Structure of convective flows of the real Solar granulation

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The temperature and velocity field within granular cells has been studied by solving the nonequilibrium inverse radiative transfer problem using neutral iron line $\lambda \approx 523.4$ nm profiles. The results are the following: the temperature and velocity maxima do not always coincide and the maxima can be shifted towards the boundaries in large granules; the temperature inversion takes place. The temporal changes of the shapes of the reconstructed distributions of the temperature and the vertical velocity on the subgranulation scales has been investigated. Also the effect of finite resolution on spatial variations of the velocities and temperature in the solar photosphere has been estimated.

Introduction

Convective motions in the solar atmosphere have been studied in detail during the past decades, using different types of observations, their analysis, and interpretation. High resolution images of the solar surface show a pattern of bright granular cells surrounded by dark intergranular lanes: granules are upwellings of hot material, originating from the convective zone and overshooting into the stably stratified photosphere, radiative losses make the overshooting material relatively cold and its overturning motion supplies the network of intergranular downflows.

However the detailed structure of granulation is not as simple as suggested by its convective origin: the intensity maximum and the maximum of the upward line-of-sight velocity do not always coincide [6, 8], an asymmetrical character of the distribution of the line of sight velocity takes place inside large convective flows [4, 9, 14]. Moreover, intensity contrast sign reversal and velocity sign reversal could occur in the higher photosphere [2, 5, 6, 9, 13, 15]. So there are some difficulties in selecting velocity and temperature variations corresponding to the same granular cells in the higher layers of solar photosphere. In [11] the λ-meter technique as a good oppotunity to "trace" the non-thermal motions along the whole photosphere up to the temperature minimum and lower chromosphere was proposed.

The structural evolution of solar granules has been studied by many authors [1, 3, 10]. But the detailed description of an individual granule needs observational data of much better quality. Observations, however, suffer from limited spatial resolution, which adversely affects the study of, in particular, small granules. Besides the smoothing of the original image produced mainly by atmospheric "seeing" takes place.

So the aim of the present work is to gain insight into the structure of individual granules and their time evolution and to estimate the effect of finite resolution on spatial variations of the physical parameters in the solar photosphere. The exploration of the velocity field and the temperature has been performed in the framework of the real solar granulation using profiles with high spatial resolution and considering nonlocal thermodynamic equilibrium effects.

Observational data

For this study we used the neutral iron line $\lambda = 532.4$ nm profiles observed by N. Shchukina on the 70-cm German Vacuum Tower Telescope (VTT) located on the Canary Islands. The observations were taken around the centre of the solar disc in the quiet region. The image tremor on the input slit of the spectrograph did not exeed 0.5 arcsec during the observations, i.e. the spatial resolution was equal to 350 km.

The data set consists of 256 profiles in total corresponding to the extent of 64,000 km over the surface of the Sun. The region of line formation extends from several kilometers up to 500 km height. The reconstruction of the parameters of inhomogeneous atmosphere was carried out by Stodilka [12], who solved the inverse radiative transfer problem using modified response functions. As a result the stratification of temperature and the velocity field in the solar photosphere was reproduced in two spatial coordinates: its depth, h, and the coordinate along the spectrograph slit, X. Acoustic and gravity waves were removed by $k - \omega$ filtration.

Results and conclusions

The distribution of velocity and temperature variations in granular cells. On the basis of analysis of observation data, we have revealed the following behaviour of spatial distributions of the temperature and the vertical velocity on the subgranulation scales presented in Fig. 1.

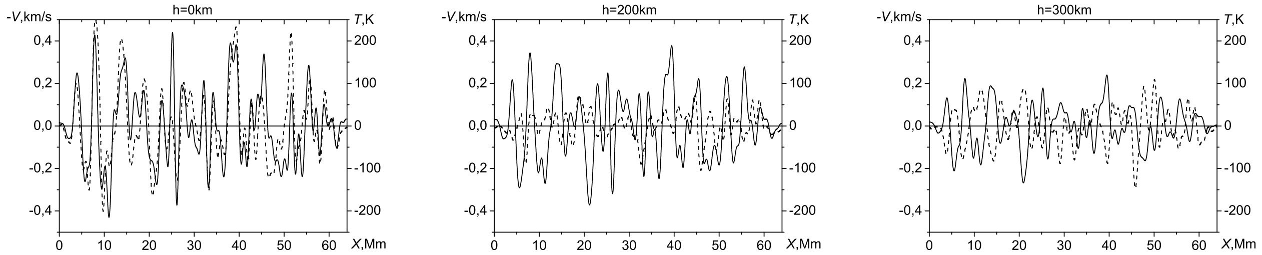

Figure 1: Horizontal distributions of the temperature T (*dashed line*) and the line-of-sight velocity V (*solid line*) at the heights $h = 0$ km, 200 km and 300 km.

