FIVE-MINUTE OSCILLATIONS AND SOLAR ATMOSPHERE HEATING

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Since Leighton's discovery of five-minute oscillations in the solar atmosphere, many authors have made suggestions that these waves probably play some role in atmospheric heating. Indeed, the theory of atmospheric heating requires observational control. Why? It is suggested in the theory that the waves heating the atmosphere are generated in a convective zone. However, both the theory of the convective zone and the theory of wave generation by convective motions, are far from perfect. As a result of this, Ulmshneider (1971), for example, in his calculations of wave dissipation in the atmosphere has chosen; of the various calculations of the wave flux the convective zone, only those calculations which may provide sufficient heating, but neglects all the other ones, drawing only on the fact that both the chromosphere and the corona must be heated. At the same time, oscillations with a period of the order of five minutes on the Sun are observed practically at all levels and in all regions.

Oscillations with periods of the order of five minutes have no yet been considered in the classical theory of quiet atmospheric heating,. mainly because these waves are "non-propagating" (as they are called by many authors). The classification of atmospheric waves is based on the dispersion equation for an isothermal atmosphere. For the sake of clarity, a diagnostical diagram is usually drawn. The solutions of the equations for acoustic and gravity waves are the following:

$$v_z = e^{z/2H} \left(C_1 e^{ik_z z} + C_2 e^{-ik_z z}\right) e^{i(\omega t + \vec{k}_\perp \vec{r}_\perp)} . \quad (1)$$

For "surface" waves (as we shall name them) k_z is a purely imaginary value.

There is no propagation alon z, therefore some authors call these waves "non-propagating" and assume that they can only transfer energy in a horizontal direction. This is only valid for an infinite atmosphere, but it is invalid for atmospheric layers of a finite thickness. The phenomena of energy transfer through the layers of a finite thickness by such waves are well known, for example, for radio wavelengths: the radio waves tunneling through the ionosphere.

It would be rather simple tó show that for the surface waves there is a tunnel effect (Zhugzhda, 1972). In reality, the following solution should satisfy the equations:

$$v_z = e^{z/2H} \left(e^{-k_z z} \sin \omega t + e^{k_z z} \cos \omega t\right) \cos \bar{k}_\perp \bar{r}_\perp . \quad (2)$$

It may be transformed to read as follows:

$$v_z = 2e^{z/2H} (\mathrm{ch}\, 2k_z z)^{1/2} \sin (\omega t + \\ + \mathrm{arctg}\, e^{2k_z z}) \cos \vec{k}_\perp \vec{r}_\perp . . \quad (3)$$

Propagation along z has appeared. The thickness of the layer for which the tunnel effect must be taken into account is $d \sim 1/2\, k_z$.

Five-minute oscillations in the chromosphere apparently are the surface waves, and in the diagram they get into this very region. The accuracy of this conclusion depends on the measurements of the horizontal wavelength. In recent papers, Tannenbaum et al. (1969), Platov et al. (1971), and Sheeley et al. (1971), the authors arrived at the same values of of the order 3—4×10^3 km, although they applied different methods.

The presence or absence of the tunnel effect on the Sun depends on whether dissipation of these waves takes place in the upper layer of the atmosphere and whether the upward energy flux has its origin there. The theory of the dissipation of two-dimensional atmospheric waves is rather weakly elaborated, and it is difficult to calculate the tunnel effect value for the Sun.

One may adopt a different approach, e.g., to establish either the presence or absence or the tunnel effect in the chromosphere from observational data. If the 5-min oscillations are adiabatic, with the absence of the tunnel effect the oscillations would be in phase at all levels, however, if the tunnel effect is present, some lag would appear. It could be calculated for a simple model, and could be compared with the observations. It was found that the calculated phase lag is less than the observed, i.e. there is a tunnel effect in chromosphere (Zhugzhda, 1972). Hence, somewhere in the upper atmospheric layers a dissipation of the oscillations exists. However, it is important to know the mechanism of dissipation of the oscillations exists. However, it is important to know the mechanism of dissipation and of the flux of energy from the photosphere. I have already stated that it is rather difficult to calculate even a simple model of tunneling.

