LINE-OF-SIGHT VELOCITY IN A SEMIEMPIRICAL MODEL OF A DISAPPEARING GRANULE

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ABSTRACT

The behaviour of the line-of-sight velocity in the centre of a disappearing granule is analyzed using an inversion method applied to a time-series of spectra containing the Fe I 522.5 nm, 557.6 nm and 557.7 nm lines. The temporal evolution of the line-of-sight velocity $v_{\rm LOS}$ is presented in the form of the functional dependence of $v_{\rm LOS}(\log\tau_5, t)$ on the optical depth τ_5 at 500 nm and time t. An oscillatory behaviour is found in the velocity stratification with nearly constant phase through the photosphere. The amplitude of variations increases from $\log\tau_5 = -0.3$ to $\log\tau_5 = -2.5$ reaching a maximum of $\sim 1.2\,\mathrm{km\,s^{-1}}$. A zero velocity layer is detected in every instantaneous model of the velocity stratification. The results suggest, that the zero velocity may occur in a considerable range of the optical depths from $\log\tau_5 \sim -2$ to $\log\tau_5 \sim -3.5$.

Key words: Sun: granulation – Sun: photosphere – Sun: oscillations – stars: atmospheres.

1. INTRODUCTION

The instantaneous velocity vector of a small volume element in the solar photosphere results from an interaction of a multitude of phenomena occurring on a wide range of temporal and spatial scales. A short-term and small-scale velocity pattern of the photosphere is determined by the granulation and oscillations. The different characteristics of these phenomena can be investigated separately or simultaneously. Ruiz Cobo et al. (1997) and Rodríguez Hidalgo et al. (2001) studied the stratification of the oscillations with the optical depth and with the Lagrangian and Eulerian coordinates through the solar photosphere. An empirical study of the dynamics of the solar photosphere was done in the series of papers of Nesis et al. (2001 and references therein). The latter approach, i.e. the simultaneous study of the granulation and oscillations, was carried out by Khomenko et al. (2001) and Espagnet et al. (1996) who investigated the spatial relation between the 5-min oscillations and the granulation pattern. They concluded that the velocity oscillation amplitude increases with height (Ruiz Cobo et al., 1997; Khomenko et al., 2001) and that the most energetic velocity oscillations occur above granules and intergranules with the maximum contrast (Khomenko et al., 2001). In our paper, which is coupled with Koza et al. (2002) (Paper I), we aim to study the temporal evolution and radial stratification of the line-of-sight velocity in the centre of a bright granule, which gradually disappeared. Because of possible presence of the 5-min oscillations, the velocity is considered to be a sum of the oscillatory velocity and the flow velocity induced by the granulation.

2. OBSERVATIONAL DATA AND INVERSION METHOD

The observational material on which this work is based on consists of a 4-min spectral series of three lines Fe I 522.5 nm, Fe I 557.6 nm and Fe I 557.7 nm arranged in 28 sets. The observed profiles were inverted simultaneously in 28 runs using the SIR code (Ruiz Cobo & del Toro Iniesta, 1992). A more detailed description can be found in Paper I. We must stress that there are some important differences with respect to Paper I. To analyze the identical point of the granule (see Fig. 1 in Paper I) throughout its evolution, we avoided the automatic selection of the profiles from the individual spectra. Instead of this, the selection was done manually guessing by eye the centre of the granule. Further, the range of the optical depths in the initial model was decreased from $\log\tau_5 \in \langle 1.4, -4\rangle$ to $\log\tau_5 \in \langle 0.5, -4\rangle$ taking into account the response functions to temperature calculated for initial model. An idea was to prevent the SIR from waste of the nodes in the layers from which we do not have direct informations and where the response functions are being almost zero. Moreover, the SIR was instructed to synthesize the missing red