According to our results of the reconstruction the solar photosphere can be presented by the next scheme. In the lower photosphere (see Fig. 4, *left panel*) the vertical velocity quite closely reflects the temperature distribution in the granule structure. This correlation gave rise to the streamline picture of the granulation flow: the rise of the hot plasma within the granule, and the downflow of the cold plasma in the intergranular space. But in detail the temperature maximum and the maximum of the convective velocity do not always coincide: we have detected sufficient horizontal shifts of the structure of the temperature variations and the velocity field for 500 km or more. Moreover the maximum upflow does not necessarily occur in the middle of the granule: within larger granules (with the size of about $1''.5$ and more) two maxima could be found in the distribution of the velocity while the distribution of the temperature is almost symmetrical in all cases.

At the height $h = 200$ km (see Fig. 4, *central panel*) because of the temperature inversion and the structure of the granulation is smothed and some difficulties arise if the velocity field is compared with the temperature one: the temperature pattern dissolves whereas the velocity field associated to the granulation crosses the whole thickness of the photosphere decreasing with height.

In the higher layers (see Fig. 4, *right panel*) the photosphere is again highly structured and dominated by some kind of secondary features which are induced by overshooting granules. The vertical convective velocities of matter flows are found to be smaller here. The pattern of horizontal temperature fluctuations reverses so that granular regions become relatively cool compared to the intergranular network. Horozontal shifts also take place here, so it is some difficult to determine whether two different regions, for instance with high temperature in the lower photosphere and low temperature in the upper photosphere, or vice versa, belong to the same flow or not.

Kostik et al. [5] obtained the heights of the reversal at about $200 - 300$ km which is in agreement with our results.

The evolution of granular cells. Using our results of the reconstruction we have studied the different types of changes observed in individual granules (see Fig. 2-3). It is possible that the first or the last stages of the evolution of some granules have escaped our attention. In all cases we consider a granule at any location with a coherent shape of the distributions of the temperature and the vertical velocity. But if granules are not properly resolved, it is difficult to determine exactly the moment of their formation or disappearance or separate some granular cells at all.

We have analyzed all of the possible types of changes of the temperature and velocity distributions within granular cells and found that two main types of granules can be distinguished by the means of “birth” and “death” as they are the most probable:

1) Small granules (with sizes less then $1''.5$) usually originate spontaneously in the intergranular background or from a small fragment of any earlier granular cell, the shapes increase to the maximum sizes (see Fig. 2) and then dissipate.

2) Large granules (with sizes of about $1''.5$ or more) are usually formed by merging of two (or more) small fragments, the shapes increase untill they reach a maximum diameter (see Fig. 3) and then split into several fragments.

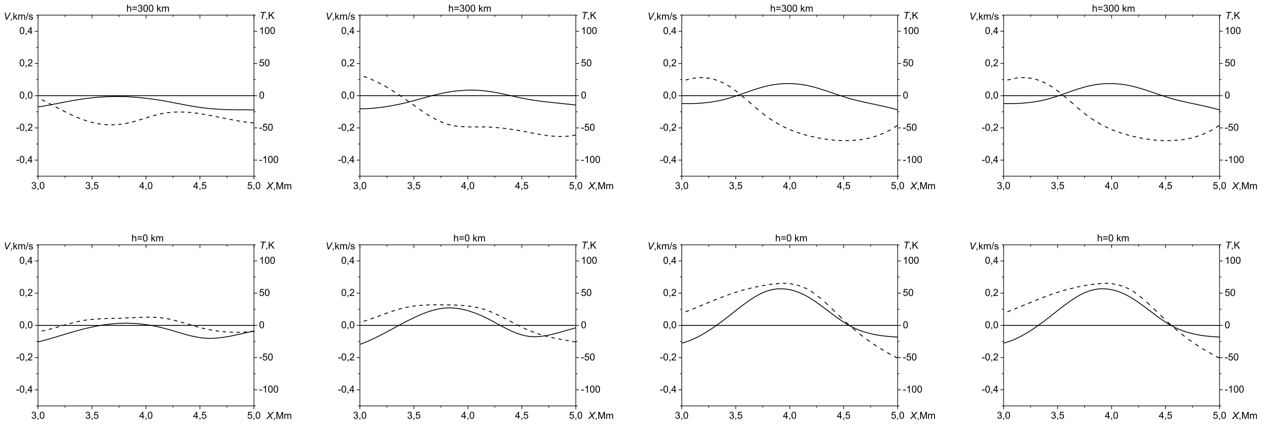

Figure 2: The evolution of the small granule at the heights $h = 0$ km (*bottom panel*) and 300 km (*top panel*). The total time interval is $t \approx 9$ min 24 s, the time interval between the images is $\Delta t \approx 3$ min 8 s (V is shown by *solid line*, T — by *dashed line*).

