TEMPORAL EVOLUTION OF PHYSICAL PARAMETERS IN A GRANULE

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ABSTRACT

The temporal evolution of the physical parameters inside a granule is presented. This is a step towards a more realistic 1D modeling of the solar granulation, avoiding the temporal averaging used up to now. The granulation is treated as a dynamical phenomenon and our model has been calculated using an inversion method applied to time series of spectra. The granular evolutionary model is presented in the form of the functional dependence of temperature \(T(\log \tau, t)\) and line-of-sight velocity \(v_{\text{LOS}}(\log \tau, t)\) on optical depth \(\tau\) and time \(t\). The observed disappearance of the granule is accompanied with significant temperature changes greater than 500 K in deeper layers (log \(\tau\) > 0.5) and upper layers (log \(\tau\) < -2.5). In contrary, the layers from log \(\tau\) ≈ 0 to log \(\tau\) ≈ -2 are more stable in the sense of temperature variations, which are less then \(\approx 300\) K. Neither regular variations nor apparent trends have been found in the line-of-sight velocity stratification from log \(\tau\) ≈ 0 downwards. Above this layer an oscillatory behavior is found with increasing amplitude reaching up to \(\approx 2\) km s\(^{-1}\) in upper layers.

Key words: Sun: granulation – Sun: photosphere – stars: atmospheres – line: profiles.

1. INTRODUCTION

The principal physical process taking place in layers near to the surface of the Sun is the intensive radiative cooling of the ascending plasma. As a direct consequence, larger convective upflows are smashed giving rise the granulation with seemingly dominant laminar behavior along with properties suggesting turbulence [11]. Due to the inertia, the granules penetrate into the stable photospheric layers overshooting their nearly-parallel structure and thus disturb the hydrostatic equilibrium. This process is accompanied with a transformation of the energy carried by the granule into the radiation, waves and shocks. To understand such conversion, it is necessary to know temporal and spatial gradients of the fundamental physical quantities in granular interior as well as overlying photosphere on scales substantially smaller than the dimension and lifetime of the granule. Presently, there are two approaches how to accomplish this. During the last two decades, the theoretical simulations based on the equations of hydrodynamics succeeded to explain many details of granular structure [1], [3]. Another approach is based on modeling of the photospheric line profiles observed with high spectral, spatial and temporal resolution. For this and many other purposes a powerful inversion method was developed [14]. In the present paper we use this inversion technique [13] to study temporal evolution and radial stratification of the temperature and line-of-sight velocity in granular photosphere.

2. OBSERVATIONAL DATA

The spectra obtained as the time series by the Echelle spectrograph of the German VTT, Tenerife, on June 1, 1993, are used as input observational data. The time series consists of 28 pairs of spectra of spectral regions around 522.5 nm and 557.6 nm. The profiles of two medium strong Fe I 522.5 nm and 557.6 nm lines and weak Fe I 557.7 nm line have been selected. The time step between exposures of subsequent pairs was \(9\) s and the whole time series covers 4 min of the decay of a granule. The spatial resolution along the slit was \(0.175\)” per pixel and the width of the spectrograph slit was 150 \(\mu\)m. The exposure time was 0.2 s. We identified the bright granule by visual inspection of individual spectra at position 5 arcsec (see Fig.1), whose disappearance has been possibly related with the extinction. For further investigation, the Fe I line profiles were used from the center of the selected granule. Because the spectra lack of absolute wavelength calibration, the wavelength scale was assigned them using the pairs of suitable lines as standards with the solar wavelengths known accurately enough from an FTS atlas [6]. The pairs Ti I 522.49 nm – Fe I 522.53 nm and Fe I 557.6 nm – Fe I 557.7 nm were adopted in relevant spectral ranges.

