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Research Paper

On the Propagation of Vertical Acoustic Waves in the Solar Chromosphere

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Abstract. Sound waves have the potential to transfer the energy needed to heat the sun's atmosphere from the lower layers to higher areas. The source of these waves can be the surface oscillations of the sun, the most famous of which are the 5-minute oscillations. In this research, we investigate the propagation of sound waves in the first 2000 km of the sun's atmosphere, which is known as the chromosphere. In the chromosphere, variations in plasma density, hydrodynamic pressure, and temperature with height cause wave propagation to be complicated. Here, we build a chromospheric model using observational data and investigate sound propagation in both pulse and wave train modes. We solve the equation of motion numerically in the linear regime using the finite difference method. The results show that due to the reflection of the wave in different layers of the atmosphere, the sound pulse does not maintain its original shape, instead, its energy is spread in a wide space of the atmosphere. Also, for sinusoidal wave trains at different frequencies, we obtain the amount of the energy of the wave penetrating to the upper layers. Results show that as the frequency of the wave increases, the capability of the wave to transfer the acoustic energy from the photosphere to the upper chromosphere increases.

Keywords: Sound Waves, Reflection, Energy Transfer

1 Introduction

What is the reason for the solar chromosphere being hotter than the photosphere? This query was initially raised over fifty years ago. Biermann [1] and Schwarzschild [2] put forward a hypothesis suggesting that heating of the chromosphere occurs through the dissipation of acoustic waves that originate from the turbulence within the convection zone. Although there has been some advancement in addressing this question, ongoing research is still striving to provide a comprehensive explanation.

To achieve a comprehensive understanding of the solar chromosphere's structure and dynamics, particularly in regions where magnetic fields have minimal influence, several factors need to be known including the power and spectra of acoustic waves. Significant progress

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towards this objective has been made, such as demonstrating that (1) the heating of the chromosphere is likely driven by acoustic processes, particularly in the presumed nonmagnetic internetwork chromosphere, and (2) the power generated by acoustic waves originating from the convection zone is substantial enough to account for the radiative emissions observed in the chromosphere.

The determination of wave propagation conditions and the identification of regions in the solar atmosphere with strong wave reflection are heavily influenced by the acoustic cut-off frequency. The concept of the acoustic cut-off was initially introduced by Lamb [3,4], who considered both isothermal and non-isothermal atmospheres with linear temperature profiles. Subsequently, other researchers extended Lamb's work and proposed various formulas for the cut-off period [5,6,7,8,9,10]. These analytical efforts were followed by numerical simulations of acoustic waves in order to investigate the role of acoustic waves in atmospheric heating [9,11,12].

It has been shown that oscillations with frequencies below 4 mHz are considered evanescent in the context of wave propagation [13]. However, frequencies higher than 4 mHz are able to freely propagate from the photosphere into the chromosphere. Similar conclusions have been reported in other studies [14,15,16]. Carlsson and Stein [15] specifically examined the chromospheric internetwork oscillations triggered by photospheric motions, demonstrating that waves propagate upward from the photosphere and their amplitude grows, eventually resulting in shocks in the upper chromosphere. It has been reported that waves above the acoustic cut-off frequency of 5 mHz in internetwork regions can easily propagate to the solar chromosphere [17]. Recent numerical simulations also confirmed the propagation of high-frequency acoustic waves from the photosphere into the chromosphere [18,19]. However, in the presence of a magnetic field, longer periods (more than 4 minutes) can easily propagate into the transition region (TR) from the photosphere [20]. Some observations also indicate the successful propagation of 5-minute waves in the TR from the photosphere, particularly in regions with high magnetic fields [21,22]. Despite these achievements, it is important to note that the conditions for the propagation of acoustic waves and waves in magnetic fields are not yet fully established or understood. Therefore, additional observational results are required to gain a better understanding of the origin, nature, and behavior of acoustic waves in the solar atmosphere, as well as the constraints imposed by the solar atmosphere on their propagation.

The focus of this study is to examine the transmission of acoustic pulses and waves generated in the photosphere into the chromosphere. To this aim, we consider a real chromospheric model using chromospheric observational data presented by Vernazza, Avrett, and Loeser [23] (hereafter VAL). In the next section, we give the chromospheric model and equations of motion. Section 3 is devoted to the numerical results. Finally we conclude the paper in section 4.