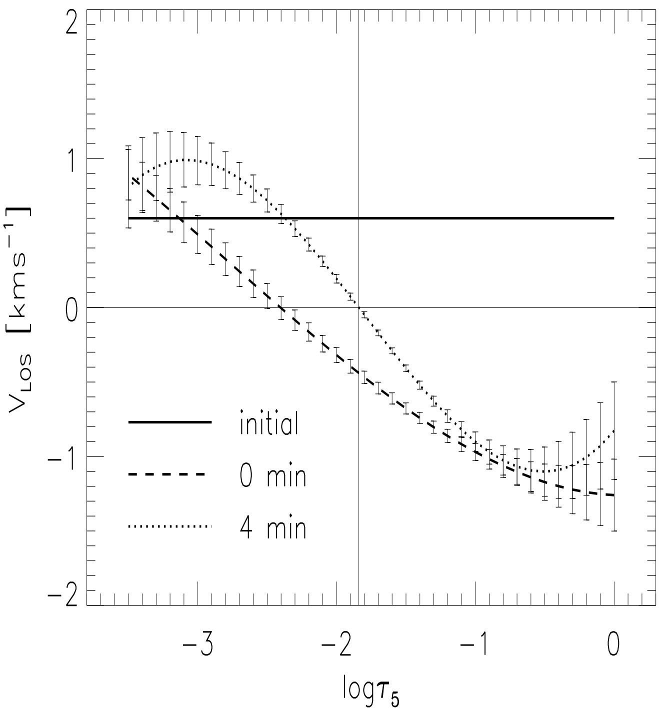

Figure 1. The line-of-sight velocity stratification in the granular photosphere at $t = 0\,min$ (dashed) and $t = 4\,min$ (dotted). The initial guess model (thick solid line) is depicted without error bars. The negative velocities indicate upflows. The velocity has been corrected for gravitational redshift by subtracting 636 m s^{-1}. The cross point of the horizontal and vertical thin solid lines helps to identify the optical depth $\log\tau_5$ with zero velocity in the model at $t = 4\,min$.

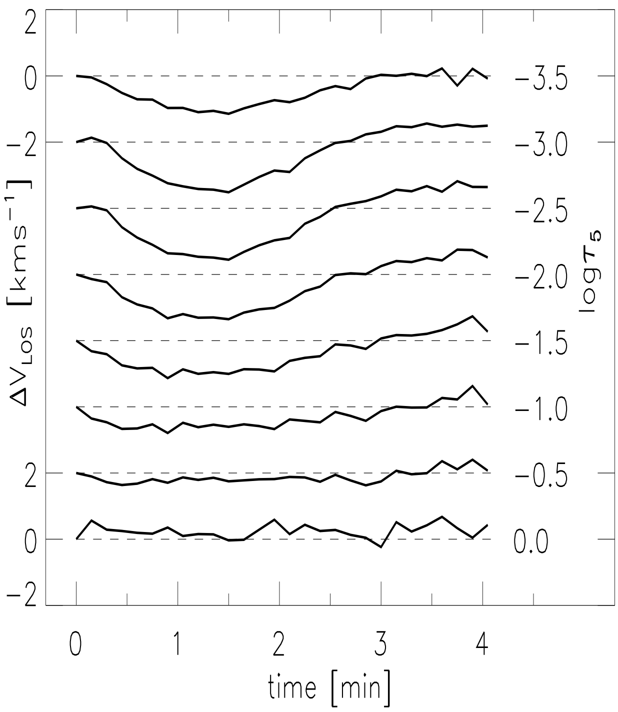

Figure 2. The temporal evolution of the line-of-sight velocity differences (solid line) with respect to the first model at $t = 0\,min$ (horizontal dashed lines) at indicated optical depths. At the given time t and at the optical depth $\log\tau_5$ the velocity differences are computed as $\Delta v_{\rm LOS}(\log\tau_5, t) = v_{\rm LOS}(\log\tau_5, t) - v_{\rm LOS}(\log\tau_5, t = 0)$.

wings of the profiles to ensure correct convolution of the profiles with the macroturbulent broadening represented by a Gaussian (Bellot Rubio, 1999). Finally, to guarantee the inherent consistency the identical combination of the nodes was used in the course of the whole inversion. Thus, the profiles were inverted simultaneously in three cycles allowing one, two and four nodes for temperature and line-of-sight velocity. The micro- and macroturbulence were assigned with one node.

