LARGE-SCALE PERTURBATIONS NEAR THE SOLAR ATMOSPHERE TRANSITION REGION

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Abstract. Peculiarities of acoustic-gravity waves near the Solar atmosphere transition region are analyzed. The investigation is based on an original characteristic relation of waves in a two layers model with a temperature jump. Special attention is paid to an analysis of the properties of the surface waves, generated by the source of mass, which crosses the Solar atmosphere transition region. An exact analytical solution of this problem, which involves several modes propagating along the boundary is found. It is shown on the basis of the obtained results that the wave front from the local instantaneous source moves in radial directions with acceleration. The obtained results are important for explanation of observed properties of wave perturbations near the Solar atmosphere transition region, whose appearance correlates with coronal mass injection.

Key words: Sun - chromosphere - corona - transition region - acoustic-gravity waves

1. Introduction

The Solar atmosphere has the temperature jump in the transition region between the chromosphere and corona (Gibson, 1973; Aschwanden, 2004). This region is 2000 km over the chromosphere base. The temperature jumps from $10^4 K$ to $5 \cdot 10^5 K$ and its altitude scale is about 100 km. As it will be considered below, the sharp temperature jump can become a waveguide for the surface waves propagated along it. Earlyer we theoretically analyzed some properties of surface waves near the temperature jump in the Solar atmosphere (Bespalov and Savina, 2006). We found an exact solution of the model equation for the vertical medium velocity in such a wave. In this paper we study in more detail horizontally propagated waves (possibly EIT-waves) that accompanied a coronal mass ejection. These waves have lower amplitude and lower speed then typical well known Moreton's waves (Athay and Moreton, 1961). The wave front (in contrast to Moreton's waves) has the form of a circle. Appearance of such waves typically correlates with the

flashes of second type radio emission. The waves in question have horizontal scales of several ten thousand kilometers and propagate practically at constant height.

2. Surface Waves

The temperature rises sharply in the transition region of the Solar atmosphere from the chromosphere to corona. When wave disturbances with vertical scale sizes considerably larger then the temperature nonuniformity scale length are analyzed, it is enough to approximate the height dependence of the temperature as the temperature jump. Waves of this type were considered in different cases by Ghosh *et al.* (1995), Bespalov and Savina (1998). The hydrodynamic disturbances of the Solar atmosphere near the temperature jump was considered by Bespalov and Savina (1998) and Savina (1997), who used a general characteristic relation for surface waves

$$\frac{\Gamma_2 + \kappa_2}{\rho_{02}(\omega_{g2}^2 - \omega^2)} - \frac{\Gamma_1 - \kappa_1}{\rho_{01}(\omega_{g1}^2 - \omega^2)} = \frac{g\left(\rho_{02} - \rho_{01}\right)\left(\Gamma_2 + \kappa_2\right)\left(\Gamma_1 - \kappa_1\right)}{\rho_{02}\left(\omega_{g2}^2 - \omega^2\right)\rho_{01}\left(\omega_{g1}^2 - \omega^2\right)}, \quad (1)$$

where ω is the wave frequency, ω_g is Vaisala Brunt frequency, κ is the scale length of the wave amplitude decrease with increasing distance from the temperature jump, $\kappa_n = \sqrt{(\omega_{An}^2 - \omega^2)/c_n^2 + k^2(\omega^2 - \omega_{gn}^2)/\omega^2}$, ρ is the equilibrium density, g - gravitational acceleration, γ is the adiabatic index, $\omega_{An} = c_n/2H_n$, c_n^2 is the sound velocity, $\Gamma_n = (2 - \gamma)/2\gamma H_n$, k is the horizontal component of the wave vector (the quantities in the upper and lower half-spaces are written with the subscripts n = 1 and n = 2 respectively).

Under the conditions of the Solar atmosphere transition region, taking into account the continuity of pressure on the boundary of two media and the value of the jump, it is possible to consider that $T_1 \to \infty$, $\rho_{01} \to 0$. In this case the general characteristic relationship significantly simplifies and reduced to the form

$$(\omega_g^2 - \omega^2) + \frac{g(2 - \gamma)}{2\gamma H} + g\kappa = 0. \quad (2)$$

Solution of the Equation (2)

$$\omega^2 = gk \quad (3)$$

is identical in form to the equation for deep water-surface waves. Surface waves exist only for the specific horizontal scale λ, which satisfy with the condition $\lambda < 4\pi H$.

The analytical solution of dispersion equation (3) in the approximation described above agree well with the numerical results, found by Bespalov and Savina (1998). These waves have following properties:

- a wavelength is lower than the height of the homogeneous atmosphere;
- a typical vertical scale is more than horizontal;
- a phase velocity increases with an increase in the wavelength;
- wave forms moves with acceleration.