2 Chromospheric Model and Equations of Motion

As a simple model of the solar chromosphere, we consider an environment in which the initial magnetic field is uniform in the z-direction (perpendicular to the surface of the sun) and the plasma background flow is zero. Plasma density, ρ, gas pressure, P_g and temperature, T are considered as functions of z. Here, we use the observational data corresponding to the chromospheric model A of VAL (VAL-A) [23]. Figure 1 illustrates the plasma density, the gas pressure, the temperature and the corresponding sound speed as a function of height (h) up to 2040 km above the photosphere.

Here, the goal is to investigate the propagation characteristics of sound waves in the

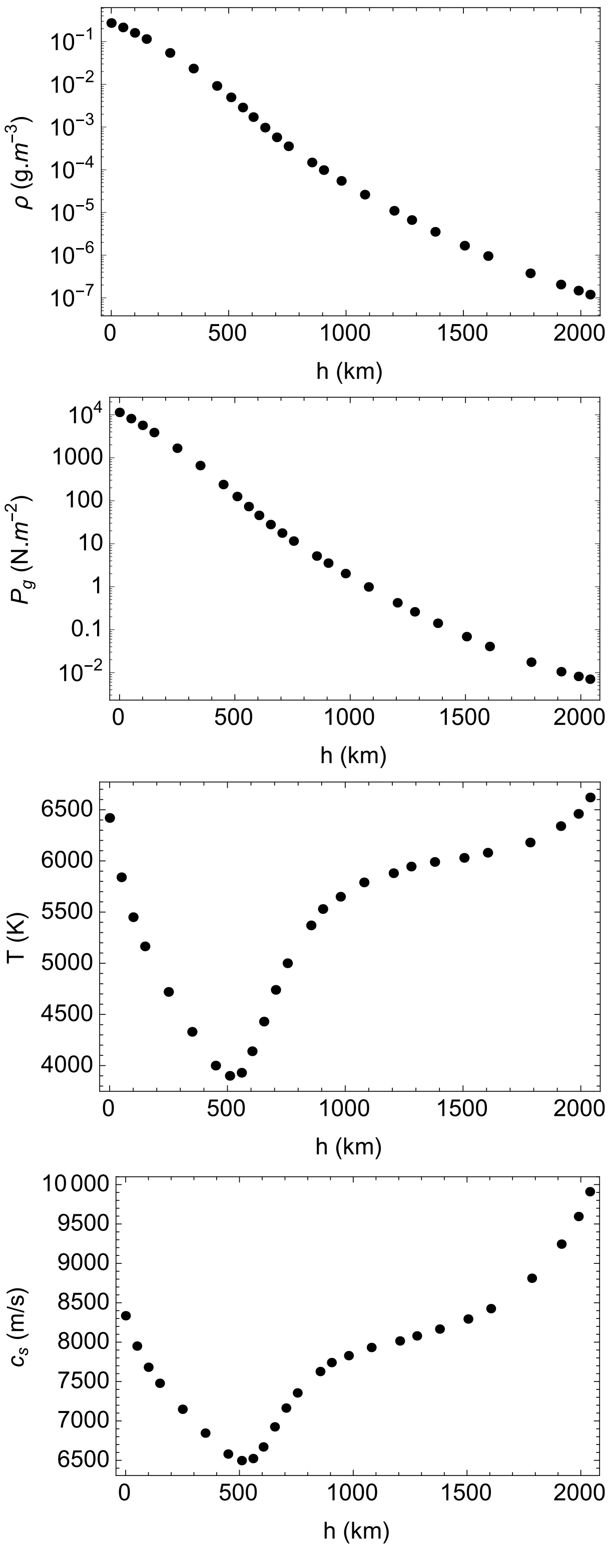

Figure 1: Variation of plasma density,ρ, gas pressure, P_g, temperature, T and sound speed, c_s with height in VAL-A model up to h=2040 km above the photosphere.

chromosphere up to an altitude of 2040 kilometers from the surface of the sun. In this model, altitudes greater than 2040 kilometers are considered as the solar transition layer. For computational use of the observational data of VAL-A, we first normalize all the data to their values in the reference state $z = 0$. We normalize the altitude to a maximum value of 2040 kilometers and fit the following functions to the density, the pressure, and the temperature data, respectively,

$$\rho(z) = \frac{1 - 9.85z + 38.56z^2 - 74.83z^3 + 77.83z^4 - 41.82z^5 + 9.16z^6}{1 - 1.34z + 32.85z^2 + 293z^3 - 6987z^4 + 55009z^5 - 19900z^6 + 283547z^7}, \quad (1)$$

$$P_g(z) = \frac{1 - 5.16z + 15.97z^2 - 26.62z^3 + 21.78z^4 - 6.76z^5}{1 + 10.74z - 130.85z^2 + 4065.8z^3 - 28279z^4 + 86432z^5}, \quad (2)$$

$$T(z) = \frac{1 - 1.59z + 10.5z^2 - 171.9z^3 + 581.5z^4 - 397.4z^5}{1 + 2.79z - 12.23z^2 - 127z^3 + 561.2z^4 - 4.4.4z^5}. \quad (3)$$

All of the fittings have a coefficient of determination, denoted as r^2, equal to 0.99.

