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Power spectra of convective motions in the solar photosphere

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We reproduced the convective velocity field and the temperature structure of the solar photosphere using neutral iron line $\lambda \approx 639.3$ nm profiles from the observations with high spatial resolution taken around the centre of the solar disc in the non-perturbed region. We obtained power spectra of vertical velocity and temperature variations at different photospheric levels in order to separate and study convective motions on different spatial scales. In the lower photosphere the main power is localized on the granular scales with a peak at scales of about 1–1.5 Mm (for the velocity variations) and 1.5–2 Mm (for the temperature variations) and it decreases with height. In the higher layers of the solar photosphere the peaks of the spectra of long-lived structures ($T > 20$ min) are slightly shifted to the larger scales (≈ 3 Mm at the height $h = 400$ km), but still present granulation. So, a separate regime of mesogranulaton at scales 5–10 Mm distinct from granulation by a power gap has not been found. Mesostructures appear as a part of a broad distribution of granular scales without further distinction from granulation.

Key words: solar convection, granule, mesogranule

INTRODUCTION

Convection is responsible for many interesting phenomena on the Sun and the study of the solar convection is important in various aspects of solar research. It is generally agreed that the granulation and the supergranulation are two different scales of the solar convection in the photosphere. The scales of granulation are about 0.5–2 Mm [13], the supergranulation — 20–70 Mm [12]. The granulation can be observed through both intensity and velocity measurements, while the supergranulation can be found only in velocity measurements (intensity fluctuations at such scales are very faint [3, 14]). However, a scale between the granulation and supergranulation (5–10 Mm), first identified as the mesogranulation by November et al. [9], is still a controversy. There has been a heated debate as to the nature of mesogranulation, and about whether mesogranulation is a distinct scale of convection or not [1, 10, 11, 17]. The most recent observational results showed that the statistical properties and behaviour of mesogranulation structures are consistent with the results of spatial and temporal averaging of random data, so it is very likely that mesogranulation is a ghost feature of surface convection generated by averaging procedures [8].

The power spectra of solar granulation computed by Espagnet et al. [2] and displayed in a $\log P$–$\log k$ scale were used for a comparison with the theory of convective turbulence. These spectra are fitted by two straight lines of corresponding slopes $-17/3$ and $-5/3$, and this fact provides some strong arguments to believe that granules are turbulent eddies and present some convective characteristics. As well Rieutord et al. [13] offer some theoretical guidelines to explain their spectra. They interpret the combined presence of $k^{-17/3}$ and $k^{-10/3}$ power laws for the intensity and vertical velocity at small subgranulation scales down to 0.4 Mm as a “signature of buoyancy-driven turbulent dynamics in a strongly thermally diffusive regime”; in the mesogranulation range and up to the scale of 25 Mm, they find a k^2 spectral power law for the vertical velocity and in the 2.5–10.0 Mm mesoscale range intensity fluctuations also follow a k^2 power law.

The aim of the present work is to represent the power spectra of the vertical velocity and the temperature variations of the photosphere convection using profiles with high spatial resolution and to determine the horizontal scale dependence of such variations at different heights in the solar photosphere. We try to find out whether the mesogranulation is just a part of the smooth spatial power spectrum, or it has energy excess in power spectra like the granulation and supergranulation.

OBSERVATIONS AND DATA PROCESSING

Here, we use the results of observations by N. Shchukina of the neutral iron spectral line with $\lambda \approx 639.3$ nm taken in August 2001 on the 70-cm German Vacuum Tower Telescope (VTT) located on the Canary Islands (Spain). The observations were taken around the centre of the solar disc in the non-perturbed region [6]. The image tremor on the input slit of the spectrograph did not exceed 0.5 arcsec, so the spatial resolution was equal to 350 km. The data set consists of time sequence (947 images, observation duration 2.6 h) of 512 profiles in total corre-

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sponding to the extent of 64 400 km over the surface of the Sun.

