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Structure of convective flows on supergranular scales in the solar photosphere

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The exploration of the velocity field of the real solar convection was performed using neutral iron line $\lambda \approx 639.3$ nm profile from the observations with high spatial resolution. The inverse procedure was applied for each profile to reproduce the velocity field in the solar photosphere. Acoustic waves were removed by $k-\omega$ filtration. To study supergranulation in the solar photosphere we selected motions with horizontal velocities less than 0.5 km/s. As the lifetime of the supergranule is larger than the observation time, we have averaged images of the vertical velocity in time. Supergranulation becomes more apparent on the distribution of the vertical velocity (the range of ΔV variations on the supergranular scales is constrained by ~ 0.04 km/s). The velocity field within such cells has been studied and compared with the distributions of the vertical velocity on smaller scales. The upward supergranular flows expand with height and intensify (as distinct from decreasing of the velocity variations on the smaller scales), and the distribution of the line of sight velocity inside supergranular flows becomes more asymmetric in the higher layers of the photosphere. The downward supergranular flows are more compact and have a complicated structure too.

Key words: photosphere, convection, supergranule

INTRODUCTION

The Sun is the closest star — this fact allows us to resolve individual features on its surface and in its atmosphere. Using many types of observations, we can collect a large amount of data describing the behaviour of the solar plasma in various phenomena.

The hierarchy of surface features found on the photosphere is customarily classified by size and lifetime as patterns of granulation, mesogranulation and supergranulation [1]. Before we head into the specific topic of supergranulation, a brief overview of smaller-scale flows at the Sun's surface, the well-known granulation and the more controversial mesogranulation, is required to set the stage completely. The solar granulation is an intensity pattern with a contrast around 15%, which displays cellular convective motions with length scales ranging from ~ 0.5 Mm to 2 Mm [12], mean granular lifetimes - $5 \div 16$ min [6] and associated velocities - $0.5 \div 1.5$ km/s [14]. Mesogranulation refers to flows at scales between the granulation and the supergranulation scales - $4 \div 12$ Mm [12] with vertical velocities of 60 [10] to 200 m/s [2]; its lifetime has not yet been accurately determined: in the first determination [10] mesogranules persisted for at least 2 hours but in other studies their lifetime is much longer.

The present study focuses on the supergranular flow field. The supergranulation refers to a physical pattern covering the surface of the quiet Sun in the range of $20 \div 70$ Mm with a preferred scale of a 36 Mm [4, 12]. The most resent estimate of the lifetime of supergranules, based on the largest sample of supergranules collected so far, is 1.6 ± 0.7 day [7]. Its most noticeable signature is a fluctuating velocity field whose components are mostly horizontal. Supergranules are traditionally described as convection eddies with horizontal flows diverging from a cell centre outward and subsiding flows at the cell boundaries outlined by strong photospheric magnetic fields and chromospheric network.

Supergranulation was discovered more than fifty years ago. A lot of work has been devoted to the subject over the years, but observational constraints, conceptual difficulties and numerical limitations have all concurred to prevent a detailed understanding of the supergranulation phenomenon so far.

The observed patterns of outflows are usually interpreted as an evidence of convective fluid motions occurring on supergranular scales, although the continuum intensity enhancement associated with the presumed upwelling of warmer fluid at cell centres remains elusive. Contrary to expectations, some measurements reveal brightness enhancements in the convergence lane network, although the brightening may be related to the presence of numerous magnetic elements that have been swept into the convergence lanes. Seeking to disentangle such effects of magnetism, in [11] detection of the weak brightening within the supergranular cells that may be consistent

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with a convective origin is reported.

The latest studies indicate that supergranules are slightly warmer at their centre. The temperature drop is less than 3 K [3, 9]. Rms horizontal velocities at supergranulation scale are of the order of 350 m/s, while rms vertical velocities are around 30 m/s [5].

The overshooting of convective motions into the solar photosphere and higher provides a direct coupling between the atmosphere and the vigorous turbulence below the surface. The height dependence of such overshooting motions is affected by both the vertical stratification of the stable atmosphere and the nature of the forcing in the subphotosphere. In principle, if we could measure the height dependence of the vertical and horizontal components of the motion in the photosphere, we should be able to place constraints on the nature of the associated flows below the surface and it should be possible to estimate the mechanical energy transported by the motions.

The aim of the present work is to gain insight into the convective structure of the solar photosphere on supergranular scales. The exploration of the velocity field of supergranular scales was performed in the framework of the real solar convection using profiles with high spatial resolution and considering NLTE effects.