Another approch exists: to estimate the energy flux from the observational data. The flux of 5-min oscillations cannot be estimated by an usual formula for the sound-wave flux. The atmospheric inhomogeneity and the two-dimensionality of the non-adiabatic wave must be taken into account. Besides, the observed parameters should enter the formula.

The general formula for the flux is

$$I_z = \overline{p' v_z} \,, \tag{4}$$

where p' and v_z are the oscillations of the pressure and vertical velocity in wave.

The linearized equations of hydrodynamics may be reduced to the two equations in terms of the two unknowns, v_z and div v. The pressure oscillations are described as

$$p' = \frac{1}{i\omega} \left[\varrho_0 g v_z - \gamma p_0 \operatorname{div} v + (\gamma - 1) Q' \right] . \tag{5}$$

With the help of the equations of hydrodynamics it would be possible to express div v in terms of v_z and to substitute in into (5), and p' into (4). Then the flux would be expressed in terms of the observed value (Zhugzhda, 1973):

$$I_{\text{wave}} = \frac{\omega^2}{A v_{\text{ph}}} \left[a_1 (\omega^2 - a_1 k_\perp^2 c^{*2}) - - (\gamma - 1)^2 a_2^2 k_\perp^2 c^{*2} \right] \frac{p w^2}{2} \,,$$

$$I_{\text{conv}} = \frac{1}{A} \left[\left(k_\perp^2 g - \omega^2 \frac{\partial \ln w}{\partial z} \right) (\gamma - 1) a_2 \omega - - (\omega^2 - k_\perp^2 c^2) a_2 \omega \frac{\partial \ln T}{\partial z} \right] \frac{p w^2}{2} \,, \tag{6}$$

where

$$A = (\omega^2 - a_1 k_\perp^2 c^{*2})^2 + a_2^2 (\gamma - 1)^2 k_\perp^4 c^{*4} \,,$$

$$a_1 = \frac{\gamma \omega^2 + q^2}{\omega^2 + q^2} \,, \qquad a_2 = \frac{\omega q}{\omega^2 + q^2} \,.$$

w is the amplitude of the vertical velocity, v_{ph} is the phase velocity of oscillations, and p is the gas pressure.

The observed parameters, such as ω, $k_\perp$, the phase velocity, and the dependence of the amplitude of the vertical velocity w on the height enter this formula. Besides, it is necessary to know the values of the density, the velocity of sound, the temperature gradient, and the characteristic time of heat exchange.

The law of heat exchange is $Q' = -q \varrho_0 c_v T'$. Prescribing the heat exchange law is the only assumption used for the deduction. No restrinc-

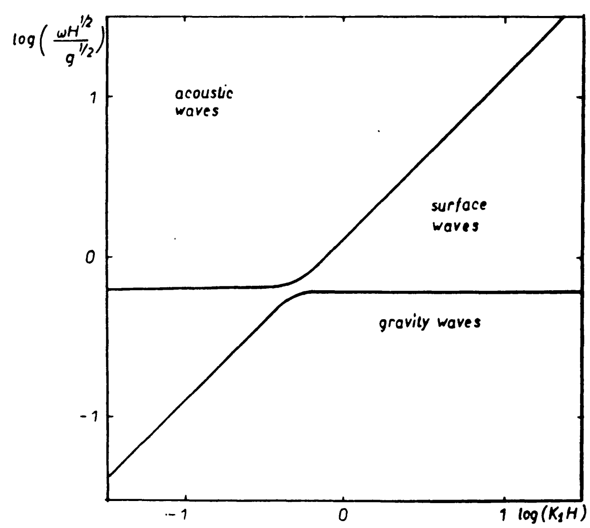

Fig. 1.

tion are imposed on the kind of atmosphere or on the wavelength. Naturally, the flux is divided into two parts. One part I_{wave} depends on the phase velocity of the waves, and there is a wave energy flux which disappears in the case of standing oscillations. The second part is a convective flux which is associated with the heat exchange of gas and which disappears for adiabatic oscillations.

Optical observations made simultaneously at two levels (i.e. in two lines) in the atmosphere give all the parameters needed for estimation, and certainly together with the standard atmospheric model. Figure 2 represents the dependence of the energy flux on $\lambda_\perp$ at the photosphere-chromosphere boundary.