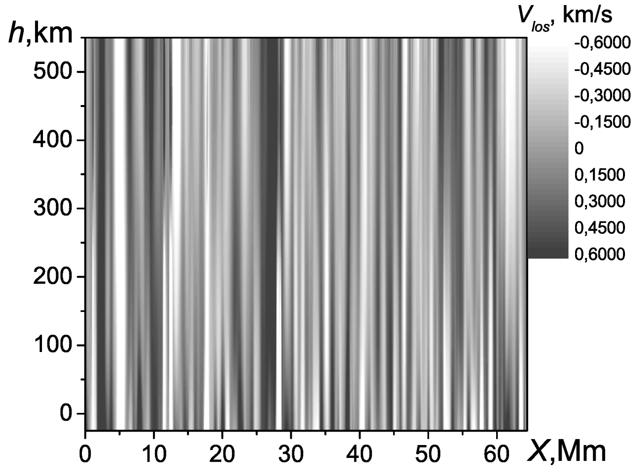

Fig. 1: The vertical velocity distribution in the solar photosphere .

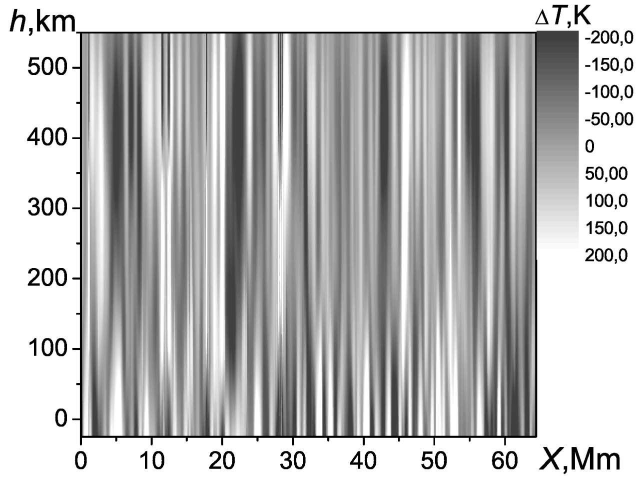

Fig. 2: The distribution of the temperature variations in the solar photosphere.

The reconstruction of the parameters of the inhomogeneous atmosphere was carried out by the sophisticated technology developed by Stodilka, who solved the inverse NLTE problem of radiative transfer using modified response functions and Tikhonov's stabilizers [15, 16]. In contrast to the previous studies [4, 5], which used the method of λ-metre to obtain intensity and velocity distributions at a certain height in the solar atmosphere, we reproduced the altitude distribution of vertical velocity (Fig. 1) and temperature variations (Fig. 2) in the solar photosphere (along two spatial coordinates: its depth, h, and the coordinate along the spectrograph slit, X).

Since we are interesting only in properties of the photosphere convection, the acoustic waves were removed using $k-\omega$ filtration: the field of Fourier transform of $w < v_s \cdot k_x$ (v_s is the speed of sound) corresponds to the convective motions (shaded vertical in Fig. 3).

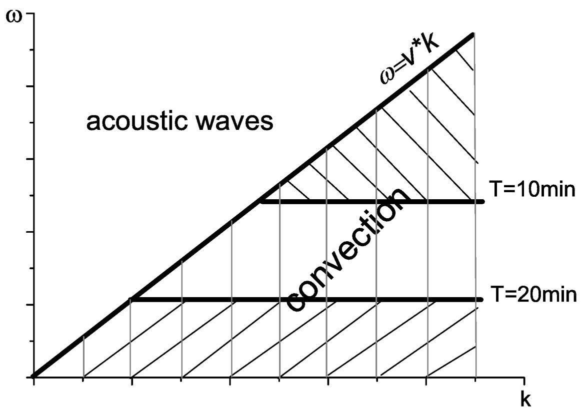

Fig. 3: $k-\omega$-filtration of the velocity and temperature variations in the solar photosphere.

Besides we separated convective motions with periods $T < 10$ min, corresponding to short-lived granules and convective motions with periods $T > 20$ min, corresponding to convective structures with a lifetime longer then average granules – mesogranules, if they exist (shaded obliquely in Fig. 3). Then we calculated power spectra of the vertical velocity and temperature fluctuations for the whole convection and for the short-lived and long-lived convective structures in order to compare them later.