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3. THE METHOD OF THE SPECTRAL INVERSION

The observed spectra are inputs of the inversion code SIR (Stokes Inversion based on Response functions). SIR iteratively modifies an initial guess model until the synthetic spectrum matches the observed one. The square of the difference $\chi^2$ between observed and synthetic spectrum is calculated in each iteration step providing a feedback information how to modify the guess model, which should lead to a minimization of $\chi^2$ in the next iteration. The code was prepared to deal with the four Stokes line profiles, but we analyze Stokes I profiles only. The basic assumptions are LTE, homogeneous plan-parallel atmosphere and hydrostatic equilibrium. As a result of the inversion, SIR provides the stratification with optical depth $\tau$ of temperature $T$, line-of-sight velocity $v_{LOS}$ and microturbulence $v_{MIC}$ along the whole atmosphere. It also returns the macroturbulence $v_{MAC}$ which is assumed to be height-independent. Thus subsequent application of the SIR code on the time series of the spectra can provide the time dependence of these parameters. The latest SIR version presented in [5] involves the advanced quantum formulation of the collisional broadening [4] as well as classical Unsöld's theory, which has demanded the introduction of the enhancement damping factor. The SIR code needs as input the atomic parameters describing considered transition the quantities summarized in Tab.1. The central laboratory wavelengths in air have been taken from [12] except for 557.7 nm line (see below). The excitation potential of the lower level and the logarithm of the oscillator strength have been adopted from [16]. The temperature parameter and cross section are needed for collisional broadening calculation and have been taken from [4]. In case of weak 557.7 nm line, the Unsöld's theory is considered to be sufficient and the enhancement factor has been set to 1. We adopt an iron abundance of 7.46 dex. This value is appropriate for LTE calculation according to [2], [15]. In addition to the atomic parameters, the inversion code requires an initial guess model. We have chosen the Harvard-Smithsonian Reference Atmosphere (HSRA) [7]. The microturbulence and line-of-sight velocity were set to 0.6 km s$^{-1}$ in all optical depths and the macroturbulence was 2 km s$^{-1}$.

The input profiles of the Fe I 522.5 nm, 557.6 nm and 557.7 nm lines were sampled at intervals of 0.35 pm, 0.39 pm and 0.39 pm respectively. The red wings of the Fe I 522.5 nm and 557.6 nm were excluded from inversion because of blending. The weak 557.7 nm lacks of the red wing because it was already out of CCD chip. Thus, total 168 data points from each spectrum have been used as inputs of the inversion.

<table>
<thead>
<tr>
<th>( \lambda_{\text{tab}}^{\text{Fe I}} ) [nm]</th>
<th>( \text{EP}_{\text{low}} ) [eV]</th>
<th>( \log(gf) )</th>
<th>( \alpha ) ( \text{[as]} )</th>
<th>( \sigma ) ( \text{[as]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>522.55261</td>
<td>0.11</td>
<td>-4.74</td>
<td>0.253</td>
<td>207</td>
</tr>
<tr>
<td>557.60888</td>
<td>3.43</td>
<td>-0.73</td>
<td>0.232</td>
<td>854</td>
</tr>
<tr>
<td>557.70248</td>
<td>5.03</td>
<td>-1.53</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4. THE PROBLEM OF THE 557.7 NM LINE IDENTIFICATION

The weak 557.7 nm line has not yet been observed in any laboratory spectra and thus it has not been listed in [12]. The line identification in [9] as neutral iron line has been based upon coincidence of the wavelength predicted from less precise energy levels and a feature in the solar spectrum. To obtain the accurate laboratory wavelength in air and to test the identification, we apply the following procedure. Knowing the multiplet number [9] and designation [10], we can determine in [12] the wavenumbers of the lower and upper level of the transition needed for the calculation of the laboratory wavelength in air [12]. Using this value, the two-component model of the solar photosphere [5] and the SIR code, we calculated the synthetic 557.7 nm line profile, providing it is an iron line. The agreement of the synthetic profile central wavelength 557.70249 nm with the central wavelength 557.70247 nm of the profile extracted from FTS atlas proves convincingly the Fe I 557.7 nm line identification.

5. RESULTS OF THE INVERSION

The profiles of all three Fe I lines were inverted simultaneously in three cycles allowing one, four and five nodes for temperature and line-of-sight velocity. The micro- and macroturbulence were inverted with one node. In very few cases, to achieve satisfying agreement between synthetic and observed profiles, six or seven nodes were used for temperature in the last cycle. As an example, we plot in Fig.2 the observed
Figure 2. Comparison between observed profiles at $t = 0$ min (circles) and synthetic profiles (solid line) resulting from inversion. $0$ pm corresponds to the central laboratory wavelength. The gravitational redshift is not corrected.

