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GRAVITO-ACOUSTIC WAVE REFLECTION

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Abstract. We study analytically reflection properties of gravito-acoustic waves at a horizontal boundary separating two isothermal regions of gravitationally stratified non-magnetized plasma. The standard set of hydrodynamic equations is used to derive the dispersion equation for gravito-acoustic waves. Propagation characteristics of acoustic waves modified by gravity and propagation characteristics of gravity waves are analyzed separately. The main aim of this paper is derivation of the reflection coefficient for these waves and its possible application to the boundary between the solar photosphere and solar corona. We have found that gravitational influence increases reflection of the acoustic waves. This influence is the most pronounced in the frequency range $2.8mHz < \nu < 5.6mHz$. It is shown that reflection coefficient for gravity waves is very high ($R \approx 1$). Acoustic waves have much more chance to pass photosphere-corona boundary. This refers particularly to high frequency ($\nu \gg 5.6mHz$) acoustic waves. They can transfer the energy flux from photosphere towards the corona. According to recent observations this may be important for the process of the coronal heating.

Key words: hydrodynamics; gravito-acoustic waves; Sun: photosphere; Sun: corona.

1. INTRODUCTION

Observations and measurments of solar oscillations have been carried out with high precision for decades in helioseismology studies [1], aiming to enlighten the internal structure of the Sun. The standard mathematical procedures in that field are based on solving eigenvalue problem for various models of solar interior and atmosphere [2]. In contrast, in this paper, we consider a problem of driven waves. This means, we assume the waves are generated in one of the two regions*, they propagate in a two region model with constant temperatures – solar photosphere and solar corona. Our approach to the problem of the waves reflection in a non-isothermal atmosphere is a simple two isothermal layer model with a discontinuous temperature step introduced by Schatzman 1956 [3]. This model has been used by Balmforth and Gough [4] to investigate pulsations of a stellar envelope. They analyzed reflection of

*How these waves are generated is not the primary task of this work. They can result from ongoing turbulent motions, or be a Fourier spectrum of some transient/impulsive process both occuring somewhere deeper in the interior and outside the two isothermal domains of our model atmosphere.

acoustic waves (p modes) in the case of normal incidence and investigated conditions for the acoustic resonance. Worall [5] used the same model to study reflections of p modes at the subphotospheric temperature decrease. Stable stratified atmospheres can support and propagate not only acoustic waves but also gravity waves. We study propagation and reflection of gravito-acoustic waves in detail with no restrictions on the angle of incidence. Our aim is to understand what part of the gravito-acoustic waves energy will be reflected back in the photosphere, and what part of the energy will be transmitted in the corona (the transmission coefficient is $T = 1 - R$). This is important for the energetics of the solar atmosphere. Namely, gravito-acoustic waves have been proposed as a candidate for the mechanical heating of stellar atmosphere more than 30 years ago by Mihalas and Toomre [6]. However, the difficulty associated with directly observing them in the Sun, have resulted in their negligence in this matter. The clearest demonstration of the presence of gravity waves in the middle photosphere was given by Straus and Bonaccini [7]. Further support to the identification of gravity waves in the photosphere is given by Magri *et al.* [8], and Krijger *et al.* [9]. Straus *et al.* [10] determined the height dependence of the energy flux of gravity waves in the lower solar atmosphere by combining high quality 2D observations and 3D numerical simulations. At higher frequencies Lites *et al.* [11] investigated acoustic waves in the photosphere and in the chromosphere. There is no doubt about the existence of gravito-acoustic waves, which can easily be proven with the help of power spectra at different heights in the solar atmosphere. The role of gravito-acoustic waves in the energetics of the solar atmosphere were examined earlier, [12, 13]. Straus *et al.* [14] have been revisited the role of gravito-acoustic waves in the dynamics and energetics of the Sun's atmosphere using high quality Doppler velocity measurments obtained with SOHO/NFI and SOT/SP on Hinode and with MDI on SOHO.

In this paper we analyzed the waves that propagate towards the plane boundary $z = 0$ between the photosphere, with temperature T_1, and the corona, with temperature T_2. We used the simple two isothermal layer model to achieve these aims:

- The presentation of analytical results for the behavior of waves at continuous temperature step in plane, static stellar atmospheres.
- The application of these results to the waves which propagate in layers of solar atmosphere with significant temperature changes such as solar photosphere and corona.
- Better understanding the role of gravito-acoustic waves in the energetics of the solar atmosphere through analysis of the reflection coefficient values.

Adiabatic fluctuations are considered because the effects of viscosity and thermal conduction on gravito-acoustic waves are negligible in astrophysical media.

