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Research Paper

Dissipation of Magnetohydrodynamic Waves in the Solar Stratified Flux Tubes

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Abstract. Chromosphere is the second layer of the Sun with high variability. The increase of the temperature and the decrease of the density are observed in this layer. This unusual behavior is one of the most important problems in the solar corona. Between the solar chromosphere and the corona, there is a thin transition zone in which the temperature rises very rapidly. Magnetohydrodynamic waves are thought to play an important role in this heating. The dissipation of Alfven waves has been investigated due to phase mixing in the presence of steady flow and sheared magnetic field in a solar stratified flux tube. The temperature variations with height ($T_0(z)$) in the flux tube has been considered. The numerical calculations showed that the amplitude of the tube oscillations decreases with time. Hence, the wave damping takes place in the flux tubes. The temperature and the density variations enhances the wave damping rate compared to the case without temperature effect.

Keywords: ISM: Solar corona, Chromosphere, ISM: Magnetohydrodynamic waves

1 Introduction

The sudden rapid increase in the temperature from the photosphere to the corona (in the order of one million Kelvin) is one of the unsolved problems in the field of solar physics. Since the mechanical movements of the photosphere layers are somehow transferred to the atmosphere above the Sun, they heat the corona by giving energy to the environment. One of the possible scenarios in this field is the convective motions of the photosphere layer and the general fluctuations of the Sun, which can cause magnetohydrodynamic (MHD) waves in the photosphere. These waves can propagate in the chromosphere and transfer the necessary energy to the solar corona [1,2].

Alfven waves are one of the important candidates which can probably transfer the necessary energy from the chromosphere to the solar corona [3,4]. For such a mechanism, the following two conditions must be met for Alfvén waves: first that these waves have enough energy in their flux, and second that they can be effectively damped and give their energy to the environment. The solar coronal magnetic field is inhomogeneous and it has many open and closed structures. This inhomogeneity improves the propagation of Alfvén waves to some extent, which means that it enables the creation of a phenomenon such as phase mixing. This phenomenon is presented by Heyvaerts and Priest (1983) based on the difference in Alfvén speed in the environment, it can provide effective damping of these waves because simple Alfvén waves cannot be damped fast enough [5].

There are some other types of waves which are damped at the sharp density and temperature gradients of the solar atmosphere. For example, acoustic, slow-mode and fast-mode oscillations have been studied in different methods. Slow mode oscillations also has been studied as a candidate for the solar coronal heating. Abedini et al (2012) have investigated the damping of these oscillations in the solar coronal loops [6]. They have applied the effect of the temperature inhomogeneity, the compressive viscosity, the thermal conduction and radiation on their calculations. They have concluded that in a gravitationally stratified loop, the wave properties are sensitive to the temperature variations and the viscosity can change the damping times significantly. Kink oscillations are one of the magnetohydrodynamic waves in the solar flux tubes which can be used as a seismological tool [7]. Ebrahimi and Javaherian (2023) have studied the effect of the resistivity and the density inhomogeneity on the kink waves of solar magnetic flux tubes [8]. They showed that resistivity is less efficient than the density variations (viscosity) in converting the wave energy to the heat.

In this article, the theoretical modeling equations, the results of our numerical calculations and the conclusion are represented, respectively.

2 Theoretical model

In the presented model to investigate the propagation of waves in the magnetic flux tubes and how they are attenuated when they reach the solar corona, we considered the stratification effects due to gravity [9] with the presence of a uniform flow and the sheared magnetic field in two dimensions $(x-z)$. The study of phase mixing and damping of Alfvén waves are carried out in a region with non-uniform Alfvén velocity. The basic equations of the problem are [10]

$$\rho\frac{d\mathbf{V}}{dt} = -\nabla p + \rho\mathbf{g} + \frac{1}{\mu_0}(\nabla\times\mathbf{B})\times\mathbf{B} + \rho\nu\nabla^2\mathbf{V}, \tag{1}$$

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}\times\mathbf{B}) + \eta\nabla^2\mathbf{B}, \tag{2}$$

where $\mathbf{V}$ is velocity, $\mathbf{B}$ is the magnetic field, ρ is the density and μ_0 is the vacuum permeability. Here, ν and η are viscosity and resistivity coefficients, which in the solar chromosphere and corona for fully ionized hydrogen plasma are $2.2\times10^{-17}T^{\frac{5}{2}}kg/ms$ and $(8\times10^8-10^9)T^{\frac{3}{2}}m^2/s$, respectively [10]. Velocity and magnetic fields are defined as [11]

$$\mathbf{V} = v_0\mathbf{k} + v_y(x,z,t)\mathbf{j}. \tag{3}$$

$$\mathbf{B} = B_0e^{-k_bz}[\cos k_b(x-a)\mathbf{i} - \sin k_b(x-a)\mathbf{k}] + b_y(x,z,t)\mathbf{j}. \tag{4}$$