OBSERVATIONAL DATA

Here, we use the results of the observations of N. Shchukina on the 70-cm German Vacuum Tower Telescope (VTT) (located on the Canary Islands [8]) taken around the centre of the solar disc in the non-perturbed region. The spectral line of the neutral iron with $\lambda \approx 639.3$ nm has been chosen for observations.

The data set consists of time sequence (947 images, observation duration 2.6 h) of 512 profiles in total corresponding to the extent of 64 400 km over the surface of the Sun. The height of the region of line formation extends from several kilometres up to 550 km.

RESULTS AND CONCLUSIONS

The inverse procedure [13] was applied for each profile to reproduce the velocity field in the solar photosphere along two spatial coordinates: its depth h, and the coordinate along the spectrograph slit X (see Fig. 1). There is one common average zero-point of vertical velocity variations for all 947 values. The white colour corresponds to the velocity of the ascending flows of hot matter and the dark grey colour to that of the descending flows of cold matter. The range of vertical velocity variations is constrained by ± 0.6 km/s in order to gain better contrast in the upper layers of the atmosphere.

The structure of the solar photosphere is defined by the wave and convective motions, so the problem arises to separate them correctly. In our work, the separation of the oscillations was carried out by Fourier transform. So acoustic waves were removed by $k-\omega$ filtration (see Fig. 2). The range of vertical velocity variations is decreased to ± 0.4 km/s in order to gain better contrast again. According to our results of the reconstruction the shape of the velocity patterns in the solar convection reflects the strong stratification: upwelling of hot material originates from the convective zone and overshoot into the stably stratified photosphere; radiative losses make the overshooting material relatively cold and its overturning motion supplies downflows. The variations of the convective velocity in Fig. 2 decrease with heights in contradiction to the high contrast in Fig. 1 caused by convection and acoustic waves and kept throughout the height.

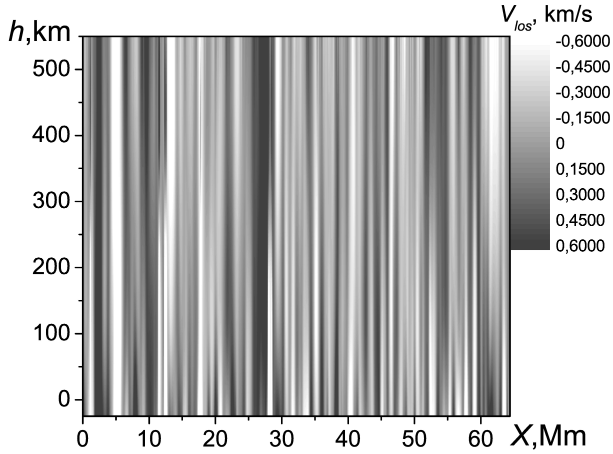

Fig. 1: The vertical velocity field in the real solar photosphere (convection + acoustic waves).

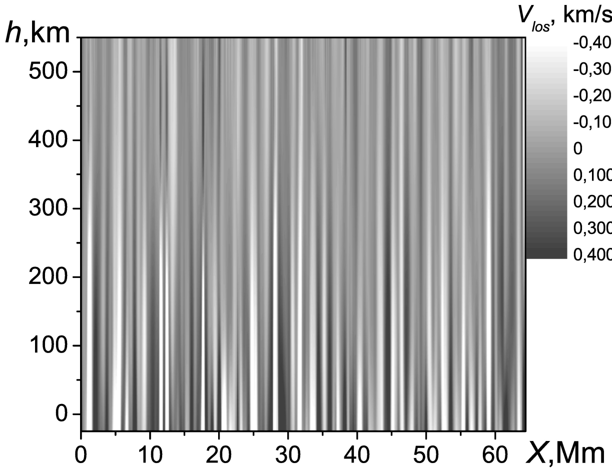

Fig. 2: The vertical velocity distribution of the solar convection.

We used the method of filtering the spatial and temporal frequencies to select the structures on smaller scales – granulation (see Fig. 3, dotted line) and mesogranulation (see Fig. 3, dashed line). The horizontal area is narrowed in order to gain better contrast of the granular flows.