This paper is organized in the following order: In Section 2 standard HD equations are used to describe the problem mathematically. Dispersion equation for gravito-acoustic waves is derived. In Section 3 gravito-acoustic waves on the plane boundary between two isothermal regions are discussed. Derived results are applied on the solar photosphere-corona boundary. Reflection coefficient for gravito-acoustic waves is derived in Section 4. Results are presented in Section 5. Observational data and conclusions are contained in Section 6.

2. STARTING HD EQUATIONS

2.1. THE BASIC STATE

We start from the standard set of non-linear hydrodynamic equations describing the dynamics of a fully ionized plasma with properties of a perfect gas. These equations are: continuity equation, momentum equation and adiabatic law for a perfect gas. The initial basic state is defined by the model itself which implies a stationary, static (*i.e.* the hydrostatic equilibrium), gravitationally stratified isothermal plasma with constant acceleration. Thus, in Cartesian coordinates, we have:

$$\vec{g} = -g\vec{e_z}, \;\; g = const.,$$

and

$$\rho_0 = \rho_0(z), \;\; p_0 = p_0(z). \tag{1}$$

The unperturbed plasma is initially in hydrostatic equilibrium and assumed to be stepwise isothermal $T_0 = const$, *i.e.* with constant temperature in each of the two regions separated by the boundary $z = 0$. The hydrostatic equilibrium is given by:

$$\frac{dp_0(z)}{dz} = -\rho_0(z)g. \tag{2}$$

Using this equation, together with equation for the perfect gas, $p_0(z) = \rho_0(z)RT_0$, we can get the equation for density profile:

$$\frac{d}{dz}\ln\rho_0 = -\frac{1}{H}.$$

Here, $H = RT_0/g$ is the constant scale height. The solution of the above equation is:

$$\rho_0(z) = \rho_{00}e^{-z/H}. \tag{3}$$

Thus, plasma density $\rho_0(z)$, as well as the pressure $p_0(z)$, decreases exponentially in the vertical direction with the same constant H. In the model used in this paper there is a constant sound speed: $v_s^2 = \gamma p_0(z)/\rho_0(z) = \gamma RT_0 = const$, where $\gamma = c_p/c_v = 5/3$ is the ratio of specific heats, $R = R_0/\bar{M}$ and $R_0 = 8.3145 \; JK^{-1}mol^{-1}$ is the universal gas constant while $\bar{M} = 0.5 \times 10^{-3} \; kg \; mol^{-1}$ is the mean particle molar mass of the considered e-p plasma. Note that the constant scale height H could be rewritten as $H = v_s^2/\gamma g$.

2.2. PERTURBATIONS

The dynamics of small amplitude waves is described by the standard set of HD equations for ideal plasma which are perturbed by taking any unknown physical quantity $\Psi(x,y,z,t)$ as a sum:

$$\Psi(x,y,z,t) = \Psi_0(z) + \delta\Psi(x,y,z,t). \tag{4}$$

Perturbations $\delta\Psi(x,y,z,t)$ have the following form:

$$\delta\Psi(x,y,z,t) = \Psi^{'}(z)e^{i(k_x x + k_y y - \omega t)}$$

with $|\Psi^{'}| \ll |\Psi_0|$. Unperturbed quantities $\Psi_0(z)$ satisfy the hydrostatic balance equation Eq.(2) of the basic state.

2.3. LINEARIZED EQUATIONS

The standard set of ideal hydrodynamic equations linearized according to Eq.(4) can be reduced to a sistem of two coupled ordinary differential equations:

$$\frac{d\xi_z^{'}}{dz} = C_1\xi_z^{'} - C_2 p^{'}, \;\; \frac{dp^{'}}{dz} - g\frac{d\rho_0}{dz}\xi_z^{'} = C_3\xi_z^{'} - C_1 p^{'}, \tag{5}$$

where $\xi_z^{'} = iv_z^{'}/\omega$ is the z-component (*i.e.* the vertical component) of the fluid displacement, while $p^{'}$ is the pressure perturbation. The coefficients in equations (5) are:

$$C_1 = \frac{g}{v_s^2}, \;\; C_2 = \frac{\omega^2 - k_p^2 v_s^2}{\rho_0(z)v_s^2\omega^2}, \;\; C_3 = \rho_0(z)\left(\omega^2 + \frac{g^2}{v_s^2}\right). \tag{6}$$