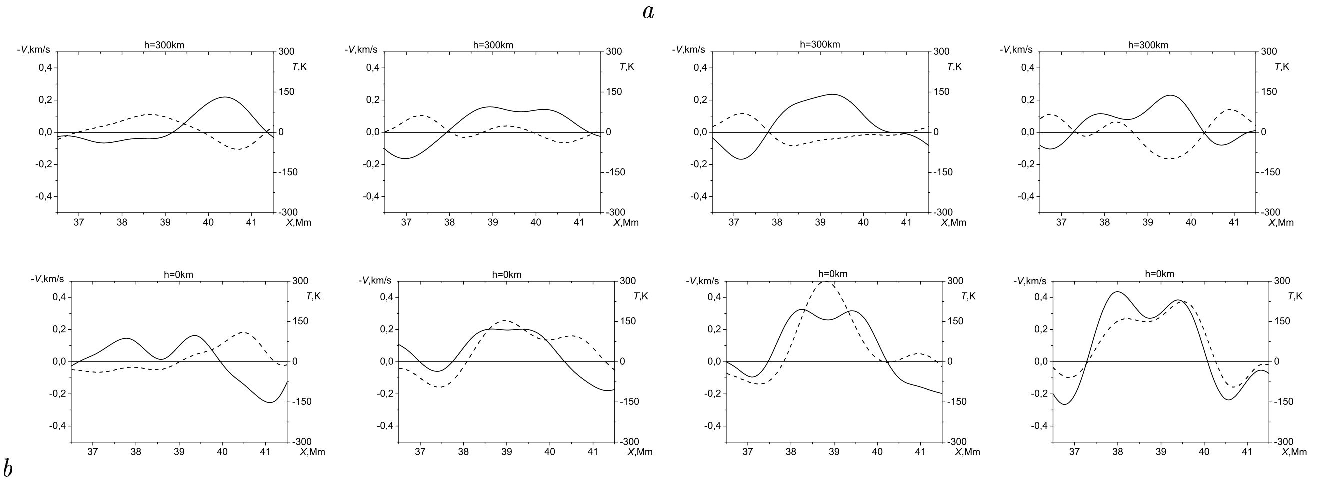

Figure 3: The evolution of the large granule at the heights $h = 0$ km (*bottom panel*) and 300 km (*top panel*). The total time interval $t \approx 9$ min 24 s, the time interval between the images $\Delta t \approx 3$ min 8 s (V is shown by *solid line*, T — by *dashed line*).

Our results confirm the previous studies [3], i.e. granules can be classified depending on their scales into two populations with different underlying physics: the scales set the limits characterizing the birth mechanism of a granule and predict its evolution to some extent.

Spatial smoothing and physical conditions in the solar photosphere. According to [7] the spatial smoothing may be described by the Gaussian function; thus the smoothed quantity V is related to the unsmoothed quantity V by:

$$V'(x_0) = \frac{1}{\sqrt{2\pi}\sigma} \int\limits_x V(x) \exp\left[\frac{-(x-x_0)^2}{2\sigma^2}\right] dx. \tag{1}$$

Thus, having the reconstructed smoothed snapshots of the solar granulation, one can easily obtain (e. g. by iterations) the realistic spatial distribution of various physical parameters (see Fig. 4-5).

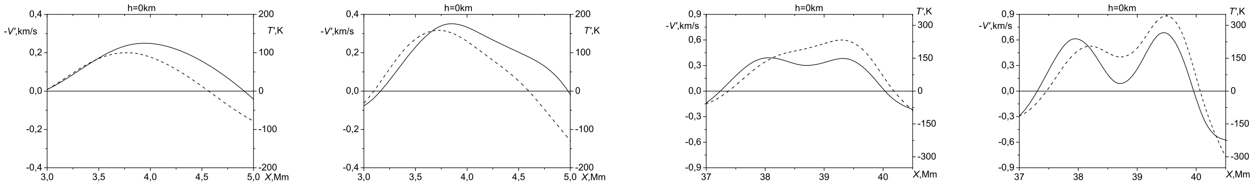

Figure 4: The smoothed (*left panel*) and unsmoothed (*right panel*) distributions of the temperature and the line-of-sight velocity within the small granule (a) and the large one(b) at the heights $h = 0$ km (V is shown by *solid line*, T — by *dashed line*).

Shapes of the unsmoothed distributions of the temperature and velocities differ from the smoothed ones: the asymmetry become apparent in the unsmoothed distribution of the velocity in the small granule (see Fig. 4a) and more expressed in the unsmoothed distributions of the temperature and velocities in the large granule (see Fig. 4b). Thus, unsmoothed images qualitatively coincide with smoothed images, but taking into account the smoothing allows one to study solar granulation on smaller spatial scales.

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