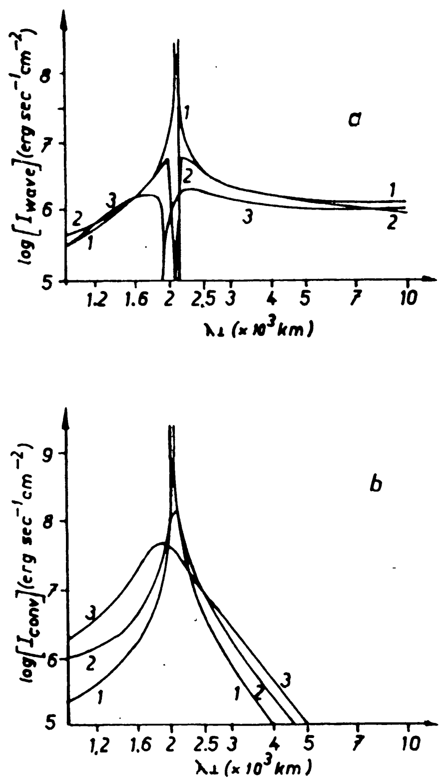

Fig. 2. Modulus of (a) wave flux I_{wave} and (b) convective flut I_{conv}, as a function of wavelength, into the chromosphere for $q=2\times10^{-3}$ (curve 1), $q=5\times10^{-3}$ (curve 2), and $q=2\times10^{-2}$ (curve 3).

It has been found that the flux depends strongly on the horizontal wavelength. The presence of a maximum at $\lambda_\perp = 2\times10^3$ km is connected with the fact that atmospheric waves prove to be mainly horizontal for such $\lambda_\perp$, and the calculation of this dependence has been made with w constant. For $\lambda_\perp = 2\times10^3$ the flux becomes too large $i\sim10^9$. This shows, in particular, that $\lambda_\perp$ may adopt any value but 2×10^3 km. If one is to believe the recent data mentioned above then $\lambda_\perp \sim 3$—4×10^3 km. A flux of the order 1—2×10^6 would then be enough for the atmospheric heating.

Thus, the 5-min oscillations are worth paying attention to from the point of view of the theory of atmospheric heating. If these oscillations carry a large energy flux, the next problem will be: how and where are they dissipated?

If the solar atmosphere is approximated at each level by an isothermal atmosphere, it would be possible to calculate $v_\perp/v_z$ at each level, and it appears that with $\lambda_\perp \sim 3$—4×10^8 km this relation would become larger in the upper chromosphere, i.e. the wave becomes practically horizontal (Zhugzhda, 1973b). The transition to horizontal waves corresponds to the resonance at Lamb's wave is a horizontal propagating sound wave. Probably just at the level where Lamb's wave occurs, the dissipation of the 5-min oscillations takes place.

Besides this, resonance-trapped waves may be excited in the transition layer between the chromosphere and corona. The natural frequencies of these oscillations were calculated by mens of a BESM-4 computer for the model where the atmosphere and corona are considerend isothermal atmospheres and the temperature increases linearly in the transition layer. The results of these calculations for a transition layer 100 km thick are

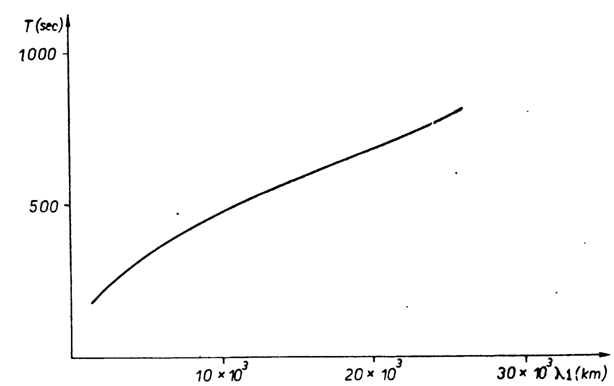

Fig. 3.

represented in Figure 3, in which one can see the relationship between the frequency and the horizontal wave vector of the trapped waves. To excite the 5-min oscillations, the horizontal wavelength would have to be equal to 3.8×10^3 km.

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