SPATIAL STRATIFICATION OF ACOUSTIC OSCILLATIONS IN THE SOLAR PHOTOSPHERE

M. I. Stodilka

Astronomical Observatory, Ivan Franko National University of Lviv
8 Kyryla i Methodia Str., 79005 Lviv, Ukraine
e-mail: `sun@astro.franko.lviv.ua`

Space-time variations of solar atmosphere parameters are derived by solving non-equilibrium radiation transfer problem. Acoustic oscillations were extracted using $k-\omega$ filtration of variations. In the lower photosphere there are evanescent remnants of underphotosphere oscillations; in the middle and high photosphere there are discrete sources of oscillations, which are excited by granule decay and formation of a new intergranule. The photosphere is penetrated by narrow "channels", by which energy of fluctuations tunnels with minimal losses into the higher atmosphere layers; such "channels" arise mostly between ascending and descending flows. Particularities of the wave propagation in the solar atmosphere are determined by relationship between wavelength and the effective size of inhomogeneities.

INTRODUCTION

Five-minute oscillations were first revealed by Leighton in 1961 while observing velocity field in the solar photosphere. Similar oscillations appear during investigation of radiation intensity, temperature, density, gas pressure etc. To tell the truth, it is still hard to answer what is really observed: either evanescent remnants of underphotosphere oscillations which are stochastically excited by the turbulent convection and nonadiabatic gas pressure fluctuations by the top of the convection zone [6], or the result of acoustic oscillation generation in the convectively stable region of overshooting convection, or, perhaps, effect of wave modulation by atmosphere inhomogeneities [8].

There are two approaches which allow us to obtain information on oscillations in the solar atmosphere. The first one (direct methods) is based on modelling the physical processes, which occur in the atmosphere of the Sun; they enable one to determine perturbations of physical parameters and to estimate their influence on the spectral lines. On the other hand, inverse methods based on observed data give a chance to get semiempirical models of investigated objects and to reproduce space-time variations of physical quantities characterizing conditions in the solar atmosphere.

Inverse methods are successfully applied to study of different nature fluctuations and also to photosphere oscillation investigation by line profiles both with a low [4, 5] and high [3] spatial resolution.

The aim of this work is to study by the morphological treatment particularities of excitation and propagation of acoustic oscillations in the solar photosphere based on reproduced time-spatial temperature variations. Atmosphere parameter variations are reproduced by solving non-equilibrium inverse radiation transfer problem using Tikhonov's stabilizers [7]. Our approach is similar to existing ones, but it has some advantages: 1) non-LTE effects are taken into account; non-LTE parameters for average atmosphere are often used in inverse problem, which is not quite correct; in our approach non-LTE parameters are determined for each iteratively defined intermediate model; 2) used in our work Tikhonov's stabilizers substantially improve reliability of reproduced values; 3) nonlinear effects are taken into account: decomposition of variations into convective and wave components is done based on reproduced data but not by the observed profiles; 4) spatial variations of parameters were obtained in geometrical altitude scale. In inverse technique the problem of defining the line formation depths is totally absent. But line formation depths are often determined by contribution functions into emission for intensity and by response functions for velocity during oscillation study. If contribution functions give some information about depths of observed radiation formation, then response functions determine regions where considered spectral line is sensitive to variations of corresponding parameter describing the atmosphere.

Study of the solar atmosphere oscillations spatial stratification gives an answer concerning five-minute oscillations nature and mechanisms of their excitation.

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METHODS OF INVESTIGATION

Spatial and time variations of parameters (temperature, velocity field) for nonuniform solar atmosphere are reproduced by the Fe I λ 532.42 nm line profiles in the solar disc centre with a high spatial and time resolution. Profiles were obtained by N. G. Shchukina with the German Vacuum Telescope (Canary Islands); time resolution is 9.3 s, while spatial one is about $0.35''$ [1]. We have calculated the set of semiempirical models using line profiles along the spectrograph slit along spatial X-coordinate on the solar surface. Each model of the nonuniform solar atmosphere is two-dimensional comprised by two spatial coordinates (X, h), where h is altitude.