RESULTS

The power spectrum of the convective motions at a certain height depends on the spatial and temporal frequency, in our investigation we calculate spectra summed by temporal frequency.

Assuming that there is no preferred direction, which comes true for the quiet solar atmosphere, we calculate spatial power spectra for two-dimensional images from those for one-dimensional images using the equation [1]:

$$P_2(k) = 2\pi k P_1(k).$$

Thus obtained (and normalized to unity at the height $h = -25$ km) power spectra of vertical velocity and temperature variations of the solar convection at the heights $h = 0$, 200, 400 km are shown in Fig. 4–5.

We got such spectra for different layers of the solar photosphere up to the height $h = 550$ km. Similarly, we calculated the power spectra of convective motions with periods $T < 10$ min (for short-lived granules) and $T > 20$ min (for long-lived convective structures (or mesogranules?)) in order to compare them.

In previous studies [2, 13] it was found that the spectra seem to follow $P(k) = k^{\alpha}$ with specific α for different spacial range and the possible physical origin of the slope coefficients is discussed. In our work we have to detect the general changes of spectra with height, thereby we approximate the entire curve of the power spectrum. We revised a class of functions and best approached the dependence $P(k) = Ak^{\alpha}e^{-\beta k}$ selecting coefficients for each spectrum individually. Thus approximated power spectra of vertical velocity and temperature variations of the solar convection at the heights $h = 0$, 200, 400 km are shown in Fig. 4–5 (thick line). The power spectra of convective motions with periods $T < 10$ min and $T > 20$ min are approximated similarly. The results of our approximation of power spectra of convection with different range of temporal frequencies selected by us (all convection, convection motions with period $T < 10$ min and convective motions with $T > 20$ min) are presented in Fig. 6–7. By analyzing these lines we found the following:

(i) All the power spectra of convective velocities are maximal in the lower layers (Fig. 6, bottom) with power peaks at spatial frequencies corresponding to the average granular scales $\lambda \approx 1.5$ Mm for $T > 20$ min and $\lambda \approx 1$ Mm for $T < 10$ min. The power spectra decrease with height (Fig. 6, middle) up to the higher layers of the solar photosphere. The spectrum of long-lived structures ($T > 20$ min) changes most rapidly with height and in the high layers (Fig. 6, top) its maximum is slightly shifted to the smaller spatial frequencies corresponding to the larger granular scales: $\lambda \approx 3$ Mm at height $h = 400$ km.

(ii) All the power spectra of convective temperature variations are maximal in the lower layers (Fig. 7, bottom) with power peaks at spatial frequencies corresponding to the granular scales $\lambda \approx 2$ Mm for $T > 20$ min and $\lambda \approx 1.5$ Mm for $T < 10$ min. At the height $h \approx 200$ km (Fig. 7, middle) the power spectrum decreases (through the temperature sign reversal in this layers). Note, that the temperature fluctuations reach a minimum at higher or lower heights depending on sizes of the convective cells (the larger the size, the higher the reversal takes place [7]). In the higher layers of the solar photosphere (Fig. 7, top) the power spectra of temperature variations increase again and the peak of the spectrum of long-lived structures ($T > 20$ min) is slightly shifted to the smaller spatial frequencies ($\lambda \approx 3$ Mm at the height $h = 400$ km), but still presents granulation.

As can be seen, the behaviour of long-lived cells (representing mesogranules) is similar to the behaviour of short-lived cells (representing granules).

CONCLUSIONS

In the present study we used the results of the high spatial resolution observations of the quiet solar photosphere to compute the power spectra of vertical velocity and temperature variations of the photosphere convection. Analyzing the power spectra of vertical velocity and temperature variations of the solar convection we have not seen apparent energy excess at the scale of mesogranulation proposed in some early works.

Based on a comparison of the approximated power spectra of vertical velocities and temperature variations of all convection, short-lived granules and the convective structures with a lifetime longer than the average duration of existence of granules, our results may be summarised as the following: the power spectra of long-lived convective motions vary with height similar to those of short-lived convective motion. So, specific differences in vertical velocity and temperature variations of long-lived and short-lived granules are not found: the variations decrease with height for convection of both small and large temporal periods; the temperature sign reversal takes place (with only a small difference in heights where it occurs); in the higher layers of the solar photosphere the power spectra of vertical velocity and temperature variations of long-lived ($T > 20$ min) structures are slightly shifted to the smaller spatial frequencies, but still present granulation.