The density distribution $\rho_0(z)$ is given by Eq.(3) and $k_p^2 = k_x^2 + k_y^2$ designates square of the horizontal wavenumber. The Eqs.(5)-(6) allow the following solutions for the vertical displacement $\xi_z^{'}$ and the pressure perturbation $p^{'}$:

$$\xi_z^{'}(z) = \xi_z^{'}(0)e^{\frac{z}{2H}}e^{ik_z z}, \tag{7}$$

$$p^{'}(z) = p^{'}(0)e^{\frac{-z}{2H}}e^{ik_z z}. \tag{8}$$

Eqs.(5) with solutions Eqs.(7)-(8) finally yield the dispersion equation:

$$k_p^2 = \frac{\omega^2(\omega^2 - \omega_{co}^2 - v_s^2 k_z^2)}{v_s^2(\omega^2 - \omega_{BV}^2)}, \tag{9}$$

where $\omega_{co}^2 = \gamma^2 g^2/4v_s^2 = v_s^2/4H^2$ is the square of the acoustic wave cutoff frequency and $\omega_{BV}^2 = (\gamma-1)g^2/v_s^2 = (\gamma-1)v_s^2/\gamma^2 H^2$ is the square of the Brunt-Väisälää frequency. Eq.(9) corresponds to gravito-acoustic dispersion equation known from the literature [2, 15]. Physical quantities in dispersion equation can be made dimensionless by appropriate scalings: $K_p = k_p H$, $K_z = k_z H$ and $\Omega = \omega H / v_s$. Here, K_p and K_z are dimensionless horizontal and vertical wavenumbers scaled to $1/H$ and Ω is dimensionless frequency scaled to v_s/H. Dimensionless form of dispersion equation (9) is:

$$K_z^2 = \Omega^2 - \Omega_{co}^2 - \frac{K_p^2(\Omega^2 - \Omega_{BV}^2)}{\Omega^2}, \tag{10}$$

with $\Omega_{co} = 0.5$ and $\Omega_{BV} = \sqrt{(\gamma-1)/\gamma^2} = 0.489$. Dispersion equation (10) is bi-quadratic in Ω and its solutions present two wave branches-acoustic branch (solution with plus sign) and gravity branch (solution with minus sign). Notice that for $\Omega \gg 1$ and for high but finite values of dimensionless wavenumbers $K_p, K_z \gg 1$, we can neglect the terms proportional to $1/\Omega^2$. In that case, dispersion equation yields:

$$\Omega \approx K. \tag{11}$$

This is a dimensionless dispersion equation for the pure acoustic waves. The waves with a very short wavelengths, much shorter than characteristic length of medium inhomogeneity H, behave as the waves in the homogeneous medium. They satisfy the laws of acoustics.
In the limit of very low frequencies, $\Omega \ll 1$, dispersion equation (10) has a form:

$$\Omega^2 \approx \frac{K_p^2 \Omega_{BV}^2}{K^2 + \Omega_{co}^2}. \tag{12}$$

This is a dimensionless dispersion equation for gravity waves. Note that K_p must be nonzero and, unlike the acoustic waves, there is no vertical gravity waves. For $K_z = 0$, but $K_p \gg \Omega_{co}$, gravity wave dispersion equation yields:

$$\Omega \approx \Omega_{BV}.$$

Notice that Brunt-Väisäläa is cutoff frequency and gravity waves cannot propagate above it.

3. GRAVITO-ACOUSTIC WAVES ON THE PLANE BOUNDARY BETWEEN TWO ISOTHERMAL REGIONS

In our earlier paper (see [16]), we have derived the vertical dimensionless phase velocities for gravito-acoustic waves in the regions (1) and (2):

$$V_{v1} = \frac{\Omega}{K_{z1}} = \frac{V_h \Omega}{\sqrt{V_h^2(\Omega^2 - \Omega_{co}^2) - (\Omega^2 - \Omega_{BV}^2)}}, \tag{13}$$

and

$$V_{v2} = \frac{\Omega}{K_{z2}} = \frac{V_h \Omega}{\sqrt{sV_h^2(\Omega^2 - s\Omega_{co}^2) - (\Omega^2 - s\Omega_{BV}^2)}}. \tag{14}$$

Here, we have introduced dimensionless parameter $s = v_{s1}^2/v_{s2}^2 = T_1/T_2$. It is constant because mediums (1) and (2) are isothermal with temperatures T_1 and T_2 respectively. For propagating gravito-acoustic waves V_{v1}^2 and V_{v2}^2 are positive (*i.e.* K_{z1}, K_{z2} are real and positive). If $V_{v1}^2, V_{v2}^2 < 0$, these waves are evanescent (*i.e.* K_{z1}, K_{z2} are imaginary). In this paper only propagating waves in region (1) are analyzed. The waves in regions (2) can propagate or be evanescent. Notice that in approximation of very high dimensionless frequencies, $\Omega \gg 1$, the terms proportional to $1/\Omega^2$ can be omitted. Then, above equations become:

$$V_{v1} = \frac{V_h}{\sqrt{V_h^2 - 1}}, \tag{15}$$

and

$$V_{v2} = \frac{V_h}{\sqrt{sV_h^2 - 1}}. \tag{16}$$

These equations describe pure acoustic waves. There are two singular points, $V_h = 1$ and $V_h = 1/\sqrt{s}$, in which vertical wavenumbers are zero. These points separate regions of propagating and nonpropagating or evanescent pure acoustic waves.
For low dimensionless frequencies, when $\Omega \ll 1$, a small terms proportional to Ω^2 can be neglected. Eqs.(13)-(14) now have a form:

$$V_{v1} = \frac{V_h \Omega}{\sqrt{\Omega_{BV}^2 - V_h^2 \Omega_{co}^2}}, \tag{17}$$

$$V_{v2} = \frac{V_h \Omega}{\sqrt{s(\Omega_{BV}^2 - sV_h^2 \Omega_{co}^2)}}. \tag{18}$$

These equations refer to low frequency gravity waves. Singular points are $V_h = \Omega_{BV}/\Omega_{co}$ and $V_h = \Omega_{BV}/\sqrt{s}\Omega_{co}$. They separate the regions of propagating gravity waves and region of evanescent gravity waves.

3.1. GRAVITO-ACOUSTIC WAVES ON THE SOLAR PHOTOSPHERE-CORONA BOUNDARY

Physical parameters with values typical for the two-region configuration of the photosphere and corona are: solar gravitational acceleration $g = 274 m/s^2$, temperature of the photosphere $T_1 = 6 \times 10^3 K$, yielding $v_{s1}^2 = 1.66 \times 10^8 m^2/s^2$, temperature of the corona $T_2 = 10^6 K$, yielding $v_{s2}^2 = 2.7 \times 10^{10} m^2/s^2$. Parameter $s = v_{s1}^2/v_{s2}^2 = T_1/T_2 = 0.006$ will be used in further calculations.

Acoustic branch Eq. (15) shows that for $V_h > 1$, there are propagating acoustic waves in the photosphere. For these waves horizontal phase velocity is higher than photospheric sound velocity $v_{hp} > v_{s1} = 1.29 \times 10^4 m/s$.
Eq. (16) shows that $V_h = 1/\sqrt{s} \approx 12.91$ is a separation point between propagating ($V_h > 1/\sqrt{s}$) and evanescent ($V_h < 1/\sqrt{s}$) acoustic waves in the corona. It means that propagating acoustic waves, transmitted through photospere-corona boundary $z = 0$, have a horizontal phase velocity $v_{hp} > 1.66 \times 10^5 m/s$. For evanescent waves horizontal phase velocity is $v_{hp} < 1.66 \times 10^5 m/s$.
When gravity effects are introduced, then we have modified acoustic waves. Unlike the pure acoustic case, propagation of the acoustic waves modified by gravity is limited by frequency. There is a dimensionless cutoff frequency Ω_{co} equivalent to the frequency $\omega_{co} = 1.77 \times 10^{-2} s^{-1}$. Modified acoustic waves do not propagate below it. Conditions for propagating modified acoustic waves in the photosphere are $\Omega > \Omega_{co}$, *i.e.*, $\omega > \omega_{co} = 1.77 \times 10^{-2} s^{-1}$, and $V_h > 1$ equivalent to $v_{hp} > 1.29 \times 10^4 m/s^{\dagger}$. Conditions for propagating modified acoustic waves in the corona are: $\Omega > \sqrt{s}\Omega_{co}$, *i.e.*, $\omega > \sqrt{s}\omega_{co} = 1.37 \times 10^{-3} s^{-1}$ and $V_h > 1/\sqrt{s}$ or $v_{hp} > 1.66 \times 10^5 m/s^{\ddagger}$. Notice that $\Omega = \sqrt{s}\Omega_{co}$ is dimensionless cutoff frequency and modified acoustic waves do not propagate below it in the corona.

Gravity branch The method used for the acoustic waves can be applied to gravity waves. It can be concluded that conditions for propagating gravity waves in the photosphere are $\Omega < \Omega_{BV} = 0.489$, or for the frequencies $\omega < 1.73 \times 10^{-2} s^{-1}$ and $V_h < \Omega_{BV}/\Omega_{co} \approx 0.98$, *i.e.* for the horizontal phase velocities $v_{hp} < 1.26 \times 10^4 m/s$. Propagating gravity waves in the corona have frequencies $\Omega < \sqrt{s}\Omega_{BV} \approx 0.038$ ($\omega < 1.34 \times 10^{-3} s^{-1}$) and horizontal phase velocities $V_h < \Omega_{BV}/\sqrt{s}\Omega_{co} \approx 12.65$ ($v_{hp} < 1.63 \times 10^6 m/s$). Gravity waves in corona are evanescent for the horizontal phase velocity $V_h < 0.98$ and in the frequency range $0.038 < \Omega < 0.489$, *i.e.*, $1.34 \times 10^{-3} s^{-1} < \omega < 1.73 \times 10^{-2} s^{-1}$. Although theoretical calculations indicate that gravity waves can propagate in the corona, in Section 5 will be shown that these waves are strongly reflected from the photosphere-corona boundary. Therefore, a significant presence of gravity waves in the corona can't be expected.