The Fe I line profiles allow one to determine the model parameters from lower layers (formation of continuum) up to the temperature minimum region.

Solar photosphere structure is determined by both wave and convective motions. Spectral features of variations allow to decompose them into convective and wave components [1, 2]. In our study decomposition of oscillations is realized by the multidimensional Fourier transform, namely by dividing the Fourier image using line ($\omega = v_s \cdot k_x$) or the Lamb hypercone ($\omega^2 = v_s^2 \cdot (k_x^2 + k_y^2 + k_z^2)$), where v_s is sound speed. Indeed, regions ($\omega = v_s \cdot k_x$) or ($\omega^2 = v_s^2 \cdot (k_x^2 + k_y^2 + k_z^2)$) correspond to acoustic oscillations. Applying the inverse Fourier transform to correspondingly defined part of the Fourier image one can easily get time-spatial variations of temperature, velocity and other values induced by acoustic motions.

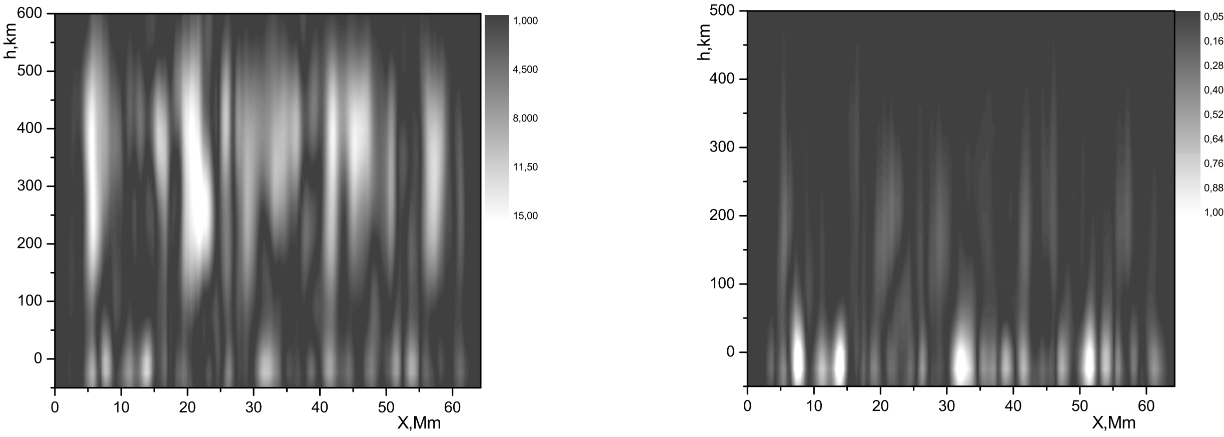
Narrow band filtering allows one to investigate generation and propagation of five-minute, low and high frequency oscillations in the solar atmosphere.

RESULTS

Solving non-equilibrium inverse radiation transfer problem, we reproduced dynamics of the temperature and velocity fields of the quiet region in the solar disc centre; its width and the observation time are 65 Mm and 31 minutes, respectively; and we used the Fe I λ 532.42 nm line profiles with a high spatial and time resolution. According to methods described above we extracted the wave component which corresponds to acoustic modes of oscillations.

As the wave capability to penetrate into the higher layers of the uniform atmosphere depends on oscillation frequency and, on the other hand, particularities of their propagation in the inhomogeneous medium are determined by relationship between wavelength and effective size of inhomogeneities [9], we shall consider five-minute, ten-minute (long-period) and two-minute (short-period) oscillations separately. The scales of the temperature and velocity oscillations in the solar photosphere are comparable with wavelength of five-minute oscillations; such oscillations will be the most scattered by granular structure of the photosphere.