3. RESULTS

Fig. 1 shows the models determined from the inversion at $t = 0\,$min and 4 min along with the initial model. The error bars of the models indicate only the formal errors of the method used, but the actual errors may be larger. There are zero crossing points in all of 28 models, where the line-of-sight velocities change sign from upflow (negative $v_{\rm LOS}$) to downflow (positive $v_{\rm LOS}$) (for more details see Paper I). Fig. 2 represents the temporal evolution of the line-of-sight velocity differences with respect to the first model at $t = 0\,$min. At the given time t and at the optical depth $\log\tau_5$ the velocity differences are computed as $\Delta v_{\rm LOS}(\log\tau_5, t) = v_{\rm LOS}(\log\tau_5, t) - v_{\rm LOS}(\log\tau_5, t = 0)$. Owing to the slightly changed conditions of the inversion, the run of the differences is smoother than in Paper I, what may justify the procedure applied. The temporal evolution exhibits apparent oscillatory behaviour with an incomplete cycle. The amplitude of variations changes with height without obvious phase-shift. The amplitude of the variations of the line-of-sight velocity in the individual layers is shown more clearly in Fig. 3. At the given optical depth $\log\tau_5$ the amplitude is computed as $\{\max[\Delta v_{\rm LOS}(\log\tau_5)] - \min[\Delta v_{\rm LOS}(\log\tau_5)]\}/2$. As it can be seen the velocity variations greater than 1 km s^{-1} are confined to the layers from $\log\tau_5 \sim -2$ to $\log\tau_5 \sim -3$ in the upper photosphere. The changes of the position of the zero velocity layer in the course of time can be viewed in Fig. 4, which suggests that the position of this layer may also oscillate in the wide range of the optical depths from $\log\tau_5 \sim -2$ to $\log\tau_5 \sim -3.5$. The relevant optical depths were inferred from all of 28 models tracking the position of the cross points in the course of time (see Fig. 1).

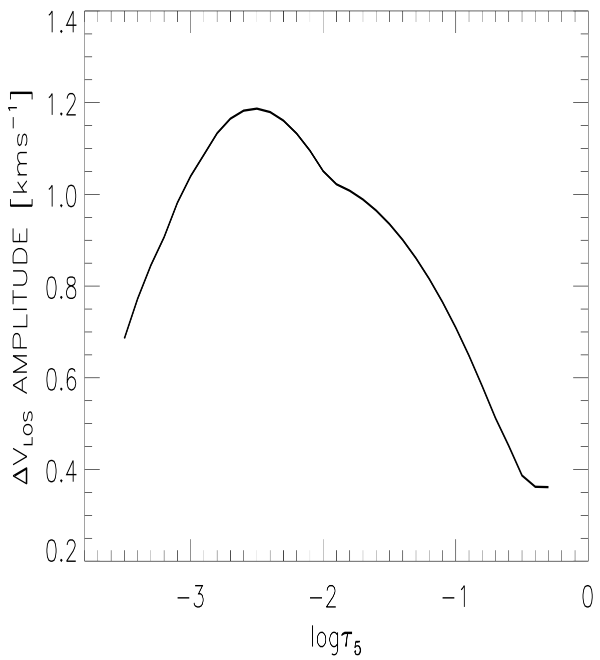

Figure 3. The amplitude of the variations of the line-of-sight velocity through the granular photosphere. For the given optical depth $\log\tau_5$ *the amplitude is computed as* $\{\max[\Delta v_{\mathrm{LOS}}(\log\tau_5)] - \min[\Delta v_{\mathrm{LOS}}(\log\tau_5)]\}/2$.

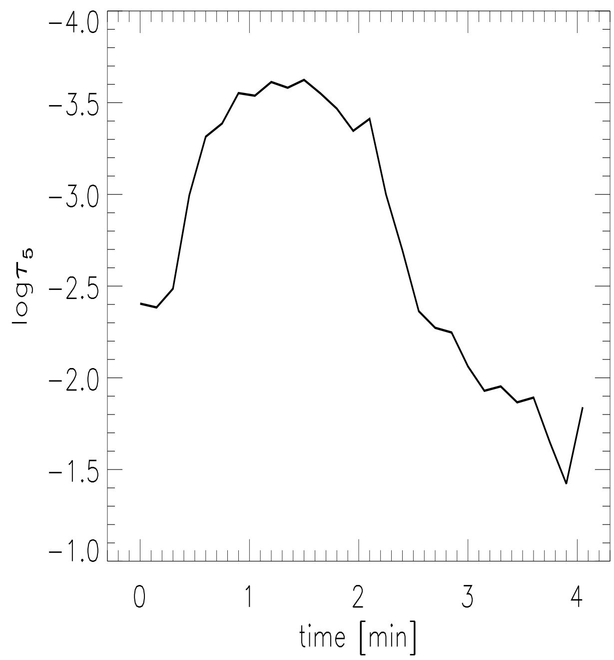

Figure 4. The time-space migration of the zero velocity layer in the $(\log\tau_5, t)$ *plane. At the given time t the transition from negative to positive velocity takes place at the optical depth* $\log\tau_5$*. Matter below the zero velocity layer moves towards an observer whereas the layers above that layer move away from an observer.*