4. REFLECTION COEFFICIENT FOR GRAVITO-ACOUSTIC WAVES

Conditions for gravito-acoustic waves reflection from the boundary $z = 0$ will be analyzed. Our aim is to derive equation for the reflection coefficient of gravito-

†These conditions are derived for $V_{v1} > 0$, Eq.(13)
‡Derived for $V_{v2} > 0$, Eq.(14)

acoustic waves. Reflection amplitude A_r is given by equation (for details see [16]):

$$A_r = \frac{G_{(1,1)} - G_{(2,1)} + g[\rho_{02} - \rho_{01}]}{G_{(2,1)} - G_{(1,2)} - g[\rho_{02} - \rho_{01}]}.$$

Using dimensionless parameters and above equation for the reflection amplitude A_r, the reflection coefficient $R = |A_r|^2$ for gravito-acoustic waves can be written in the form:

$$R = \left[\frac{\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{(s-1)}{V_h^2}\right]^2 + \frac{\gamma^2\Omega^2}{V_{v1}^2}\left(\frac{V_{v1}^2}{V_{v2}^2} \times \frac{s^2}{(sV_h^2-1)^2} - \frac{1}{(V_h^2-1)^2}\right)}{\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{(s-1)}{V_h^2}\right]^2 + \frac{\gamma^2\Omega^2}{V_{v1}^2}\left[\frac{V_{v1}}{V_{v2}} \times \frac{s}{sV_h^2-1} + \frac{1}{V_h^2-1}\right]^2} \right]^2$$

$$+ \left[\frac{\frac{2\gamma\Omega}{V_{v1}(V_h^2-1)}\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{(s-1)}{V_h^2}\right]}{\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{(s-1)}{V_h^2}\right]^2 + \frac{\gamma^2\Omega^2}{V_{v1}^2}\left[\frac{V_{v1}}{V_{v2}} \times \frac{s}{sV_h^2-1} + \frac{1}{V_h^2-1}\right]^2} \right]^2. \quad (19)$$

Vertical dimensionless phase velocities are given by Eqs.(13)-(14). For $s = 1$, there is $R = 0$, as should be expected. Namely, the plane $z = 0$ now does not separate two different regions and no wave reflection occurs at $z = 0$. The wave is fully transmitted through the boundary plane.

Note that for $\Omega \gg 1$ and finite values V_h, V_{v1} and V_{v2}, the reflection coefficient for the pure acoustic case can be derived:

$$R = \frac{\left(s\sqrt{V_h^2-1)} - \sqrt{sV_h^2-1}\right)^2}{\left(s\sqrt{V_h^2-1} + \sqrt{sV_h^2-1}\right)^2}. \quad (20)$$

If dimensionless frequencies are very low, $\Omega \ll 1$, the reflection coefficient for gravity waves becomes:

$$R = \left[\frac{\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{s-1}{V_h^2}\right]^2 + \frac{(\Omega_{BV}^2 - V_h^2\Omega_{co}^2)}{\gamma^{-2}V_h^2}\left(\frac{V_{v1}^2}{V_{v2}^2}\frac{s^2}{(sV_h^2-1)^2} - \frac{1}{(V_h^2-1)^2}\right)}{\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{s-1}{V_h^2}\right]^2 + \frac{\gamma^2(\Omega_{BV}^2 - V_h^2\Omega_{co}^2)}{V_h^2}\left[\frac{V_{v1}}{V_{v2}}\frac{s}{sV_h^2-1} + \frac{1}{V_h^2-1}\right]^2} \right]^2$$

$$+ \left[\frac{\frac{2\gamma\sqrt{\Omega_{BV}^2 - V_h^2\Omega_{co}^2}}{V_h(V_h^2-1)}\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{s-1}{V_h^2}\right]}{\left[\left(1-\frac{\gamma}{2}\right)\left(\frac{1}{V_h^2-1} - \frac{s^2}{sV_h^2-1}\right) + \frac{s-1}{V_h^2}\right]^2 + \frac{\gamma^2(\Omega_{BV}^2 - V_h^2\Omega_{co}^2)}{V_h^2}\left[\frac{V_{v1}}{V_{v2}}\frac{s}{sV_h^2-1} + \frac{1}{V_h^2-1}\right]^2} \right]^2. \quad (21)$$

Vertical dimensionless phase velocities are given by Eqs.(17)-(18).