The governing equations on the vertical acoustic waves in the absence of dissipation and background plasma flow in a stratified atmosphere, are obtained by perturbing and linearizing the equation of the continuity of mass, the Euler equation and the energy equation, respectively as

$$\frac{\partial \rho_1}{\partial t} + v_1 \frac{\partial \rho_0}{\partial z} + \rho_0 \frac{\partial v_1}{\partial z} = 0, \quad (4)$$

$$\rho_0 \frac{\partial v_1}{\partial t} = -\frac{\partial p_1}{\partial z} - \rho_1 g, \quad (5)$$

$$\frac{\partial p_1}{\partial t} + v_1 \frac{\partial p_0}{\partial z} - c_s^2 \left(\frac{\partial \rho_1}{\partial t} + v_1 \frac{\partial \rho_0}{\partial z} \right) = 0. \quad (6)$$

Here, ρ_0 and p_0 are the plasma density and gas pressure of the equilibrium state; $g = 274\ m.s^{-2}$ is the gravitational acceleration at the surface of the sun; v_1, ρ_1 and p_1 are the Eulerian perturbations of velocity, density and gas pressure, respectively. $c_s = \sqrt{\gamma p_0/\rho_0}$ is the sound speed in which $\gamma = 5/3$ is the ratio of the specific heats for an ideal gas. We Define the dimensionless variables as

$$\bar{\rho} = \frac{\rho}{\rho_0(z=0)}, \qquad \bar{p} = \frac{\rho}{p_0(z=0)}, \qquad \bar{v}_1 = \frac{v_1}{c_s(z=0)}, \qquad \bar{t} = \frac{t}{\tau_s}, \qquad \bar{z} = \frac{z}{L}, \quad (7)$$

in which, L is the length of the computational region in the z direction and $\tau_s = L/c_s(z = 0)$ is the time scale of the propagation of the sound along the length L. Using equations (4)–(17) and the dimensionless variables defined in equation (7) one can obtain the equation governing on the perturbation of the velocity in the dimensionless form, namely

$$\frac{\partial^2 v_1}{\partial t^2} - A(z)\frac{\partial^2 v_1}{\partial z^2} - B(z)\frac{\partial v_1}{\partial z} - C(z)v_1 = 0, \quad (8)$$

where

$$A(z) = \frac{p_0(z)}{\rho_0(z)}, \quad (9)$$

$$B(z) = \frac{1}{\rho_0}\frac{dp_0}{dz}\left(\frac{\gamma+1}{\gamma}\right) + g^*, \quad (10)$$

$$C(z) = g^* \frac{1}{\rho_0}\frac{d\rho_0}{dz} + \frac{1}{\gamma\rho_0}\frac{d^2 p_0}{dz^2}, \quad (11)$$

in which $g^* \equiv g\ \tau_s/c_s(z=0)$.

3 Solution and Results

Here, we solve equation (8) with the following boundary conditions

$$v_1(z=0,t) = f(t), \tag{12}$$
$$v_1(z=L,t) = 0, \tag{13}$$

and initial values

$$v_1(z,t=0) = 0, \tag{14}$$
$$\frac{\partial v_1}{\partial t}\Big|_{z>0,t=0} = 0, \tag{15}$$

using the finite difference method. The problem is 2D with $0 \leq z \leq 1$ and $t > 0$. The results would be obtained up to a finite time before which the wave reaches the boundary $z = L$ and is reflected into the computational region. We set up the computational region with the step size in the z direction as $\Delta z = 0.002$ and the time step $\Delta t = 0.001$. The truncation error of the calculations that comes from the discretization of the wave equation is of the order of $(\Delta t)^2 + (\Delta z)^2$.

