UNIWERSYTET TECHNOLOGICZNO-PRZYRODNICZY
IM. JANA I JĘDRZEJA ŚNIADECKICH W BYDGOSZCZY
ZESZYTY NAUKOWE NR 268
TELEKOMUNIKACJA I ELEKTRONIKA 21 (2018) 61–68

PECULIARITIES OF CONVECTIVE FLOWS FORMATION IN THE SOLAR PHOTOSPHERE

Myroslaw I. Stodilka, Oleksandra A. Baran

Ivan Franko National University of L'viv –
Astronomical Observatory
8 Kyryla i Mefodia st., 79005, L'viv, Ukraine

Summary. We studied the development of convective flows in the solar photosphere on the basis of semi-empirical models of granulation constructed from observable profiles in the neutral iron line $\lambda \approx 639{,}3$ nm (taken on VTT with high spatial resolution) by solving the inverse radiative transfer problem. We analysed the temporal changes in the reproduced variations of kinematic and thermodynamic parameters of the solar convection at different heights of the photosphere (h = 0–550 km). Peculiarities of the formation of convective flows (ascending and descending ones) associated with differences in vertical velocities, temperature and pressure variations were established.

Keywords: solar photosphere, granulation, line of sight velocity, thermodynamic parameters

1. INTRODUCTION

The most prominent intensity variations on the solar surface, aside from sunspots and faculae, are granules – the bright locations of upflowing hot plasma surrounded by dark lanes with downflowing cool plasma at the scales about 0.5–2 Mm [9, 11]. The average lifetime of a single granule ranges from 5 [18] to 16 min [8].

Over the past few years, significant efforts have been made to determine the stratification of physical quantities throughout the solar photosphere and to investigate the vertical structure of granulation. As a rule, the solar granulation structure is studied by analyzing the variations of intensity (temperature) and convective velocities [5, 6, 16, 17]. Such studies show that the classical picture of the convection breaks in the solar photosphere, starting at least from 50 km above the continuum formation level. The higher layers of the photosphere are dominated by some kind of secondary features, which are induced by overshooting granules: the evidence of the temperature and vertical velocity sign reversal was detected in a wide range of heights up to 650 km.

An important role in the formation of the convective structure of the solar photosphere is played by the pressure variations, since they determine the geometry of convective flows in the stratified medium [4, 7]. According to the modeling results [3], to do work over long return path of convective flows the pressure within granules should exceed the pressure within intergranules, since the difference in pressure causes ascending and descending flows, as well as horizontal motions of matter. It is shown in [13] that the granular cells in the process of their development are influenced by the adjacent cells: the granules with the highest pressure expand and grow, while the ones with lesser pressure excess have their growth limited and may even shrink. In [1, 10], based on the observational data, it is confirmed that the variations of pressure are mainly positive in the ascending flows and negative in the descending ones. The results of our previous studies [2] indicate that high values of positive pressure variations lead to fragmentation of granular flows.

In this paper we present the kinematic and thermodynamic parameters (line of sight velocity, temperature and pressure) of the real solar convection using the observable profiles with high spatial resolution. We analyze their temporal changes at different heights of the solar photosphere in order to understand better the development process of the convective flows.

2. OBSERVATIONS AND DATA PROCESSING

The data used for the study consist of the observed 1D brightness series of the Fe I line $\lambda \approx 639{,}3$ nm taken by N. G. Shchukina at the 70-cm German Vacuum Tower Telescope (VTT) located on the Canary Islands (Spain) [5]. The observations have been performed at the solar disc centre in the non-perturbed region. The duration of the observations – 2 h 36 min, the time resolution – 10 s. 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 correspond to the extent of approximately 64 Mm over the surface of the Sun. The region of line formation extends from several kilometres up to 550 km in height.

The models for the solar inhomogeneous photosphere at granulation scales were constructed by the solution of the inverse non-equilibrium radiative transfer problem with use of modified response functions and Tikhonov's stabilizers [14, 15]. In this case, the merit function is: $\chi^2 = \chi_0^2 + \alpha T_s(x)$, where $\chi_0^2 = \frac{1}{\nu}\sum_{i=1}^{M}(I_i^{obs} - \tilde{I}_{1,i})^2 / \sigma_i^2$ is a standard merit function [12], which is a

measure of the closeness of the experimental and theoretical line profiles,
T_s is Tikhonov's stabilizer (or linear combination of stabilizers);
α is a regularization parameter.