Let us consider the results of the temperature wave field reproduction. The snapshot of the reproduced five-minute oscillations is shown in Fig. 1 (temperature in absolute value; the same is for the rest of figures).



a) temperature

b) energy flow (in relative units)

Figure 1. Spatial distribution of five-minute temperature oscillations (in absolute value)

Oscillation amplitude increases in the higher and also in the lower layers of the atmosphere; the size of regions filled with oscillations is 1–5 Mm across the surface. Despite amplitude increase with height, in the layers 50 km $< h <$ 150 km the oscillations are suppressed because of the wave front distortion caused by the photosphere inhomogeneities (Fig. 1a), and also because of radiation smoothing of temperature fluctuations. At these heights wave fronts are most distorted [8]. When the perturbation increases, the size of the region that is oscillating also increases in horizontal and vertical directions. The oscillations are mostly localized in the photosphere in the corresponding places and stay there during their existence or change slightly their location. One can often meet sources that give rise to running waves; but the latter ones damp rapidly enough. Because of the quick damping the length of the wave train is approximately equal to the wavelength. Thus, at $X = 5.5$ Mm, in the middle photosphere there is an intensive source of oscillations. The damping oscillations are spreading from it. The region of the increased temperature, that is in the lower photosphere at 7.5 Mm, reflects the state of the wave, which has spread by 2 Mm from its excitation source in 180 s. The second powerful source is located at $X = 20$ Mm in the middle photosphere at a depth of approximately 200 km. The perturbations from both sources propagate into low and high layers and also horizontally, but along definite direction. One can have an impression that there is a vertical wall from which the waves are reflected. In both cases the bright and wide granules act as such a wall. It is difficult to determine the velocity of oscillation propagation, because: 1) we observe projection of horizontal motions in the direction along the spectrograph slit, 2) sources of oscillation are diffused in space, 3) size of a region filled by oscillations depends on magnitude of the oscillation. We can only roughly estimate the velocity of horizontal displacement of oscillations; it has the same order of magnitude as a sound speed.

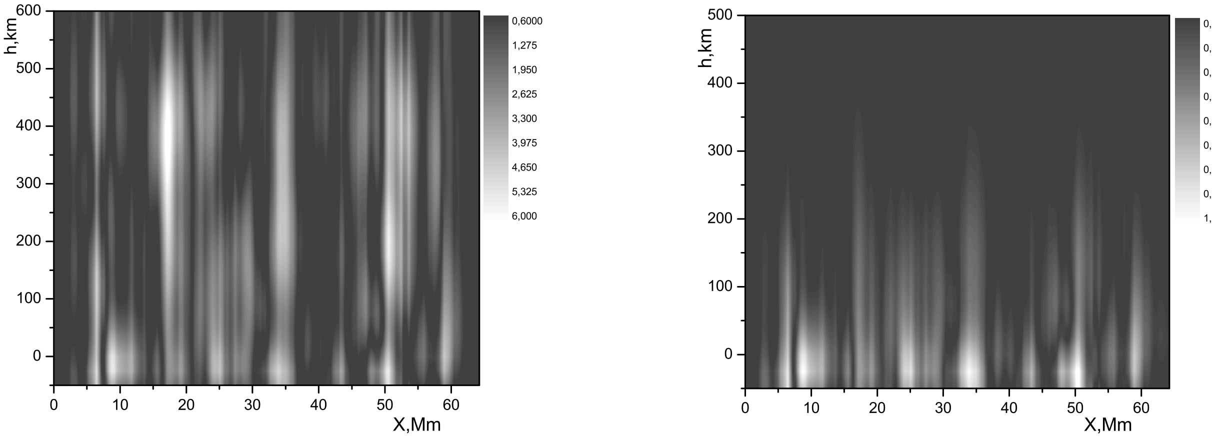
Oscillation intensity studies reveal a sharp amplitude's increase in higher layers of the atmosphere. This increase is mainly due to density decrease with height, but also it may be due to existence of oscillation sources in the higher layers of the atmosphere. To exclude the first factor, we should consider internal energy flow of oscillations that is reduced to a formal multiplication of the temperature change by the density and sound speed. The corresponding energy flow is shown in Fig. 1b. One can see that the height stratification of the amplitude flow is radically changed. Analysing energy flow it is easy to determine (when the energy is not transformed into other forms) a location of oscillation sources. Using Fraunhofer lines one can carry out a diagnostics of the solar atmosphere layers only. Most oscillation sources lie in lower layers of the photosphere $h < 100$ km (Fig. 1b). So, we observe only the top of these oscillations which are located much below. In other words, lower photospere oscillations are rather evanescent remnants of the underphotospere oscillations. In the middle photosphere (100 km $< h <$ 400 km) there are oscillation sources too: at $X = 5$ Mm, 20 Mm, 29 Mm (Fig. 1b). Having compared location of the intensive sources, mentioned above, to convective distribution of the temperature and velocities at the given point of time, we revealed that: the source at $X = 5$ Mm corresponds to disappearance of a narrow granule, located between two narrow intergranules. There is no temperature inversion in this granule. The granule that disappears and narrow intergranule develop into wide intergranule with descending flow. At the position of the second source ($X = 20$ Mm) the granule (with temperature inversion) decays, it leads to the following creation of the intergranule. The mentioned granule (upflow) is located between two descending flows. Ascending and one descending flows fade away with time, but the second downflow increases. The next source ($X = 29$ Mm) is between two granules with temperature inversion. The first granule rises and the second one develops into intergranule: the cooler matter of the granule, which is in higher layers, begins to move down, and as a result a new intergranule (with no temperature inversion) appears.