3.1 Propagation of an Acoustic Pulse

In this section, we will investigate the propagation of a sinusoidal pulse. This means that the acoustic driver at $z = 0$ lasts only half of the wave period. So we have

$$\mathbf{v_1}(z=0,t) = \begin{cases} Sin(\omega t), & 0 < t \leq P/2, \\ 0, & t > P/2. \end{cases} \tag{16}$$

in which $P = 2\pi/\omega = \tau_s(2\pi/\bar{\omega})$ is the period of the wave. Here, ω is the frequency and $\bar{\omega}$ is the dimensionless frequency of the wave. Based on the VAL-A data for $P_g(z=0) = 11351 N.m^{-2}$ and $\rho(z=0) = 0.27 g.m^{-3}$ we have $\tau_s = L/c_s(z=0) = 244.7s$. The propagation of the sound pulse allows us to easily observe the reflection of the wave by the change in shape that occurs in the pulse during propagation. Figure 2 shows the propagation of a sinusoidal pulse generated at $z = 0$ for two cases with $P = 50s$ and $P = 200s$. As it was expected from the previous studies, the amplitude of the pulse increases as it propagates to regions with smaller densities. Figure 2 also shows that in both cases of $P = 50s$ and $P = 200s$ the pulse does not retain its shape while it propagates through the chromosphere. This is because of the reflection of the pulse since the temperature and consequently the sound speed are not constant in the region (see Figure 1). It should be noted that reflection occurs in both directions of propagation $+z$ and $-z$, but the net result of reflection in different layers for both forward and backward traveling waves is to move the wave to higher altitudes. When the wave reaches a layer where the speed of sound has decreased, the reflected wave is in the opposite phase with respect to the incoming wave, and if the sound speed increases along with the propagation, the reflected wave is in the same phase as the incoming wave. As seen in Figure (3), in chromosphere, with the increase in height, the speed of sound first decreases and then starts to increase again. This causes the passage of the wave in this area to be accompanied by reflection and finally change the shape of the wave.