Tikhonov's stabilizers allow one to obtain smooth solutions and to include prior information concerning the dependence under consideration; also, they substantially improve the convergence of the inverse radiative transfer problem.

To evaluate the total pressure, we solved the hydrodynamic equilibrium equation under the condition of the horizontal balance of the total pressure on the bottom boundary. In our approach, the gas pressure stratification is recalculated for every variation of the temperature or velocity field.

The inverse procedure was applied for each profile reproducing the velocity, temperature and pressure along two spatial coordinates: its depth, h, and the coordinate along the spectrograph slit, X. The seperation of the wave and convective motions was carried out by Fourier transform. Such a transformation of space-time variations allows to remove the wave component using a line $\omega = v_s \cdot k_x$ (v_s – speed of sound): the region of Fourier transform of $\omega < v_s \cdot k_x$ corresponds to the convective motions.

3. RESULTS AND DISCUSSION

3.1. STRUCTURE OF THE PHOTOSPHERE CONVECTION

For better visualization of our models we chose the area with a width of ΔX≈15 Mm (i.e. ≈ 1/4 of the observable region) to show the reproduced line-of-sight (vertical) velocities and the variations of thermodynamical parameters (temperature, pressure) of the photosphere convection (Figs. 1–3).

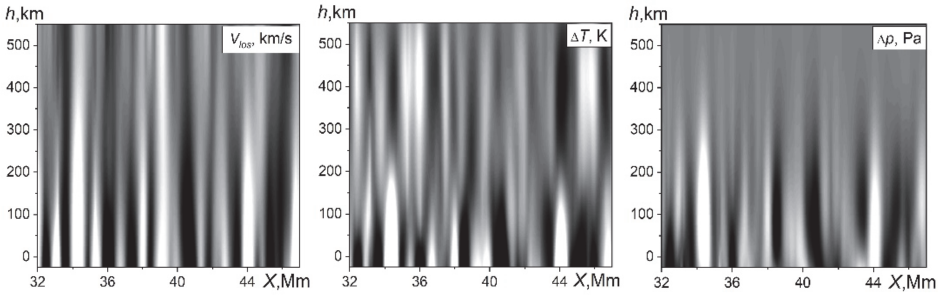

Fig. 1. Stratification of vertical velocities, variations of temperature and variations of pressure (convective component) in the solar photosphere at a fixed time point

Fig. 1, left panel, shows the vertical velocity field at this area at a fixed time point. The white colour corresponds to the velocities of the ascending flows of the matter and the black one − to the velocities of the descending flows. The range of the vertical velocity variations is constrained by ±0.35 km/s in order to gain better contrast in the upper layers of the photosphere. The variations of temperature and pressure are presented at the same area and at the same time in Fig. 1, central and right panels, respectively. In order to gain better contrast the range of the variations are constrained by ±125 K for temperature and ±200 Pa for pressure: light shading depicts positive variations and dark shading depicts negative ones.

According to the results of reconstruction the solar photosphere can be presented by the next scheme:

- the vertical velocity field has a columnar structure: the velocities are negative (ascending flows) within granules and positive (descending flows) within intergranules; this structure crosses the whole photosphere decreasing with height; rarely the inversion of the velocities takes place;
- in the lower photosphere the temperature quite closely reflects the vertical velocity distribution: the temperature variations are positive within ascending flows and negative within descending flows; at the heights $h \approx 200$ km the temperature inversion occurs;
- the pressure variations are maximal in the lower photosphere – they are mostly positive within granules and negative within intergranules; above these heights they sharply decrease.

We analyzed changes in the motion of the matter within granules and intergranules at different stages of their development. The results are shown in Fig. 2 (the development of variations inside a typical granule) and in Fig. 3 (the development of variations inside a typical intergranule): left panel – changes in the vertical velocities inside convective flows, central panel – changes in the temperature variations, right panel – changes in the pressure variations within these flows at the same time. For the granule the development duration time is 6 min 40 s, for the intergranule it is 7 min 20 s.