Thereby we have confirmed that the main power of the convective motions is distributed on the granular scales and mesostructures appear as a part of a broad distribution of granular scales without further distinction from granulation.

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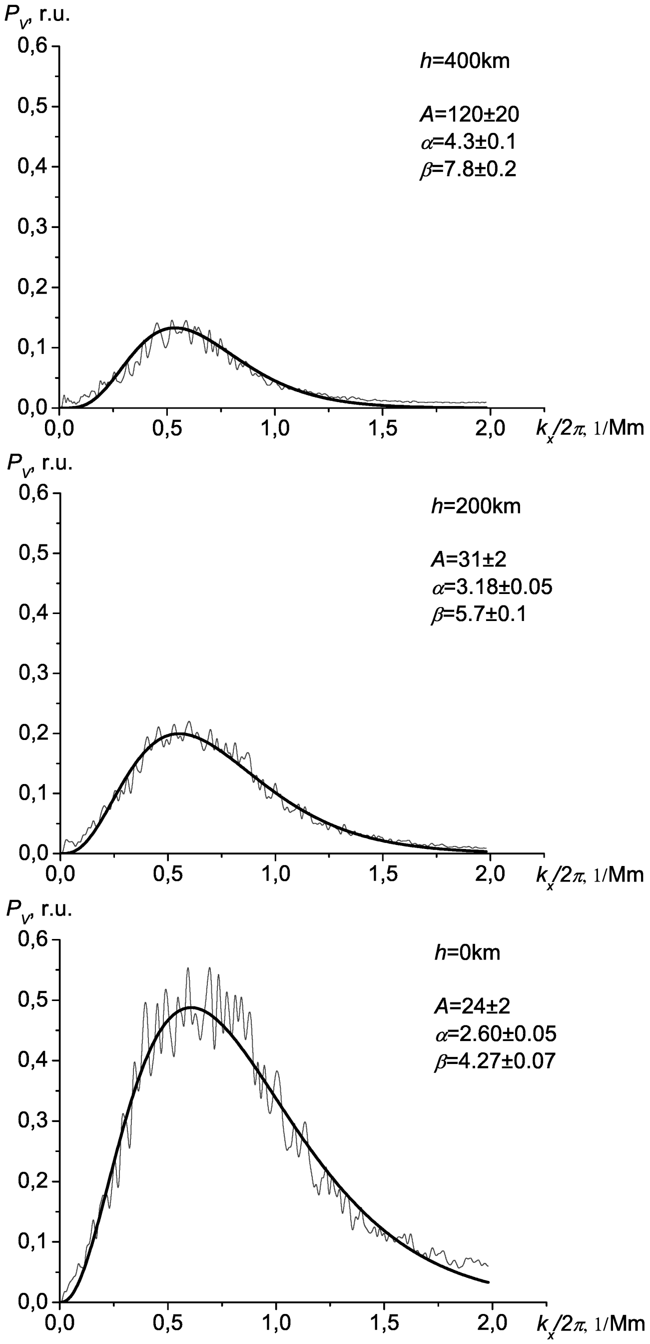

Fig. 4: The power spectra of the vertical velocity variations in the solar photosphere at heights $h = 0$, 200, 400 km.

