WAVE PROPAGATION IN THE SOLAR ATMOSPHERE

E. V. Khomenko

Main Astronomical Observatory, NAS of Ukraine
27 Zabolotnoho St., 03680 Kyiv, Ukraine
e-mail: khomenko@mao.kiev.ua

The theory of a wave propagation in the solar atmosphere has been applied to study peculiarities in the wave behaviour above granules and intergranular lanes. We introduced oscillations into a 3D snapshot of the theoretical time dependent solar model atmosphere. NLTE synthesis of the two solar lines was performed: the relatively strong Fe I 5324 Å which is formed over all the photosphere and a weaker Ni I 6768 Å line. The latter is widely used in helioseismology. We compared our modeling with the high spatial resolution observations obtained from the ground using VTT on Tenerife and from space using SOHO/MDI. We conclude that many differences in oscillations above granules and lanes can be induced by variations of the physical conditions in these structures.

MODEL OF OSCILLATIONS

We solved analytically the standard hydrodynamical equations of mass, momentum and energy conservation under assumptions that there are no magnetic field; viscosity and thermal conduction terms can be omitted; the effects of solar rotation are negligible; to the 0^{th} order the atmosphere is plane parallel, horizontally homogeneous and in radiative equilibrium. The matter is described by equation of state neglecting ionization effects. The effects of radiative relaxation are taken into account by using the Newtonian cooling approximation. The motion is restricted to one dimension. Solution of the system of partial differential equations was obtained by approximating the atmosphere as a series of isothermal layers each of a given thickness (10 km) moving with a constant velocity. In each layer we linearized the fundamental equations with:

$$T = T_0 + T_1, \quad P = P_0 + P_1, \quad \rho = \rho_0 + \rho_1, \quad V = V_0 + V_1, \tag{1}$$

where T_0, P_0, ρ_0 are unperturbed model temperature, pressure and density and V_0 is convective velocity. The system has an exponential solution at the fixed frequency of the form of a plane wave.

$$V_1,\, T_1,\, \rho_1 \;\sim\; e^{z(1 \pm k_i)} e^{\pm i k_r (\pm t V_{ph} - t V_0 - z)}, \tag{2}$$

where $V_{ph} = \omega / k_r$ is the phase velocity of the wave, k_r and k_i are the real and imaginary parts of the vertical wave number k_z. Upward and downward solutions were selected by choosing the corresponding sign of k_r and k_i.

A wave crossing the boundary between the layers experiences a partial reflection due to the discontinuity of atmospheric parameters. At the interface between two layers the conditions of total pressure and total velocity continuity take place. These conditions lead to the expression for reflection and transmission coefficients in the form [2]:

$$\tilde{R} = \frac{V_r}{V_i} = \frac{(C_t - C_i) + g/\omega(\rho_u - \rho_l)}{(C_r - C_r) - g/\omega(\rho_u - \rho_l)}, \tag{3}$$

$$\tilde{T} = \frac{V_t}{V_i} = \frac{(C_r - C_i)}{(C_r - C_r) - g/\omega(\rho_u - \rho_l)}, \tag{4}$$

where C is the complex proportionality coefficient between velocity and pressure perturbations; subscripts i, r and t denotes respectively the incident, reflected and transmitted waves; ρ_u and ρ_l are densities of the upper and lower layer. We calculated the $\tilde{R}$ and $\tilde{T}$ for all the 102 boundaries in our model. The resulted velocity perturbation was computed as a superposition of all the reflected waves and transmitted wave. The waveforms for the thermodynamic perturbations T_1/T_0 and ρ_1/ρ_0 and P_1/P_0 were obtained from the polarization relations.

Variations of the thermodynamical quantities were introduced into the model atmosphere and then profiles of the Fe I 5324 Å and Ni I 6768 Å lines were synthesized. In the present study we utilize a snapshot of the 3D model atmosphere from the most recent numerical simulations by Asplund *et al.* [1]. We use the interpolation from the original simulated box which has physical dimensions of $6.0 \times 6.0 \times 3.8$ Mm with nearly 1.0 Mm being located above the continuum optical depth unity. For the line profiles calculations we chose one slice from the snapshot and extracted a set of 50 1D granular and intergranular models by taking the height-variation of the thermodynamical quantities at the selected gridpoints of the slice.

We computed the line intensity using the formal solution of the time–dependent radiative transfer equation for the case of the moving atmosphere perturbed by oscillations. Line profiles were synthesized using NLTE departure coefficients found for each of the 50 models from the self–consistent solution of the kinetic and radiative transfer equations [3]. Time series of Fe I 5324 Å and Ni I 6768 Å line profiles were synthesized with the overall computational time of 1 wave period ($\sim$ 5 minutes). Initial amplitude of the wave perturbation was chosen equal to $V_0 = 100$ m s^{-1} at height 0 km, with the period being 270 s.

Then we restored velocity and intensity oscillations at 11 levels of the computed Fe I line profiles applying the method described by Stebbins and Goode [5]. For the case of Ni I line profile series we computed MDI velocity and intensity oscillations in the way described by Scherrer *et al.* [4].

OBSERVATIONS

We compared the results of our computations with the high spatial resolution observations obtained both from the ground with VTT on Tenerife and from space with SOHO/MDI.

The ground observations were carried out with the 70-cm German VTT at the Observatorio del Teide, Tenerife, in August 1996. The CCD images contain the photospheric line Fe I 5324 Å. The observed area (0.38×89 arcsec^2) was placed near the quiet solar disk centre. The spectrograms were taken every 9.3 s during 31 minutes. The spatial resolution of this observations was about 0.5 arcsec.

For our study we have used also the 58 min of the filtragrams from the "Line Profile Study" campaign on October 11, 1999 taken in the high resolution mode of MDI with 0.625 arcsec/pixel. The observed area was 160×160 arcsec^2 large, virtually quiet and placed near the disc center. We constructed a proxy for velocity, line and continuum intensity signals using the filtragrams.

CONCLUSIONS

The main results of our study are the following:

(i) amplitudes of velocity and intensity oscillations change with granulation contrast at all height layers of the photosphere. At average, the amplitudes are larger above the dark intergranular lanes.

(ii) velocity–intensity phase shift above the lanes is 30 degrees lower than above granules.

(iii) velocity oscillations at the lower layers of the atmosphere lead oscillations at the upper layers in intergranular lanes. In granules the phase shift is nearly zero.

We summarize that many differences in oscillations above granules and intergranular lanes can be reproduced with the help of the wave propagation theory. Even if all the initial and boundary conditions are equal at $H = 0$, oscillations above granules and intergranular lanes turn out to have different amplitudes and phases at the upper layers of the photosphere. This changes are caused by modulation of the propagating wave by the variations in the physical conditions in these structures.

Acknowledgements. We would like to thank R. Kostik for the helpful discussions. Special thanks to M. Asplund for the kind permission to use 3D model atmosphere for the purposes of our study. We are grateful to A. Kosovichev for the help with MDI data processing and useful suggestions.

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