3.2. ASCENDING FLOW FORMATION

Fig. 2 shows how the matter in the ascending flow moves throughout its development. According to the obtained results, at the beginning of the development (a) the upward motion of the matter appears in the lower layers of the photosphere – the small vertical velocities and the small positive temperature variations are observed here, the small positive variations of pressure occur with a maximum at the height $h \approx 50$ km. Over time (b) the flow reaches the upper layers – the velocities increase along the entire height of the penetration. At the heights $h \geq 200$ km the temperature inversion occurs. The variations of pressure also increase and their maximum moves slowly upwards. At a time of $t \approx 2$ min 40 s (c), the vertical velocities reach essential values in all layers of the photosphere, the highest velocities are observed at the height $h \approx 0$ km. The positive temperature variations are maximal in the lower layers of the photosphere, and the negative variations reach the maximal values at the height $h \approx 250$ km. The highest variations of pressure are observed at the heights $h = 0$–150 km. Further (d–e) the process of depletion of the flow occurs. The velocities and the variations of temperature rapidly decrease in the upper layers of the photosphere and slower – in the lower layers; the variations of pressure also decrease as well.

3.3. DESCENDING FLOW FORMATION

On the edges of the developing granule, an intergranular structure is formed, where the cooled matter flows down. According to our results (Fig. 3), in the region of origin of the intergranule, the small vertical velocities are initially observed, which can appear along the whole photosphere, more often in the middle and upper photosphere (at $h > 100$ km) (a). At this time the temperature variations are insignificant, but we observe the significant negative variations of pressure with a maximum at the height $h \approx 150$ km. After a while (b) the vertical velocities increase along the entire height, the maximum of the velocities shifts down. At the heights $h < 200$ km the negative temperature variations and the pressure variations increase. At a time of $t \approx 4$ min 00 s (c) the vertical velocities begin to decrease in the upper layers of the photosphere. At the heights $h \geq 200$ km the positive temperature variations appear. The negative pressure variations are maximal at the height $h \approx 100$ km. Further (d–e) the velocities decrease along the entire height: such changes occur faster in the upper layers of the photosphere, slower – in the lower layers. At the end of the downflow development (e) the pressure variations sharply decrease at the heights $h > 0$ km and the temperature structure disintegrates.

