} = 2.91 \times 10^{-8} n_p \frac{1}{0.232 + T_{ion}/T_p} \left( \frac{T_{ion}}{T_p} \right)^{0.39} e^{-T_{ion}/T_p} \quad [sec] \tag{12}
$$

### 2.2 Model: A Stratified and Partially Ionized Plasma

The background atmosphere is the isothermal and gravitationally stratified atmosphere in ionizaiton equilibrium. The gravitational acceleration $g$ is constant with height. Given a temperature $T$, the neutral fraction, $\xi_n$, is uniquely determined assuming that the ionisation equilibrium:

$$
\Gamma_n^{rec} + \Gamma_n^{ion} = 0 \tag{13}
$$

Then the pressure scale height $H_p$ can be expressed as follows:

$$
H_p = \frac{k_B T}{m_i g} (2 - \xi_n) \tag{14}
$$

Using this, the total density $\rho_{tot}$ of the hydrostatic atmosphere is given as

$$
\rho_{tot} = \rho_{tot0} \exp\left[ -\frac{z}{H_p} \right] = \rho_{tot0} \exp\left[ -\frac{m_i g}{k_B T} \frac{z}{2 - \xi_n} \right] \tag{15}
$$

Then we can obtain the plasma and neutral densities:

$$
\begin{aligned}
\rho_n &= \xi_n \rho_{tot} & (16)\\
\rho_p &= (1 - \xi_n) \rho_{tot} & (17)
\end{aligned}
$$

Pressures $P_n$ and $P_p$ are given from the equations of state. This is the unperturbed background atmospheric structure.

To excite a wave, we introduced an initial disturbance to the velocities in the form of

$$
\begin{aligned}
v_n(z) &= v_0 \exp\left[ -((z - z_{ptb})/w)^2 \right] & (18)\\
v_p(z) &= v_0 \exp\left[ -((z - z_{ptb})/w)^2 \right], & (19)
\end{aligned}
$$

where $v_0 = 0.3 C_{sn0}$, $z_{ptb} = 2H_p$ and $w = 0.2 H_p$.

The simulation domain is $[0, 10H_p]$. We set $T = 10^4$ K, which is smaller than the ionisation temperature of the hydrogens $T_{ion} = 1.58 \times 10^5$ K. The unit of the density is $10^{10}$ 1/cc. The length, velocity and time are normalized by $H_p$ (pressure scale height of the neutral gas), $C_{sn}$ and $H_p/C_{sn}$, respectively.

At $z \sim 5H_p$, the collisional frequency is close to unity. This means that the collisional coupling timescale and the dynamical timescale (sound crossing time) are similar at this height. Therefore, when below this height the plasma and neutral fluid move separately, but when above this height they can move separately.

## 3. Results

After the simulation starts, due to the strong coupling in a low atmosphere, the plasma and neutrals move together. After the wave reaches $z \sim 5$, we can find the decoupling of the plasma and neutrals motions, namely, the shock front splits into two, which means that a shock of the plasma and a shock of the neutral gas start to propagate separately. Figure 1 shows the collisional (solid line), recombination (dashed line) and ionization (dashed-dotted line) interaction frequencies against height at time = 3. In this numerical experiments, the recombination and ionization timescales are much longer than the dynamical timescale, which means that the recombination and ionization effects does not affect the results.

We can discern the separation of shocks in Figure 2. Because the sound speed of the plasma is larger than that of the neutrals, the plasma shock propagates faster than the neutral shock. As a results, the ionisation degree just behind of the plasma shock is strongly enhanced. Note that the ionisation degree is enhanced due to the separation of the shock fronts not due to the ionisation processes by the shock heating.

We also found that at the neutral shock, the plasma temperature is enhanced through the collisional processes.

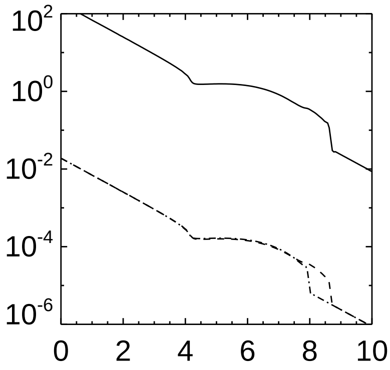

Fig. 1 Frequencies against the height. Solid: Collisional frequency, Dashed: Recombination frequency, Dashed-dotted: Ionization frequency. Note that the dynamical frequency, the inverse of the neutral-gas sound crossing time, is unity.

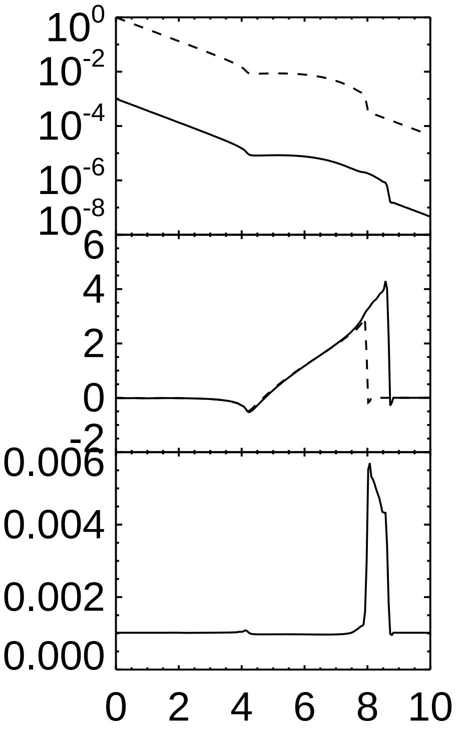

Fig. 2 Top: density, Middle: velocity, Bottom: the ionization degree. The horizontal axis shows the height. The solid and dashed lines show the results of the plasma and neutral gas, respectively.

## 4. Discussion

In the parameter regime studied here, we find the separation of the shock fronts. This leads to the enhancement of the ionisation degree in the region between the plasma and neutral shock fronts. The ionisation and recombination effects are negligible, probably because we do not consider the ionisation of metals like Ca and Mg which have the lower ionisation temperatures than the hydrogen.

The separation of the shock fronts could be crucial when we interpret observations. In the region where the coupling is weak, the plasma shock front is enhanced in the lines of the ions and the neutral shock front is enhanced in the lines from neutral atoms. We speculate that they will not coincide in the domain where the collisional frequency is smaller than a dynamical timescale.

Through the collisional processes, the thermal energy is transported from the neutrals to the plasma behind the neutral shock. This could be important for determining the ionization degree behind the shocks.

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