3. Wave Equation and its Solution

The general differential equation for the vertical component of the velocity of medium on the boundary of the temperature jump has the form (Bespalov and Savina, 2006):

$$\frac{\partial^4 w}{\partial t^4} + \frac{g^2}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right) = 0 \tag{4}$$

for appropriate initial conditions the solution of this equation is:

$$w(t,r) \propto \frac{1}{t}F\left(\frac{r}{gt^2}\right). \tag{5}$$

The disturbance (5) at the initial time is concentrated mainly near the coordinate origin and decays with time; its characteristic form moves with an acceleration proportional to g. The general solution of equation (4) takes the form:

$$u(\tau,r) = \frac{1}{\sqrt{2\pi}}\int\limits_{-\infty}^{+\infty} A(\omega)e^{-i\omega\tau}H_0^{(1)}(\omega^2 r)d\omega, \tag{6}$$

where $\tau = \sqrt{gt}$, $H_0^{(1)}(\omega^2 r)$ is the Hankel function of the first kind and $A(\omega)$ is determined by the initial condition. For the initial condition $u(0,r) = C/\sqrt{r}$ the self-similar solution (5) has a relatively simple analytical form, because:

$$F\left(\frac{r}{gt^2}\right) = \sqrt{\frac{\pi}{2}}\frac{gt^2}{4r}\left\{\left[J_{-\frac{1}{4}}\left(\frac{gt^2}{8r}\right)\right]^2 - \left[J_{\frac{1}{4}}\left(\frac{gt^2}{8r}\right)\right]^2\right\}, \tag{7}$$
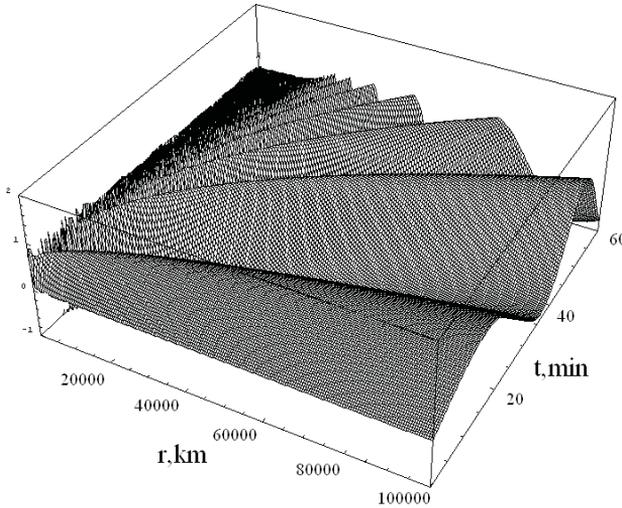
Figure 1: The vertical velocity of medium on the boundary for the time (t) and the distance from the source (r).

where J_ν is the Bessel function . The function (5) is plotted in Figure 1.

We see from this figure that, if initial disturbance is localized near $r = 0$, then after 20 minutes the disturbance passes a distance of about 100000 km. It was shown by the authors, that the fastest maximum moves with an acceleration close to g. Its equation of motion is $r = 0.4gt^2 = 0.8gt^2/2$. In Figure 2 we can see the picture of disturbances in region 100x100 Mm in 30 minutes after the source action.

When the source of the mass traverses the boundary between the two layers an emission of different wave modes (Denisov *et al.*, 1989) occurs. In that case a relationship of EIT waves and coronal mass ejection is possible.

In conclusion of this section let us discuss the influence of the magnetic field on the disturbances. The magnetic field influence on the gas dynamic motion is determined by the parameter $\beta = 2\left(c_s/v_A\right)^2$, where c_s is the sound velocity, $v_A = B/\left(4\pi\rho\right)^{\frac{1}{2}}$ is the Alfvén velocity. When $\beta \gg 1$, the gas-dynamic solution is usually realized, because a gas-kinetic pressure is much more than the magnetic pressure. A stable realization of such inequality near the transition region is problematic. However, it is necessary to mean other properties of MHD waves. So, Alfvén wave propagates without the disturbance of density and pressure. The group velocity of an Alfvén wave
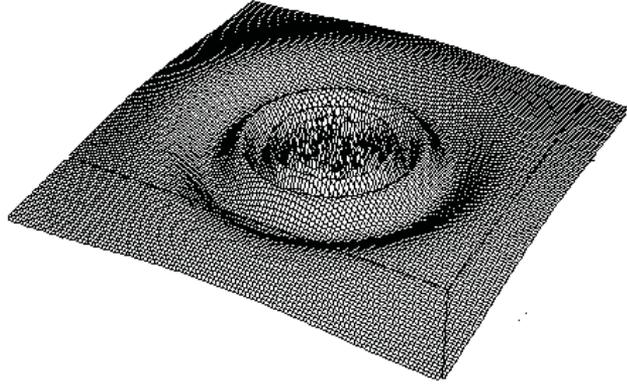
Figure 2: The spatial disturbances of the vertical velocity of medium on the boundary for t=30 min.

is directed along the magnetic field. Therefore even a small inclination of the magnetic field leads to transport of disturbances along the magnetic field. A slow magnetosonic wave also has the group velocity along the magnetic field and this velocity is much smaller then the velocity typical for surface waves. While a velocity of fast magnetosonic wave near transition region can be compared with the velocity of a surface wave. However, a fast magnetosonic wave does not have the fluctuations of the vertical velocity of a medium typical for the surface wave. Fast magnetosonic waves in contrast to surface waves are propagated without dispersion, and often isotropically.

4.   Conclusion

The transition region plays a significant role in the dynamics of the solar atmosphere. In this paper, we considered the surface waves near the temperature jump. Our investigation is based on the characteristic relation for surface waves in a two layers model (layers have different temperatures). We found the exact solution of this equation, which contains the new surface modes, propagated along the boundary. In the natural approximation when the Solar corona is represented by a medium with a very low density and very high temperature, we made sure that surface waves whose main vertical structure is localized near the transition region could exist. Waves of this type can be excited during Solar flares accompanied by coronal mass ejections.

Acknowledgements

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