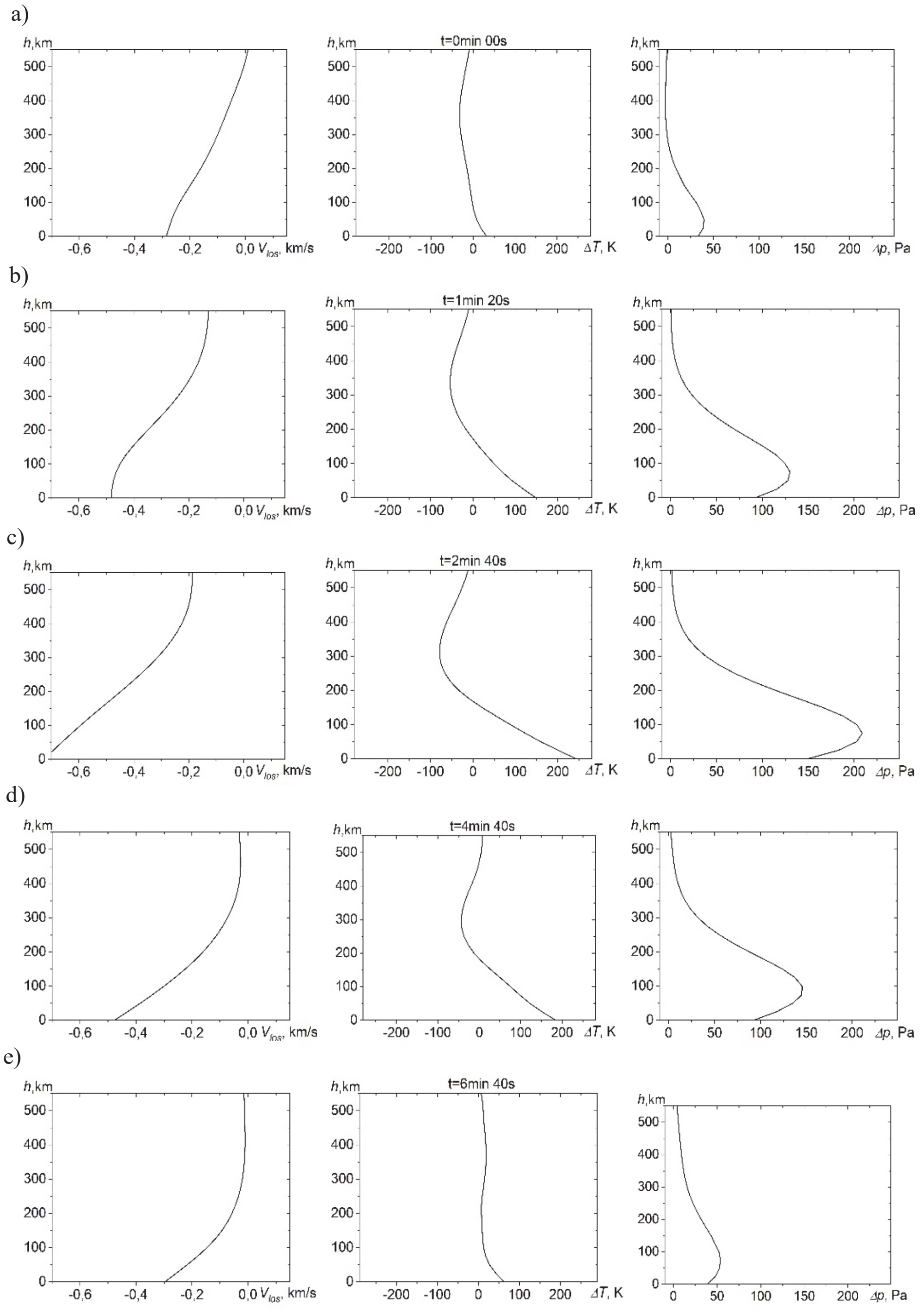

Fig. 2. Changes in the vertical velocities (left panel), the variations of temperature (central panel) and the variations of pressure (right panel) inside the typical granule at different moments of time

