VELOCITY FIELD IN THE INTERGRANULAR ATMOSPHERE

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Abstract. The line-of-sight velocity v_{LOS} and macroturbulent velocity v_{MAC} are studied in the centre of the intergranular space in the solar photosphere. An inversion method is applied to a 4-min time sequence of Stokes I spectra of the Fe I 522.5 nm, Fe I 557.6 nm and Fe I 557.7 nm lines observed with high spatial and temporal resolutions at solar disk centre. The results are presented in the form of the functional dependence of v_{LOS}(log \tau_5,t) and v_{MAC}(t) on the continuum optical depth \tau_5 at 500 nm and time t. A v_{LOS} of several hundreds of meters per second was found in the upper photosphere (log \tau_5 \leq -1.5), where the plasma flows away from the observer. On the contrary, upflows directed towards the observer were found in deeper layers (log \tau_5 > -1.5). The typical value of v_{MAC} in the centre of the intergranular space is found to be \sim 1.7 \text{ km s}^{-1}, which is about 0.5 \text{ km s}^{-1} greater than in the adjacent granule.

Key words: Sun - photosphere - granulation - intergranular space

1. Introduction

The structure of the granular velocity field is usually described as an ensemble of ascending and descending flows with typical velocities of the order of 100 m s^{-1} (Rodríguez Hidalgo et al., 1995). There exist many theoretical predictions and observations that intergranular spaces (IG) and granule (GR) - intergranular space borders frequently manifest remarkable dynamic
and magnetic phenomena. We can mention, in particular, photospheric shocks, enhanced turbulence, excitation of 5-min oscillations, intergranular holes, strong downdrafts and small magnetic flux-tubes that are still challenging observers as well as theoreticians (e.g. Espagne et al., 1996; Steiner et al., 1998; Kučera et al., 2003; Domínguez Cerdeña et al., 2003). Two-dimensional time sequence of spectra with high resolution may serve as a useful tool for investigation of physical conditions prevailing in IG.

To obtain the evolution and vertical stratification of $v_{\text{LOS}}$ in the centre of IG we applied an inversion technique (Ruiz Cobo and del Toro Iniesta, 1992) to 4-min time sequence of spectra. The evolution of $v_{\text{MAC}}$ in the centre of IG and an adjacent GR is also investigated. This paper is closely linked with three previous ones dealing with the temporal evolution of physical parameters in GR and IG (Koza et al., 2002a, 2002b and 2003, hereafter Paper I, Paper II and Paper III respectively).

2. Observational data, targets and inversion method

A detailed description of the used spectra was given in Paper III. The Fe I 522.5 nm, Fe I 557.6 nm and Fe I 557.7 nm line profiles obtained in the centre of the selected GR at $\sim 5$ arcsec and IG at $\sim 7$ arcsec (see Figure 1 in Paper III) were analysed by means of the inversion procedure outlined in Paper I and Paper II. The initial model HSRA (Gingerich et al., 1971) was iteratively modified by the inversion code SIR until the synthetic line profiles matched the observed ones.

To obtain the real velocity structure of the granulation we assigned the absolute wavelength scale to the input spectra. The pairs of spectral lines Ti I 522.49 nm – Fe I 522.5 nm and Fe I 557.6 nm – Fe I 557.7 nm were used for calculation of dispersions in relevant spectral regions. The accurate solar wavelengths $\lambda_S$ of these lines were adopted from an FTS atlas (Neckel, 1999). The laboratory wavelengths $\lambda_{\text{lab}}$ of the lines Fe I 522.5 nm and Fe I 557.6 nm taken from Nave et al. (2003) are considered as standards of the rest and the wavelength differences $\Delta \lambda$ are computed as $\Delta \lambda = \lambda_S - \lambda_{\text{lab}}$.

The inversion provided the stratification of temperature $T$ and $v_{\text{LOS}}$ throughout the atmosphere. It also returned $v_{\text{MAC}}$ which is assumed to be height-independent.
3. Results of the inversion

In general, SIR succeeded very well in reproducing all line profiles originating in the centre of IG. The typical discrepancies between synthetic and observed line profile intensities were smaller than 4%.

Figure 1 shows two instantaneous models of \( v_{\text{LOS}} \) in the centre of IG corresponding to the beginning \((t = 0 \text{ min})\) and the end \((t = 4 \text{ min})\) of the time sequence. The inversion method provided the formal errors of the models depicted as error bars, but the actual errors may be greater. Positive \( v_{\text{LOS}} \) indicates flows away from the observer (downflow) and negative \( v_{\text{LOS}} \) indicates flows toward the observer (upflow). Our results reveal that \( v_{\text{LOS}} \) of the downflow in the upper layers \((\log \tau_5 \leq -1.5)\) decreases to zero at the layer below which the plasma motion may turn into an upflow.