So, the process of granule decay with formation or expansion of the intergranule on their place is accompanied by intensive excitation of five-minute oscillations. Energy from such sources propagates into higher and lower layers, but along slender directions.

Besides, in Fig. 1b one can neatly see "narrow canals", where energy tunnels into higher layers of the atmosphere; along these "canals" energy damping is minimal. Such "canals" are at $X = 5.5$ Mm, 17 Mm, 24 Mm, 26 Mm, 42 Mm, ... They usually correspond to vertical regions that are between granule and intergranule, and both can be with temperature inversion or without it; gas flows in the granule and intergranule are in opposite directions. Sometimes, "canals" could be found between two rising flows; and one of them is weaker or is at the border of the intergranule. Such a situation may take place when the spectrograph slit crosses the intergranule border. One can probably identify the mentioned above "canals" with local acoustic events.

Similar investigation has been done for ten-minute oscillations. The amplitude of the oscillations is approximately ten times smaller than that for five-minute oscillations. It also increases with height. In the lower atmosphere there is inconsiderable decrease probably due to scattering, which is less effective, than in the five-minute case; the wavelength of long-period oscillations is larger than the inhomogeneity size, and waves partly bend them round (Fig. 2a). The regions occupied by ten-minute oscillations are much larger than those of five-minute ones.

During the wave propagation into the higher layers the amplitude is defined by factors that partly compensate each other. They are: a) increase of the amplitude as a result of matter density decrease; b) decrease of the amplitude because of the energy scattering; and c) its increase in the higher layers as a result of the energy transport velocity decrease. In the higher layers a region with a sharp decrease of amplitude appears to be



a) temperature

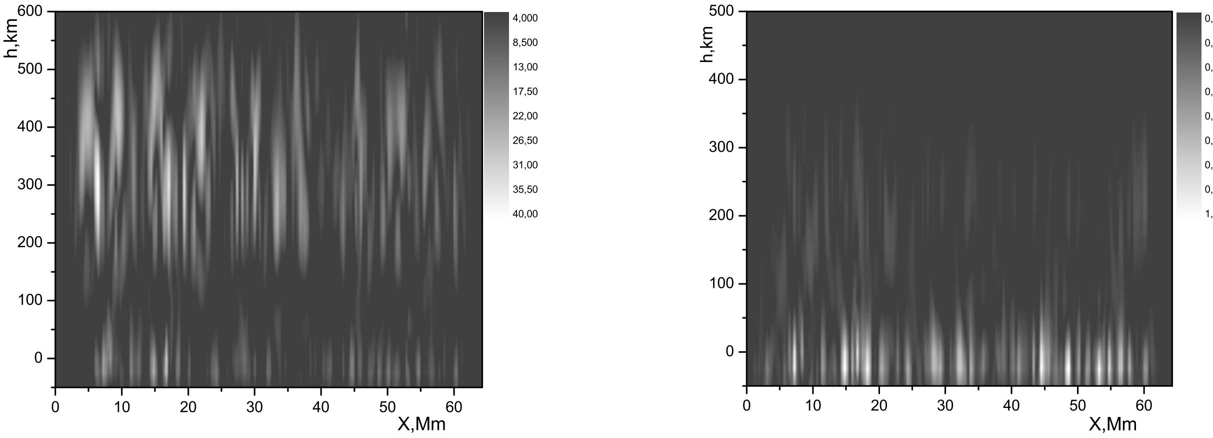
b) energy flow (in relative units)