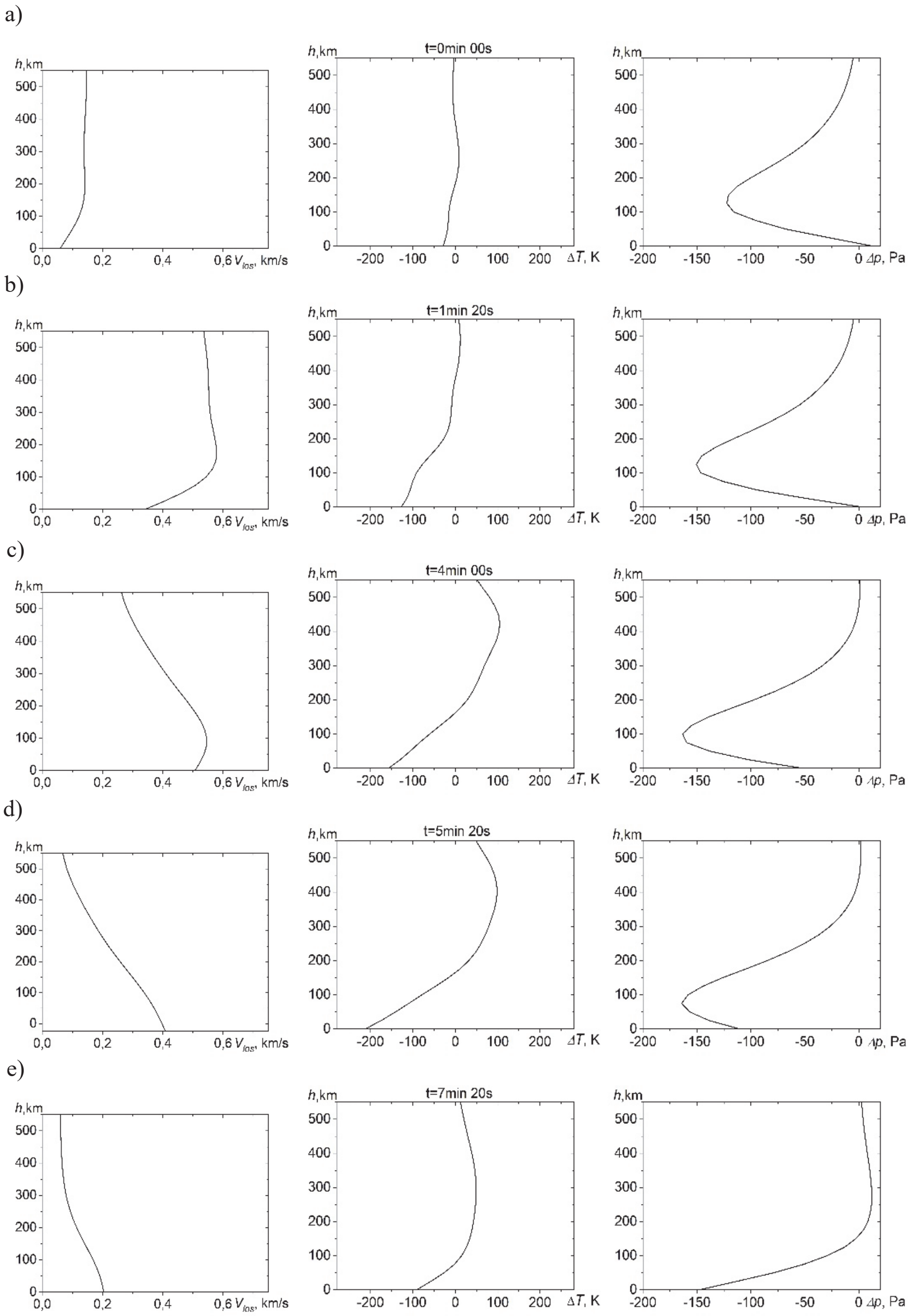

Fig. 3. Same as in Fig. 2 inside the typical intergranule

The curves in Fig. 2 and Fig. 3 reflect the typical changes that occur inside the granules and the intergranules. Thus, the obtained results indicate that the ascending convective flows appear in subphotospheric layers and propagate into the upper layers of the photosphere; the descending convective flows originate along the whole photosphere: they are primarily manifested in the upper and middle photosphere, and then the disturbance region shifts down. During the development of the ascending/descending flow the maximum of the positive/negative pressure variations appears in the lower photosphere layers. Depletion of the flows in both considered cases starts from above, in the lower layers of the photosphere the variations decrease slower.

The obtained results are consistent with the numerical simulation of solar convection [3, 9, 13], in which the evolution of the granules is associated with phenomena occurring near the solar surface.

4. CONCLUSIONS

The investigation of the evolution of solar granulation was carried out by analyzing the spatial-temporal variations of vertical velocities, temperature and pressure in the solar photosphere obtained from VTT-observations with high spatial resolution.
Our basic results can be summarized as follows:

- the descending flows of granulation originate along the entire photosphere: most of them firstly appear in the upper and middle photosphere, and then the perturbation region goes down; the ascending flows appear in the lower layers of the photosphere and eventually spread into the upper layers;
- during the development of the ascending/descending flow the maximum of the positive/negative pressure variations appears in the lower photosphere layers;
- the depletion of ascending and descending flows starts from the upper layers, in the lower layers of the photosphere the vertical velocities, variations of temperature and pressure decrease slower.

The obtained data on the study of the convective flows evolution are consistent with the numerical simulation of solar convection [3, 9, 13].

BIBLIOGRAPHY

[1] Baran O.A., Stodilka M.I., 2015. Convection structure in the solar photosphere at granulation and mesogranulation scales. Kinematics Phys. Celestial Bodies 31, 65–72.