Because the magnetic field is force-free, the balance between gravitational force ($\mathbf{g}=g\mathbf{k}$), and pressure gradient force is established

$$-\nabla p_0(x,z) + \rho_0(x,z)\mathbf{g} = 0.$$

The density function is obtained as follows

$$\rho_0(x,z) = \frac{\rho_0(x)T_0}{T_0(z)}\exp\left(-\int_{z_r}^{z}\frac{dz'}{H(z')}\right). \tag{5}$$

The function $\rho_0(x)$ is obtained from the Alfvén velocity for a stratified and phase mixed atmosphere [12]. We have for the pressure scale height, $H(z) = \frac{RT_0(z)}{\mu g}$ (μ, the mean molecular weight) and for the temperature

$$T_0(z) = T_0\Big[1 + \frac{T_{ch}}{T_c} + (1 - \frac{T_{ch}}{T_c})\tanh(\frac{z - z_t}{z_\omega})\Big], \tag{6}$$

where, $T_{ch} = 20\times10^3K$ and $T_c = 2\times10^6K$ are the chromospheric and coronal temperatures. Also $z_\omega = 200km$ is the width of the transition zone for $z_t = 2000km$. The dimensionless linearized MHD equations are obtained as

$$\frac{\partial v_y}{\partial t} = \frac{1}{\rho_0(x,z)}\Big[B_0(x,z)\frac{\partial b_y}{\partial x} + B_0(x,z)\frac{\partial b_y}{\partial z}\Big] - v_0\frac{\partial v_y}{\partial z} - \nu\nabla^2 v_y, \tag{7}$$

$$\frac{\partial b_y}{\partial t} = \Big[B_0(x,z)\frac{\partial v_y}{\partial x} + B_0(x,z)\frac{\partial v_y}{\partial z}\Big] - v_0\frac{\partial b_y}{\partial z} - \eta\nabla^2 b_y. \tag{8}$$

The considered initial perturbation in velocity is

$$v_y(x,z,t=0) = V_{A0}\exp\Big[-\frac{1}{2}(\frac{x-1}{d})^2\Big], \tag{9}$$

where d is the Gaussian packet. For the initial magnetic field we have considered it as zero.

3 Results

Numerically solving of the equations (8) and (9), Figures 1 and 2 show the temporal changes of the perturbed velocity field and the perturbed magnetic field in the situation: $x = 500km$ and $z = 5000km$, values of the radius and height of a typical flux tube respectively. Notice that in these diagrams, the perturbed velocity and magnetic field are normalized to V_{A0} and B_0, respectively. We have investigated these variations for different heights and we have seen that at the beginning height of the tube, the amplitude of the oscillations have values close to their initial values. But as height increases, the oscillation amplitudes decrease. From each of the figures, one can see the damping of the oscillations with time. The Figure 3 shows the temporal variation of the total normalized energy for $d = 0.6a$. In this figure, we can see at $t = 50\tau(sec)$ the energy decreases to zero.

4 Conclusion

We considered a magnetic flux tube at the solar chromosphere. A steady flow and a sheared magnetic field have been considered in this structure. Also, the plasma inside the tube is under the influence of the gravity force and some inhomogeneity such as viscosity and resistivity. According to the results from the above-mentioned figures, the amplitudes of the perturbed velocity field and the magnetic field decreased with time and height. The effect of density variations along with the temperature variations with height appeared more for the damping of Alfvén waves with respect to time than space. Depending on the type and lifetime of the considered magnetic flux tube in the solar atmosphere, a rapid dissipation mechanism will be needed to transfer energy to the solar corona. The calculations show that considering the above factors enhances the wave-damping rate. We also obtained that the total energy (sum of the kinetic and magnetic energy) decreases with time.

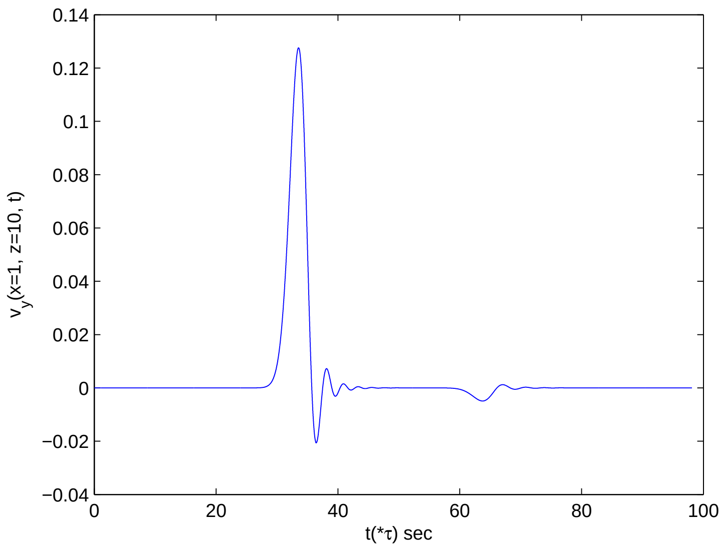

Figure 1: Variation of the perturbed velocity field with time in situation: $x = 500km$ and $z = 5000km$.