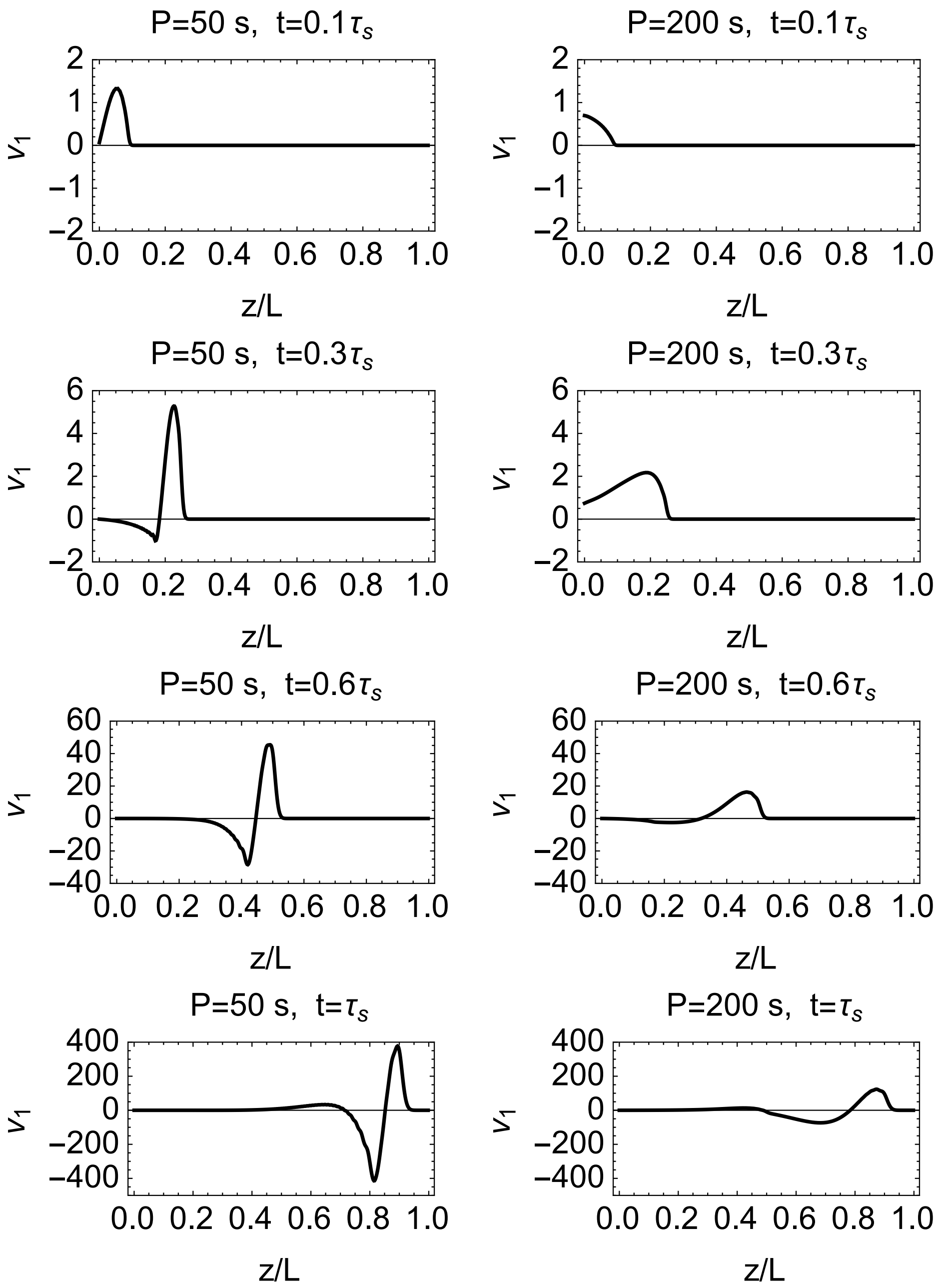

Figure 2: Eulerian perturbation of the velocity versus z for acoustic pulses with $p = 50s$ (left panels) and $p = 200s$ (right panels). Panels from top to bottom denote the propagation times $t = 0.1\tau_s,\ 0.3\tau_s\ 0.6\tau_s,\ \tau_s$, respectively.

3.2 Propagation of a Sinusoidal Acoustic Wave

For a continuous sinusoidal driver at $z = 0$ we have $f(t) = Sin(\frac{2\pi}{P}t)$. Figure 3 shows the results for $P = 10s, 100s, 200s$. It is clear from the figure that the amplitude of the wave increases as it propagates to higher altitudes which is due to longitudinal stratification of the atmosphere. This is in agreement with those obtained by e.g. De Moortel and Hood [24]. It is clear from Figure 3 that the growth of the amplitude of the wave as it propagates to higher altitudes decreases when the period of the wave increases. Here, we can deduce that the larger the period of the acoustic waves the smaller the ability of transforming energy to upper layers of the chromosphere. So, we expect that above a specific period the acoustic wave can not propagate along the chromosphere. To show how the ability to transfer energy to the upper layers decreases with increasing period, we calculate the fraction of wave energy stored in the second half of the propagation, E^*, to the total energy injected into the chromosphere, E_t, at time $t = \tau_s$. The propagation length, d_s at $t = \tau_s$ is obtained numerically as the upper limit of the following integral

$$\int_0^{d_s} \frac{dz}{c_s(z)} = \tau_s. \tag{17}$$

The kinetic energy of the acoustic wave stored in the interval $[z_1, z_2]$ at $t = \tau_s$ is obtained as

$$E = \int_{z_1}^{z_2} \frac{1}{2}\rho(z)v_1(z,\tau_s)^2 dz. \tag{18}$$

Hence, the value E^*/E_t is obtained as

$$\frac{E^*}{E_t} = \frac{\int_{d_s/2}^{d_s} \frac{1}{2}\rho(z)v_1(z,\tau_s)^2 dz}{\int_0^{d_s} \frac{1}{2}\rho(z)v_1(z,\tau_s)^2 dz}. \tag{19}$$

Figure 4 shows the variation of the quantity $\frac{E^*}{E_t}$ versus the period, P, of the wave for periods in the range $[5, 1570]$ seconds or equivalently frequencies in the range $[1257, 0.004]$ Hz. Figure clears out that as the period of the wave increases (frequency decreases) the fraction of the total energy of the wave that propagates to the second half of the length d_s decreases. Results show that the quantity $\frac{E^*}{E_t}$ is about 0.42 for $p = 5s$ ($\omega = 1257$ Hz) and 0.001 for $P = 1570s$ ($\omega = 4$ Hz). This result is in agreement with those obtained by e.g. Lites and Chipman (1979) that obtained cut-off frequency $\omega_c = 4$ mHz. However, the results obtained here show that the power of the penetration of the wave to the upper layers in the chromosphere decreases monotonically as the period of the wave increases.

4 Conclusions

In this paper, we investigated the propagation of linear acoustic waves generated from the photosphere into the chromosphere. Using the VAL-A observational data we set up the equilibrium state of the chromosphere. In this study, both sound pulses and wave trains were considered. Our goal was to know how sound waves with different frequencies propagate in the first 2040 km of the sun's atmosphere. The influence of the chromosphere on the propagation of vertical sound wave is important since to deliver the energy of sound wave generated in the surface of the sun to upper layers of the atmosphere the acoustic wave must first pass through this region.