5. RESULTS

In this Section the reflection coefficient values for acoustic waves, modified by gravity acoustic waves and gravity waves on the photosphere-corona plane boundary will be discussed.

Reflection coefficient for the acoustic waves If dimensionless horizontal phase velocity of acoustic waves is very high, $V_h \gg 1$, or $v_{hp} \gg v_{s1}$, as for the almost vertical waves (normal incidence), the reflection coefficient R is given by relation: $R = (\sqrt{s}-1)^2/(\sqrt{s}+1)^2 \approx 0.97$. In the separation point $V_h = 1$ or $v_{hp} = 1.66 \times 10^5 m/s$, the reflection coefficient is equal to unity, $R = 1$. This is a point of the total internal reflection for the acoustic waves. There are no transmitted acoustic waves from photosphere to corona and total waves energy is reflected back to the photosphere. Another characteristic point is $V_h = \sqrt{(s+1)/s} = 12.95$, or $v_{hp} = 1.67 \times 10^5 m/s$. In this point the reflection coefficient for acoustic waves is zero and the waves energy is completely transmitted in the region of corona. In the optics, this point is equivalent to the Brewster's angle [17].

Reflection coefficient for the modified acoustic waves Acoustic wave properties are modified by gravity. Fig. 1 shows the reflection coefficient R for these modified acoustic waves as a function of frequency Ω, while V_h is given parameter. Coefficient $R = 1$ for $\Omega = \Omega_{co}$, *i.e.*, for the waves whose frequency is equal to acoustic cutoff frequency of the lower region-photosphere $\omega_{co} = 1.77 \times 10^{-2} s^{-1}$. Note that for $V_h = 1/\sqrt{s} = 12.909$, *i.e.*, $v_{hp} = 1.66 \times 10^5 m/s$, regardless of the frequency value, the reflection coefficient is $R = 1$. This is a point of the total internal reflection for modified acoustic waves. The waves with $V_h \leq 1/\sqrt{s}$ are evanescent. For propagating waves ($V_h > 1/\sqrt{s}$) we compute the reflection coefficient from the equation (19). The minimal reflection coefficient for propagating waves is for $V_h = \sqrt{(s+1/s)} = 12.95$. In contrast to the pure acoustic case, its value for the modified acoustic waves is always greater than zero. This means that gravity increases the reflection coefficient value of the acoustic waves. Figure 1 shows that gravity influence is the most significant for the frequency range $\Omega_{co} < \Omega < 1$ ($1.77 \times 10^{-2} s^{-1} < \omega < 3.5 \times 10^{-2} s^{-1}$). For $\Omega \gg 1$ ($\omega \gg 3.5 \times 10^{-2} s^{-1}$), the figure is similar to that in the pure acoustic case.

Reflection coefficient for the gravity waves Reflection coefficient for the gravity waves, given by Eq.(19), is presented in Fig. 2. Gravity waves propagate from the solar photosphere, through the boundary $z = 0$, towards the solar corona. For all allowed values of horizontal phase velocities $V_h < 0.98$, *i.e.*, $v_{hp} < 1.26 \times 10^4 m/s$,

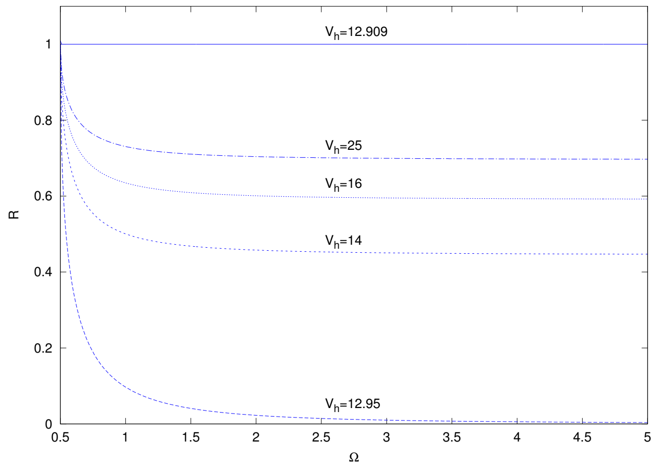

Fig. 1 – Reflection coefficient R for modified acoustic waves that propagate from solar photosphere to corona, when $s = 0.006$. It is a function of the frequency Ω. Reflection coefficient is equal to unity in two cases-if $\Omega = \Omega_{co}$, *i.e.* if the wave frequency is equal to acoustic cutoff frequency of the lower region (photosphere), or if the horizontal dimensionless phase velocity is $V_h = 1/\sqrt{s} \approx 12.91$, *i.e.* when the wave is evanescent.