[2] Baran O.A., Stodilka M.I., Prysiazhnyi A.I., 2018. Structure of the long-living elements of solar granulation. Kinematics Phys. Celestial Bodies 34, 13–18.

[3] Gadun A.S., Hanslmeier A., Pikalov K.N. *at. al.*, 2000. Sizedependent properties of simulated 2-D solar granulation. Astron. Astrophys. Suppl. Ser. 146, 267–291.

[4] Hurlburt N.E., Toomre J., Massaguerand J.M., 1984. Two-dimensional compressible convection extending over multiple scale heights. Astrophys. J. 282, 557–573.

[5] Kostyk R.I., Shchukina N.G., 2004. Fine structure of convective motions in the solar photosphere: Observations and theory. Astron. Rep. 48, 769–780.

[6] Kostik R., Khomenko E., Shchukina N., 2009. Solar granulation from photosphere to low chromosphere observed in BaII 4554 Å line. Astron. Astrophys. 506, 1405–1414.

[7] Massaguer J.M., Zahn J.-P., 1980. Cellular convection in a stratified atmosphere. Astron. Astrophys. 87, 315–327.

[8] Mehltretter J.P., 1978. Balloon-borne imagery of the solar granulation. II. The lifetime of solar granulation. Astron. Astrophys. 62, 311–316.

[9] Nordlund Å., Stein R.F., Asplund M. (2009): Solar surface convection. Living Rev. Sol. Phys. 6(2), 1–117.

[10] Puschmann K., Ruiz Cobo V., Vázquez, M. *et. al.*, 2005. Time series of high resolution photospheric spectra in a quiet region of the Sun. II. Analysis of the variation of physical quantities of granular structures. Astron. Astrophys. 441, 1157–1169.

[11] Rieutord M., Roudier T., Rincon F. *et al.*, 2010. On the power spectrum of solar surface flows. Astron. Astrophys. 512(A4), 11.

[12] Ruiz Cobo B., del Toro Iniesta J.C., 1992. Inversion of Stokes profiles. Astrophys. J. 398(1), 375–385.

[13] Stein R.F., Nordlund Å., 1998. Simulations of solar granulation. I. General properties. Astrophys. J. 499, 914–933.

[14] Stodilka M.I., 2002. The inverse problem for a study of solar and stellar atmosphere inhomogeneities. Zh. Fiz. Dosl. 6, 435–442.

[15] Stodilka M.I., 2003. Tikhonov stabilizers in inverse problems of spectral studies. Kinematics Phys. Celestial Bodies 19, 334–343.

[16] Stodilka M.I., Baran O.A., 2008. Structure of the solar photospheric convection on subgranulation scales. Kinematics Phys. Celestial Bodies 24, 70–76.

[17] Stodilka M.I., Baran O.A., Malinich S.Z., 2006. Peculiarities of the convection in the solar photosphere. Kinematics Phys. Celestial Bodies 22, 134–141.

[18] Title A.M., Tarbell T.D., Topka K.P. *et. al.*, 1989. Statistical properties of solar granulation derived from the SOUP instrument on Spacelab 2. Astrophys. J. 336, 475–494.

OSOBLIWOŚCI FORMOWANIA POTOKÓW KONWEKCYJNYCH W FOTOSFERZE SŁONECZNEJ

Streszczenie

Zbadano rozwój potoków konwekcyjnych w fotosferze słonecznej na podstawie półempirycznych modeli granulacji, zbudowanych z obserwowalnych profili neutralnej linii żelaza $\lambda \approx 639{,}3$ nm (wykonanych na VTT o wysokiej rozdzielczości przestrzennej), rozwiązując problem odwrotnego transferu promieniowania. Analizowano zmiany czasowe odtwarzanych wariacji parametrów kinematycznych i termodynamicznych konwekcji słonecznej na różnych wysokościach fotosfery słonecznej (h = 0–550 km). Wyznaczono osobliwości tworzenia potoków konwekcyjnych (rosnących i malejących), związane z różnicami prędkości pionowych, wariacjami temperatury i ciśnienia.

Słowa kluczowe: fotosfera słoneczna, granulacja, prędkość wzdłuż linii wzroku, parametry termodynamiczne