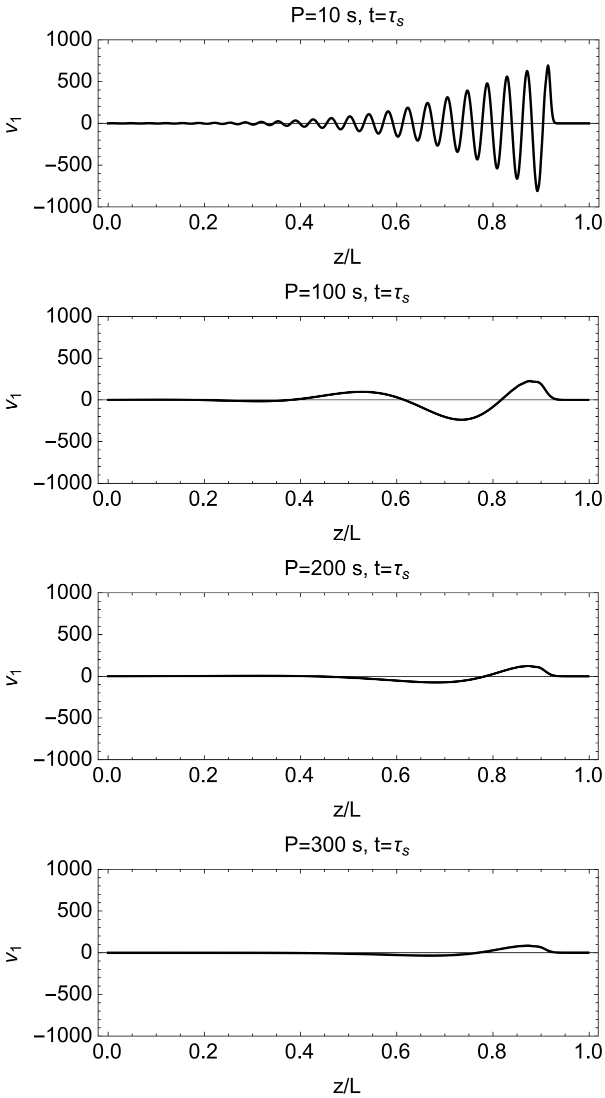

Figure 3: Eulerian perturbation of velocity versus z at $t = \tau_s$ for $P = 10, 100, 200, 300$ seconds.

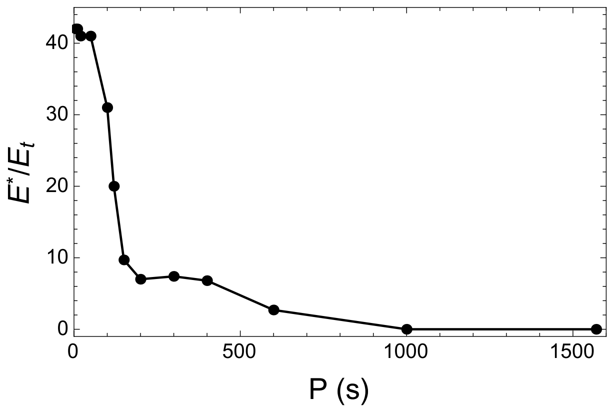

Figure 4: A fraction of the wave energy propagated to the second half of the propagation length versus the period of the wave.

Results show that the shape of an acoustic pulse and its localization change while passing through the chromosphere. The reason for this is the variation of the sound speed in the chromosphere and the reflection of the wave when it passes through regions with different sound speed. This is an important result that should be considered in the context of seismology of the chromosphere using the acoustic waves.

We investigated the propagation of sound waves and showed that waves with larger periods are less capable to transfer the acoustic energy to upper layers of the atmosphere. Against the previous studies that present a cut-off frequency above which the sound wave can travel freely to upper layers of the atmosphere, we showed that the ability of sound waves to transfer their energy to higher altitudes does not change at a specific frequency but changes in a monotonic manner.

The results of this study were obtained for linear sound waves. However, as can be seen from the results, the amplitude of the waves increases as they propagate to higher altitudes. Thus, it would be useful to take into account the nonlinearity of the disturbances. This is an interesting topic that could be the subject of future work.

Authors' Contributions

All authors have the same contribution.

Data Availability

No data available.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Ethical Considerations

The authors have diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

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