and for the frequencies smaller than $\sqrt{s}\Omega_{BV} \approx 0.038$, *i.e.*, $\omega < 1.34 \times 10^{-3} s^{-1}$, the reflection coefficient is very high ($R \approx 1$). It could be concluded that gravity waves are likely to be strongly reflected back to the photosphere from the photosphere-corona boundary [18]. A very small part of their energy could propagate through the solar corona. Therefore, gravity waves are not a good candidate for the waves energy transmission into the corona. Notice that the reflection coefficient is equal to unity if $\Omega = \sqrt{s}\Omega_{BV}$, *i.e.*, for the waves whose frequency is equal to gravitational cutoff frequency of the corona, $\omega = 1.34 \times 10^{-3} s^{-1}$. It means that $\Omega = \sqrt{s}\Omega_{BV}$ is characteristic frequency for which the total internal reflection of gravity waves occurs. In approximation of a small parameter s, $s \ll 1$, all alowed frequencies of gravity waves (lower than $\sqrt{s}\Omega_{BV}$) are very small. Then, for the reflection coefficient of low-frequency gravity waves Eq.(21) could be used. This equation also shows that $R \approx 1$. Reflection coefficient for a low-frequency gravity waves propagating from the solar photosphere to corona is presented in Fig.3. It is a function of dimensionless horizontal phase velocity V_h and dimensional parameter s, with $V_{v1}/V_{v2} = \sqrt{s(\Omega_{BV}^2 - sV_h^2\Omega_{co}^2)/(\Omega_{BV}^2 - V_h^2\Omega_{co}^2)}$, (Eqs.(17)-(18)). For the $V_h \approx 0.98$, which is a separating point between propagating and evanescent incident gravity waves, the reflection coefficient is $R = 1$.

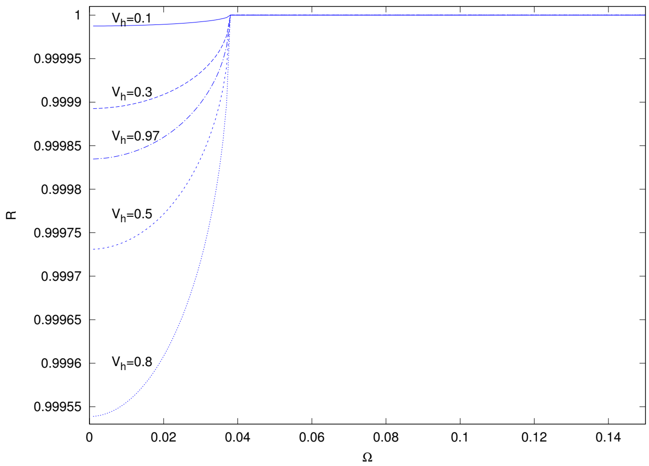

Fig. 2 – Reflection coefficient R for gravity waves that propagate from the solar photosphere to corona, when $s = 0.006$. It is a function of the frequency Ω. Allowed values of horizontal phase velocities are $V_h < 0.98$. Frequency $\Omega = \sqrt{s}\Omega_{BV} \approx 0.038$ is characteristic frequency that separates regions of propagating ($\Omega < \sqrt{s}\Omega_{BV}$) and evanescent gravity waves ($\Omega > \sqrt{s}\Omega_{BV}$). Gravity waves with frequencies $\Omega > \sqrt{s}\Omega_{BV}$ can't propagate through the solar corona. This means that $\Omega = \sqrt{s}\Omega_{BV}$ is a frequency above which total internal reflection of gravity waves occurs and the reflection coefficient is equal to unity.

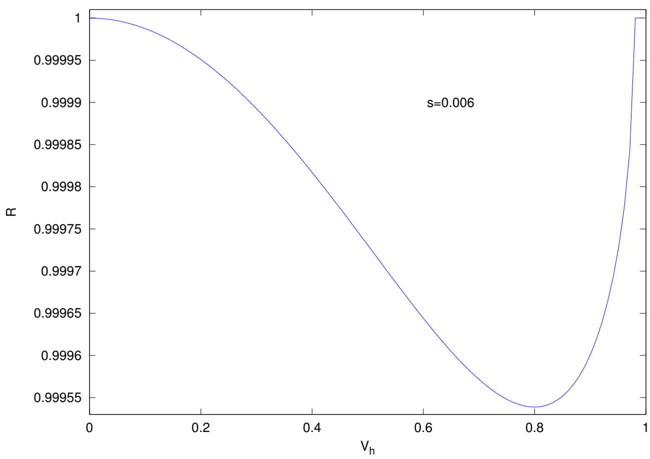

Fig. 3 – Reflection coefficient R for low-frequency gravity waves that propagate from the solar photosphere to corona, when $s = 0.006$. It is a function of horizontal phase velocity V_h. Reflection coefficient of these waves is very high, $R \approx 1$, for all allowed values $V_h < 0.98$. For $V_h = \Omega_{BV}/\Omega_{co} \approx 0.98$, when incident gravity waves become evanescent, reflection coefficient is $R = 1$.