Figure 3. The temperature and line-of-sight velocity stratifications in the granular photosphere at $t = 0$ min (solid line) and $t = 4$ min (dotted line). The mean models (dashed line) resulting from averaging of all 28 models are depicted without errorbars. Negative velocities indicate upflows. The velocity has been corrected for gravitational redshift by subtracting 636 m s$^{-1}$ (a), (b). The temporal evolution of the temperature and line-of-sight velocity differences (solid line) with respect to the mean models (horizontal dashed lines) in indicated optical depths. For clarity, the curves have been shifted by $\Delta T = 600$ K and $\Delta v_{\text{LOS}} = 2$ km s$^{-1}$ (c), (d).
profiles at \( t = 0 \text{ min} \) and the synthetic profiles resulting from the inversion. In general, SIR succeeded to reproduce very well the line cores of the whole series. The discrepancies with maximum relative errors up to 4% appeared sometimes in the blue wing of the Fe I 557.6 nm. Figs.3a) and 3b) show the models determined from the inversion of the profiles at \( t = 0 \text{ min} \) and 4 min. Surprisingly, the errors of the temperature stratifications of all 28 inferred models have been less than \( \pm 60 \text{ K} \) in all optical depths. There are also depicted the mean models (without errorbars) resulting from averaging of all 28 temperature and line-of-sight velocity models. Figs.3c) and 3d) represent the temporal evolution of the temperature and line-of-sight velocity differences with respect to the mean models in selected optical depths.

6. DISCUSSION

The temporal evolution of the temperature stratification \( T(\log \tau, t) \) shown in Fig.3c) exhibits non-uniform response of the granular photosphere on the decay of the bright granule. Because our observational data do not reflect directly the state of the sub-photospheric layers, the temperature of them is just an extrapolation. Whereas deeper layers \( (\log \tau > 0.5) \) exhibit systematic cooling with temperature decrease greater than 500 K, the low and middle photosphere from \( \log \tau \approx 0 \) to \( \log \tau \approx -2 \) exhibit certain temperature stability with temperature changes less than \( \approx 300 \text{ K} \). On the contrary, more pronounced temperature changes greater than 500 K occur again in upper layers \( (\log \tau < -2.5) \) probably phase shifted with respect to deeper layers \( (\log \tau > 0.5) \). Note the raise of temperature of upper layers \( (\log \tau < -2) \) between third and fourth minute, when the granular evolution is close to the final stage. Comparable results were achieved in HD simulations of the relative temperature fluctuations in the granular photosphere (Fig.5 in [3]). The models of the velocity stratification at \( t = 0 \text{ min} \) and 4 min as well as the mean model in Fig.3b) posses the crossing points, in which the line-of-sight velocities change the sign from upflow (negative \( v_{\text{LOS}} \)) to downflow (positive \( v_{\text{LOS}} \)). This apparently weird behavior of the granular velocity field is fully testified both theoretically by HD simulations (Fig.2 in [3]) as well as observationally as the anticorrelation between the vertical velocities and temperature fluctuations in the upper photosphere [3]. The layers, where the crossing points occur, may be considered as boundaries above which mainly non-convective, so called secondary motions plus oscillations predominate [8]. Although in [5] a similar trend was found, the discussed velocity models are probably not realistic from \( \log \tau \approx 0 \) downwards, where the indicated velocity increase towards positive values may be an artefact of inversion reflecting the lack of direct observational data from deeper layers, for which the velocity response function is close to zero. The temporal evolution of the velocity stratification \( v_{\text{LOS}}(\log \tau, t) \) shown in Fig.3d) exhibits apparent oscillatory behavior from \( \log \tau \approx 0 \) upwards with increasing amplitude reaching up to \( \approx 2 \text{ km s}^{-1} \) in upper photosphere. This characteristics expresses the contamination of the observational data with 5-min oscillations. To obtain the actual granular velocity field free of oscillations it is necessary to apply spatio-temporal filtering on the time series considerably longer than the studied, what is the main aim of our near future work.

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