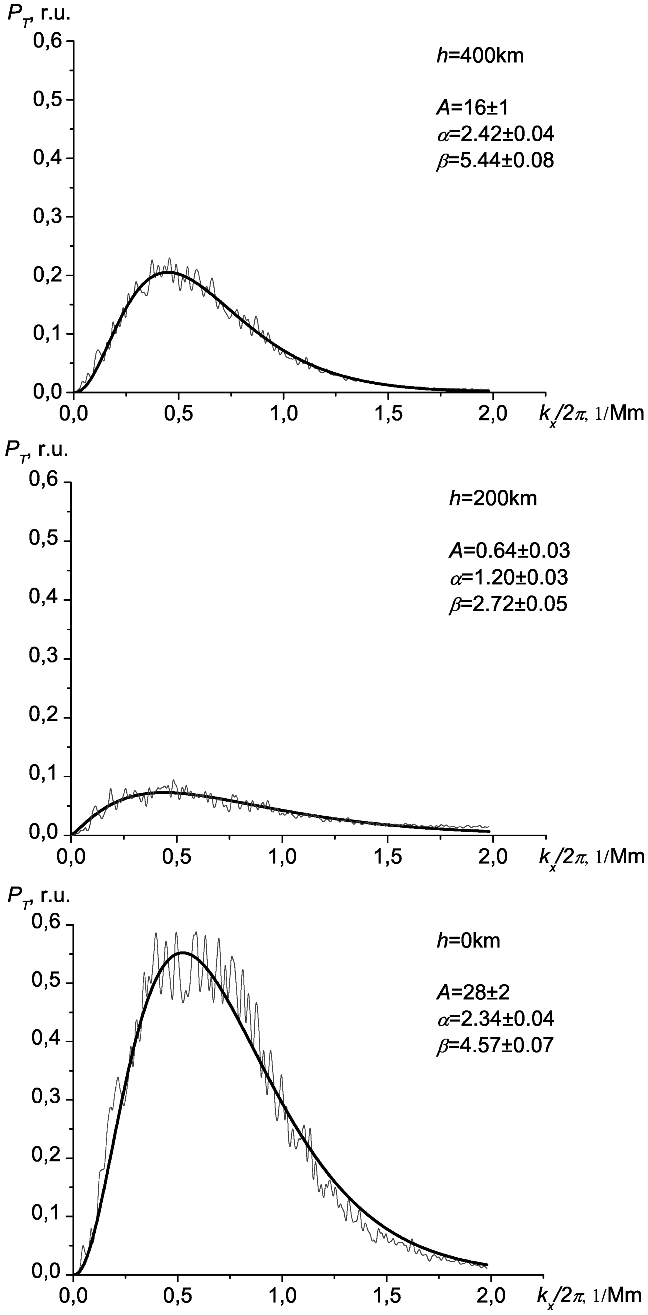

Fig. 5: The power spectra of the temperature variations in the solar photosphere at heights $h = 0$, 200, 400 km.

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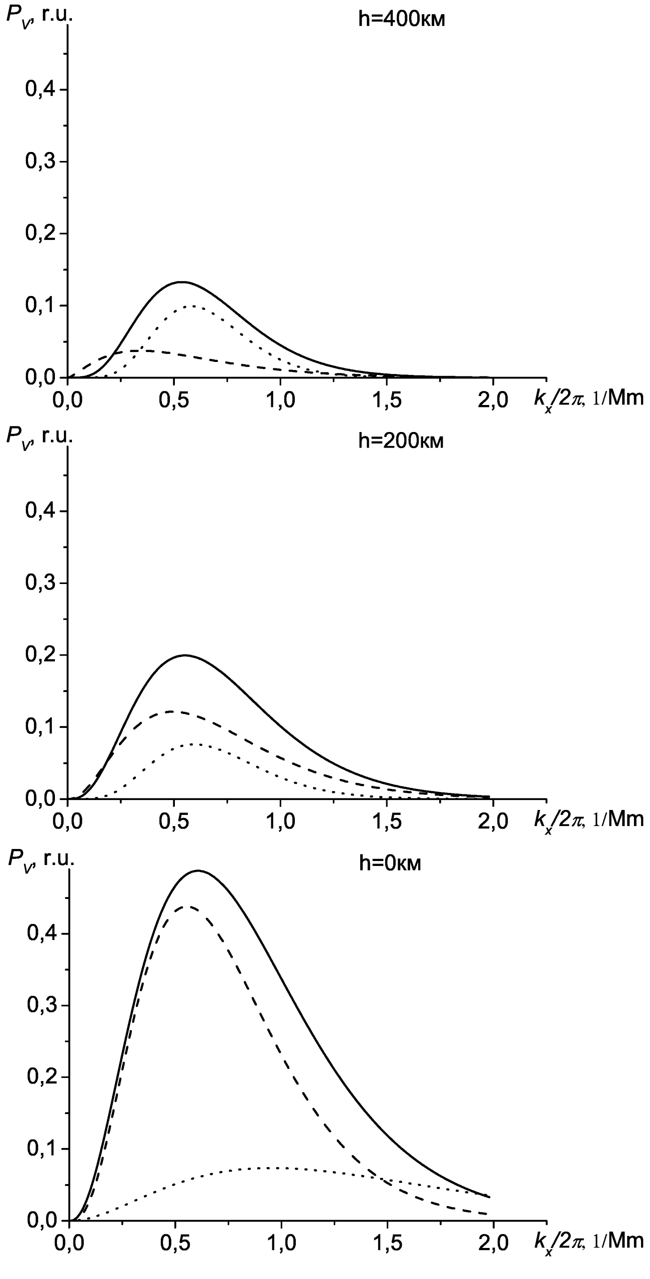