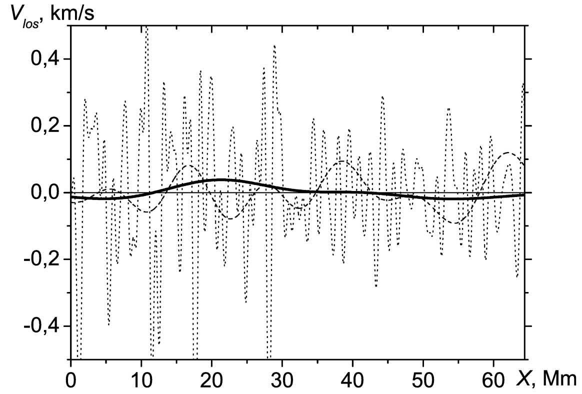

Fig. 3: The vertical velocity distribution in the solar photosphere on granular (dotted line), mesogranular (dashed line) and supergranular (solid line) scales at the height h=0 km.

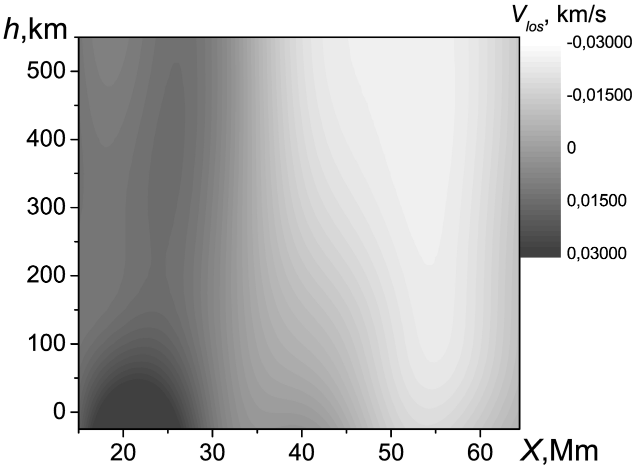

Fig. 4: The vertical velocity distribution in the solar photosphere on supergranular scales.

Characterising the supergranulation velocity pattern requires monitoring solar surface flows over long times, over wide field of views, or over a large set of independent observations [12]. To study supergranulation in the solar photosphere we selected convective structures with horizontal movements at speeds up to 0.5 km/s (rather higher as indicated above [5]). As the lifetime of the supergranule is larger than the observation time, we have averaged obtained images of the vertical velocity in time. So the convective flows on supergranular scales were selected (see Fig. 3, solid line). The range of vertical velocity variations on granular scales is the largest, the variations of vertical velocities on meso- and superscales are much less. Thus, large-scale coherent patterns detected in the quiet Sun are simply superimposed on a stochastic granulation [12].

Figures 4 and 5 present the vertical velocity distribution in the solar photosphere on supergranular scales and the height stratification of the vertical velocity in the supergranular flows.

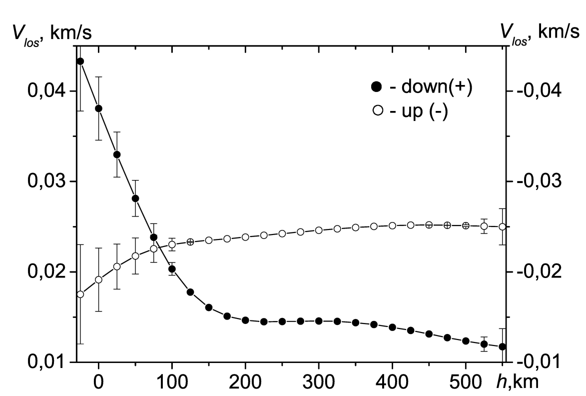

Fig. 5: The height stratification of the vertical velocity in the upward and downward supergranular flows.

We base our analysis of the structure of convective flows on supergranular scales in the solar photosphere and our final conclusions on its comparison with the smaller scales are the following:

- According to our results of the reconstruction the shape of the velocity patterns in the solar convection reflects the strong stratification on small, middle and large scales.
- The range of velocity variations in the supergranular flows is constrained by ±0.04 km/s (it is much less then ±1 km/s on granular scales and ±0.1 km/s on the mesogranular scales in the lower photosphere).
- The vertical velocities caused by convection are maximal in the lower layers and decrease with height (see Fig. 2). Only a part of the convective flows reaches the temperature minimum layers.
- The variations of the vertical velocity in the supergranular flows reach the temperature minimum layers and much higher layers, perhaps. The upward supergranular flow (the highlights in Fig. 4) is rather wide and the velocity distribution inside the supergranular flows is not quite symmetrical (the maxima is some shifted from the cell centre). The vertical velocities in such a flow (see Fig. 5, empty circles) increase slightly with heights.
- The downward supergranular flow (the lowlights in Fig. 4) is narrower. The variations of the vertical velocity in such a flow (see Fig. 5, full circles) decrease rapidly in the middle photosphere and slightly vary in the higher layers of the solar photosphere.

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