4. DISCUSSION

4.1. Velocity variations

The wave pattern of the velocity variations is clearly visible in Fig. 2 with an estimated period of about 5 min. This feature unveils the presence of 5-min acoustic mode of the velocity oscillations in the investigated granule, because the observational data were not filtered from the 5-min oscillations. This scenario is supported by Khomenko et al. (2001) who reported that the amplitude of the 5-min velocity oscillations increases with brightness of the granules as well as with the height in the atmosphere. Since the continuum contrast of the investigated granule is about 15% (see Fig. 1 in Paper I), there is high possibility of occurrence of the particularly strong oscillation above such bright granule. Also a simplified model of the velocity field in the granule supports this hypothesis. The granular upflow is divergent (see e.g. Ruiz Cobo et al., 1996) which means that the vertical flow changes with height to the horizontal and thus its line-of-sight component gradually vanishes. Consequently, an oscillation-free granule should exhibit a decrease of the velocity variations with height at least in the low and middle photosphere what is in contrast with the results shown in Fig. 2 and Fig. 3. An interpretation of the obtained velocities as the sum of the oscillatory and granular velocities is the most natural way how to explain the run of the amplitudes shown in Fig. 3 at least in the layers from $\log\tau_5 = -1$ to $\log\tau_5 = -2.5$. Outside this range, the results can not be regarded as reliable owing to the fall of the sensitivity of the response functions to velocities in the lower ($\log\tau_5 > -1$) and upper ($\log\tau_5 < -3$) photospheric layers. Moreover, we lack the red wings of the lines and thus the velocity information from the deep layers is incomplete. Further we will concentrate on the layers from $\log\tau_5 = -1$ to $\log\tau_5 = -2.5$ where the amplitude of velocity variations increases from $0.6 \pm 0.1\,\mathrm{km\,s^{-1}}$ to $1.2 \pm 0.1\,\mathrm{km\,s^{-1}}$ (see Fig. 3). The uncertainties are estimated using Fig. 1. The typical velocity amplitudes of the 5-min oscillations are up to $0.5\,\mathrm{km\,s^{-1}}$ (Ruiz Cobo et al., 1997). The excess of the amplitude at $\log\tau_5 = -2.5$ (see Fig. 3) can be explained by means of Fig. 5d published in Khomenko et al. (2001). The extrapolation of the amplitude for the continuum contrast 15% characteristic for investigated granule can provide the value $\sim 0.9\,\mathrm{km\,s^{-1}}$. If we take into account the velocity variations of a few hundreds $\mathrm{m\,s^{-1}}$ caused by the evolution of the granule then the value of $1.2 \pm 0.1\,\mathrm{km\,s^{-1}}$ can be explained. Finally, the decrease of the amplitude in the upper layers $\log\tau_5 < -2.5$ can not be regarded as realistic because of considerable uncertainties (see Fig. 1) of the inferred velocities in these layers. We conclude that the observed velocity variations in the bright granule are mainly due to strong 5-min oscillations and the amplitude of the variations increases with height reaching the maximum of $1.2\pm0.1\,\mathrm{km\,s^{-1}}$ at $\log\tau_5 = -2.5$.

4.2. Zero velocity layer

The zero velocity layers, where upflow-downflow reversal takes place, can be identified by means of Fig. 4. The accuracy of the zero velocity layer is influenced by the accuracy of the zero point of the velocity given by the accuracy of the solar and laboratory wavelengths. We recall, that the solar wavelengths taken from the FTS atlas (Neckel, 1999) were needed for wavelength calibration of the spectra (Allende Prieto, 1998) and the laboratory wavelengths (Nave et al., 1994) were used as inputs of the SIR code. The typical accuracy of the FTS atlas is about $50\,\mathrm{m\,s^{-1}}$ at 500 nm (Allende Prieto, 1998) and the accuracy of the laboratory wavelengths of the Fe I lines used is better than $70\,\mathrm{m\,s^{-1}}$ (Nave et al., 1994). Then the accuracy of the zero velocity point is $\sim 0.1\,\mathrm{km\,s^{-1}}$ and the corresponding accuracy of the position of the zero velocity layer is ~ 0.1 in $\log \tau_5$ scale.

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