Fig. 6: The approximated power spectra of the vertical velocity variations in the solar photosphere at heights $h = 0$, 200, 400 km: solid line - all convection, dashed line - convective motions with $T > 20$ min, dotted line - convective motions with $T < 10$ min.

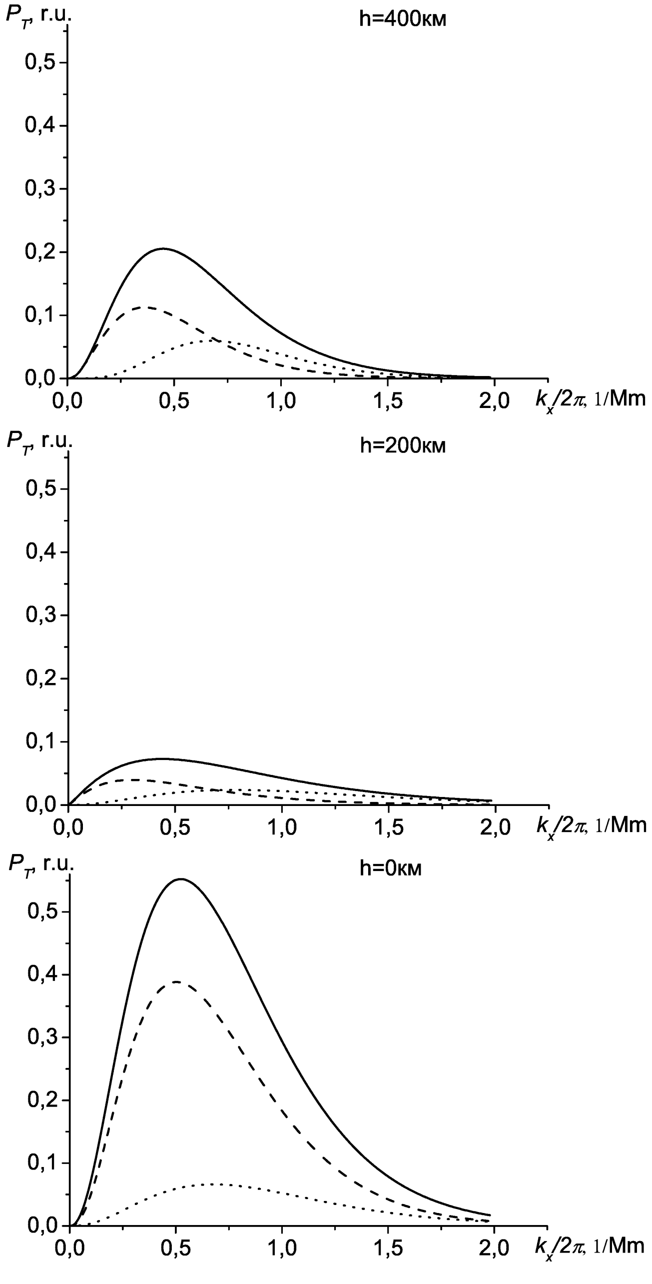

Fig. 7: The approximated power spectra of the temperature variations in the solar photosphere at heights $h = 0$, 200, 400 km: solid line - all convection, dashed line - convective motions with $T > 20$ min, dotted line - convective motions with $T < 10$ min.