6. CONCLUSION

It is well known that sound waves are prevalent in the Sun's interior. The first direct observation of waves propagating into and through the solar corona was made with SOHO space-borne solar observatory. These waves are observed in structures called coronal loops. The coronal loop oscillations were first reported in 2002 by Williams *et al.* [19], but it was not clear whether they were purely magnetic fluctuations or giant acoustic waves. New observations with SOHO confirm that they are associated with pressure fluctuations in the loops, making them acoustic waves. The fast damping of coronal loop longitudinal oscillations, which is observed in the extreme UV range, is among remarkable recent discoveries in the physics of the solar corona. According to some data the radiation effect can explain this phenomenon [20]. These oscillations with periods about three and five minutes are interpreted as acoustic waves. They penetrate into the corona through coronal loop. This phenomenon is of importance because the penetration of oscillations, which were generated in dense layers (photospheric or subphotospheric) into the corona can make a certain contribution to the wave energy transferred into the corona.

The study of gravito-acoustic wave propagation characteristics requires simultaneous measurements in at least two different heights in the solar atmosphere [14]. Gravity waves have low frequencies and small spatial scales and a proper horizontal wavenumber separation is essential for their study. For high frequency waves a short cycle time is the key requirement. Therefore, Straus *et al.* 2009, developed different observing programs, one targeted at gravity waves, the other at high frequency waves. This technique confirms the presence of gravity waves in the upper photosphere, and because of the high wavenumber and frequency resolution on the SOT/NFI and MDI, reveals interesting ridge/interridge structures in the region of p-modes [21]. With Hinode data they find an acoustic flux $3-5$ times larger than Fossum and Carlsson [22, 23]. The contribution of gravito-acoustic waves to the heating of the solar atmosphere is still in debate. In their studies Fossum and Carlsson and Carlsson *et al.* [24] concluded that high frequency acoustic waves ($\nu > 10mHz$) are not sufficient to heat solar chromosphere. Others question these results and argue for high frequency waves to play an important role. On the other hand, observations have shown that the energy flux carried by the low frequency ($\nu < 5mHz$) acoustic waves into the chromosphere is about factor of 4 greater than that carried by high frequency waves [25]. It seems that there is a lot of controversy about the acoustic waves.

In this paper we found that gravity waves propagate in the solar photosphere. This is in agreement with Straus *et al.*, [14]. In the two-layer model used to study the propagation of gravito-acoustic waves in stratified solar atmosphere, reflection coefficient for gravity waves on the photosphere-corona boundary is very high ($R > 0.9$). Therefore, gravity waves are not expected to play a significant role in the solar corona. Indeed, there is no observational data to support the existence of gravity waves in the solar corona yet. Unlike gravity waves, the acoustic waves can be transmitted into the corona. This is confirmed by aforementioned observations. Figure 1 shows that acoustic waves with $V_h \geq 12.95$ and for the frequencies $\Omega > \Omega_{co} = 0.5$, can be transmitted from the photosphere to the corona. In the frequency range $0.5 < \Omega < 1$, when gravity mostly influences acoustic waves properties, reflection is higher than for the frequencies $\Omega \gg 1$, when the waves are almost pure acoustic in their nature. Therefore, the low frequency acoustic waves with $2.8mHz < \nu < 5.6mHz$ will harder pass the photosphere-corona boundary than the high frequency acoustic waves with $\nu \gg 5.6mHz$. These high frequency waves carry certain amount of energy which can influence the heating of the corona. There is an open question about the efficiency of this heating mechanism. Alfvén waves are considered to be the best wave candidates that can carry adequate energy fluxes to heat the corona [26–28]. Unfortunately, this theoretical results are opposite to the observational result of footpoint heating [29]. The role of gravito-acoustic waves in the energetics of the solar atmosphere has been revisited in accordance with observations from SOT/NFI and SOT/SP on Hinode and MDI [30]. Finally, implied physical parameters (for the solar photosphere and corona) do not restrict the application of these results in any fundamental way, because one may replace a solar photosphere and corona with any piece-wise constant temperature profile.

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