Figure 2. Spatial distribution of ten-minute temperature oscillations (in absolute value)

under affect of these factors during decrease of the energy flow from the oscillations source. Vertical size of that region (with small amplitude) increases, and it makes illusion of existence of a local source in the higher photosphere (Fig. 2a, $X = 6$ Mm).

According to Fig. 2b which shows the spatial stratification of the internal energy flow of ten-minute oscillations, the main oscillation sources take place in the lower photosphere (they are evanescent remnants of the underphotosphere oscillations); there are also sources of oscillations not connected with the mentioned sources; they are generated by the decay processes. The latter sources are allocated mainly in the lower part of the middle photosphere, 50 km $< h <$ 200 km, and their energy is much less than the energy of lower photosphere sources.

Also, there are discrete "canals" that ensure tunneling of oscillations into the higher layers of the atmosphere (Fig. 2b). They are allocated between granules and intergranules (opposite flows). Seldom, one can nevertheless meet the "canals" between equally directed flows.



a) temperature

b) energy flow (in relative units)

Figure 3. Spatial distribution of two-minute temperature oscillations (in absolute value)

Short-period oscillations (1 min $< T <$ 3 min) in the lower photosphere represent the analogous system of evanescent remnants of underphotosphere oscillations (Fig. 3a). Their amplitude is in several times smaller than five-minute oscillations. The short-period oscillations are very relaxed in the transition region from the classic to overshooting convection, and sources of the oscillations appear again in the middle photosphere: $100\ \text{km} < h < 400\ \text{km}$ (Fig. 3b). As we see in Fig. 3, there are too much sources of oscillations, as it is needed for granule decay processes. Most of the granule-intergranule lanes are filled by these oscillations. That confirms theoretical conclusions on the possibility of short-period oscillation capture by elements of the granulation structure [9]; as a result the amplitude of the oscillation increases in these lanes.

Having compared a distribution of oscillations in different points of time, it is easy to see that short-period oscillations are standing waves (incident and reflected waves superposition) that are produced as a a result of reflection from layers $h \approx 100$ km (beginning of the overshooting convection region) from below and from layers $h \approx 400$ km from above. As our investigation shows, at heights of $h \approx 400$ km there appear intensive horizontal flows; and captured short-period waves may be reflected from them.

As can be seen, the features of the wave propagation in the solar photosphere are determined by oscillation frequency or more correctly by relationship between wavelength and effective size of inhomogeneities. Of course, the morphological method cannot widely describe all features of oscillation generation and propagation in the solar atmosphere. The results must be completed by the proper statistical study.

CONCLUSIONS

We localized the discrete sources of oscillations and revealed their origin: in the lower photosphere there are evanescent remnants of underphotosphere oscillations; in the middle and upper photosphere the oscillations are excited by the granule decay processes and formation of a new intergranule or increasing the existing one.

The solar photosphere is penetrated by narrow "canals", where oscillation energy spreads with minimal losses into the higher layers of the atmosphere (till the temperature minimum); such "canals" arise mostly between ascending (granule) and descending (intergranule) flows.

Energy of long-period oscillations ($T \approx 10$ min) is less than five-minute oscillation energy by a factor more than 10. Long-period oscillations are excited in the lower photosphere (evanescent remnants) and in the layers $50\ \text{km} < h < 200\ \text{km}$.

Short-period oscillations ($T < 3$ min) are generated in the lower photosphere ($h < 100$ km) as evanescent remnants of underphotosphere oscillations. At the heights $100\ \text{km} < h < 400\ \text{km}$, short-period oscillations represent a set of standing waves, trapped by the granule-intergranule lanes; middle photosphere acts as a resonance cavity, which is bounded by the beginning of the overshooting convection region from below and by the layers ($h \approx 400$ km) with intensive horizontal flows from above.

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