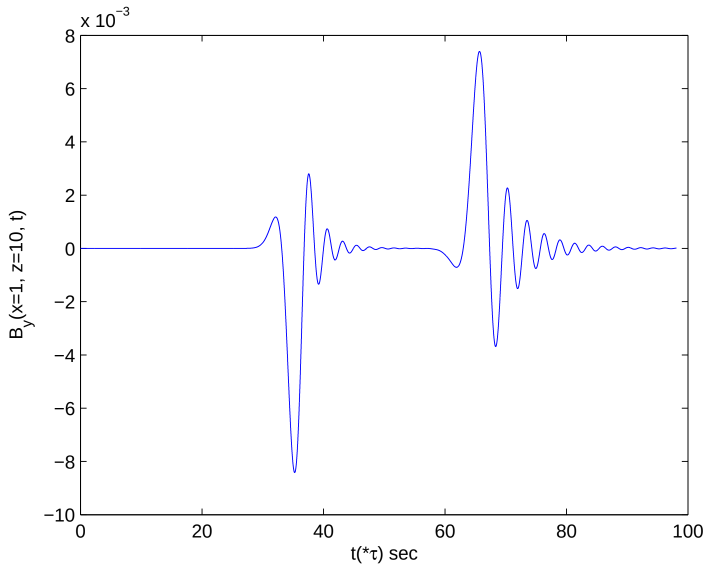

Figure 2: Variation of the perturbed magnetic field with time in situation: $x = 500km$ and $z = 5000km$.

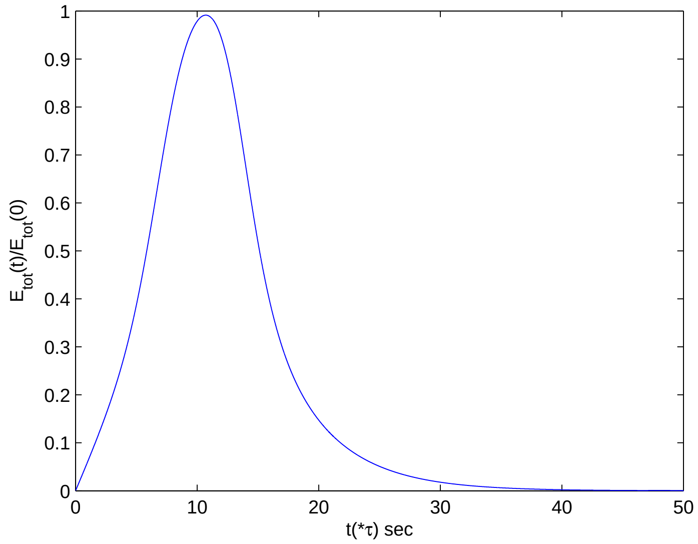

Figure 3: Temporal variation of the normalized total energy.

Authors' Contributions

The author contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all aspects of this work.

Data Availability

No data available.

Conflicts of Interest

The author declares that there is no conflict of interest.

Ethical Considerations

The author has 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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References

[1] Konkol, P., Murawski, K., & Zaqarashvili, T. V. 2012, A&A, 537, 96.

[2] Murawski, K., Musielak, Z. E., & Wojcik, D. 2020, ApJ, 896, 1.

[3] Niedziela, R., Murawski, K., & Poedts, S. 2021, A&A, 652, 124.

[4] De Mortel, I., & Nakariakov, V. M. 2012, Astrophysical processes on the Sun, 370, 3193.

[5] Heyvaerts, J., & Priest, E. R. 1983, A&A, 117, 220.

[6] Abedini, A., Safari, H., & Nasiri, S. 2012, Solar Phys., 280, 137.

[7] Morton, R. J., & Ruderman, M. S. 2011, A&A, 527, 53. Landau, L. D., & Lifshitz, E. M. 1959, Fluid Dynamics. Pergamon Press, Oxford.

[8] Ebrahimi, Z., & Javaherian, M. 2023, MNRAS, 520, 3641.

[9] Safari, H., Nasiri, S., & Sobouti, Y. 2007, A&A, 470, 1111.

[10] Priest, E. R., 1982, Solar magnetohydrodynamics, Reidel, Dordrecht.

[11] Murawski, K., & Zaqarashvili, T. V. 2010, A&A, 519, 8.

[12] De Mortel, I., Hood, A. W., & Arber, T. D. 2000, A&A, 354, 334.