Figure 2 represents the temporal evolution of the line-of-sight velocity differences \( \Delta v_{\text{LOS}} \) with respect to the first model at \( t = 0 \text{ min} \) (hereafter reference model) at selected layers. At a given time \( t \) and optical depth \( \log \tau_5 \), the velocity differences are computed as:

\[
\Delta v_{\text{LOS}}(\log \tau_5, t) = v_{\text{LOS}}(\log \tau_5, t) - v_{\text{LOS}}(\log \tau_5, t = 0)
\]  

Figures 1 and 2 enable to estimate the value of \( v_{\text{LOS}} \) at an arbitrary time and optical depth. Figure 2 indicates weak oscillatory and evolutionary variations of \( \Delta v_{\text{LOS}} \). In the lower layers \((\log \tau_5 \in (-0.5, -1.5))\) the \( v_{\text{LOS}} \) was typically greater than in the reference model at \( t = 0 \text{ min} \). In turn, the plasma motion in the upper layers \((\log \tau_5 \leq -1.5)\) was almost always slower than in the reference model. Some oscillatory signatures of \( v_{\text{LOS}} \) are noticeable between the optical depths \( \log \tau_5 = -2.5 \) and \( \log \tau_5 = -3 \). A period of about 3 min can be estimated in the time interval from \( t = 0.2 \text{ min} \) to \( t = 3 \text{ min} \).

The temporal evolution of \( v_{\text{MAC}} \) in the centre of IG and GR is shown in Figure 3. Shaded areas are formal errors of \( v_{\text{MAC}} \). This Figure 3 and Figure 1 in Paper III demonstrate that the disappearance of the GR was accompanied by an increase of \( v_{\text{MAC}} \) from 1.1 km s\(^{-1}\) to 1.4 km s\(^{-1}\). However, the value of \( v_{\text{MAC}} \sim 1.7 \text{ km s}^{-1} \) stayed nearly unchanged in IG centre without obvious evolutionary trends.
4. Discussion

The goal of our study was a modelling of the temporal evolution of $v_{\text{LOS}}$ and $v_{\text{MAC}}$ in the intergranular space centre which are going to be discussed separately.

4.1. Line-of-Sight Velocity

The upper IG layers ($\log \tau_5 \leq -1.5$) exhibited typical $v_{\text{LOS}}$ values of the order 100 m s$^{-1}$ and the plasma receded from the observer (see Figures 1 and 2). In turn, we found a plasma upflow in the lower layers ($\log \tau_5 > -1.5$). This non-typical behaviour of $v_{\text{LOS}}$ in IG was already predicted by the hydrodynamic simulations of Stein and Nordlund (1998). The lower left quadrant of Figure 3 in the mentioned paper contains a numerous bunch of dark intergranular lanes ($\Delta I/I < 0$) representing upflowing cool plasma (negative velocity) at the optical layer $\tau = 1$. Stein and Nordlund (1998) explained this feature as a consequence of intensive turbulence taking place in the centre of IG. The turbulence would cause the recirculation of the cool...
fluid back to the surface. Also Kostyk (2003) empirically found a number of intergranular spaces having upflows in deep layers.

The velocity field of IG stayed unchanged without global evolutionary trends. Time intervals longer than 4 minutes are certainly needed to catch some meaningful variations in $v_{\text{LOS}}$ stratification. Although we have studied just one selected IG in a short time interval, our results do not confirm the results of Espagnet et al. (1996). They claim that the most energetic 5-min oscillations usually occur in downflows only. We found some oscillatory signatures between $\log \tau_5 = -2.0$ and $\log \tau_5 = -3$ only, for which a period of about 3-min can be estimated.

4.2. Macroturbulent Velocity

Stein and Nordlund (1998) arrived to the conclusion that the plasma flow in the intergranular spaces is highly turbulent, whereas in the granules they found laminar flows. Results presented in Figure 3 would confirm these facts. To interpret $v_{\text{MAC}}$ we must take into account also the results presented by Asplund et al., (2000). They showed that the classical concept of macroturbulent velocity can be fully explained by the self-consistently
calculated convective velocity fields and oscillations. Thus the introduction of $v_{\text{MAC}}$ into 1D stellar atmosphere analyses is necessary to account for missing line broadening mechanisms (i.e. representation of the real velocity field), limited spatial resolution and some other phenomena hampering observations (stray light, instrumental degradation etc.). We conclude that the inferred values of $v_{\text{MAC}}$ are those needed for additional broadening of synthetic line-profiles to compensate the line profiles degradation induced by seeing, spectrograph and limited spatial resolution.

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POLJE BRZINA U MEĐUGRANULARNOJ ATMOSFERI

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Izlaganje sa znanstvenog skupa

Sažetak. Istražuju se brzina u doglednici, \( v_D \) i brzina makroturbulencije, \( v_M \) u središtu međugranularnog prostora Sunčeva fotosfere. Primjenjena je se metoda inverzije na 4-minutni niz spektara linija FeI 522.5 nm, FeI 557.6 nm i FeI 557.7 nm snimljenih u središtu Sunčeva diska s velikim prostornim i vremenskim razlučivanjem. Rezultati se prikazuju u obliku funkcionalne ovisnosti \( v_D(\log \tau_5, t) \) i \( v_M(t) \) o optičkoj debljini kontinuuma \( \tau_5 \) na 500 nm i o vremenu \( t \). Izmjerena je brzina \( v_D \) od nekoliko stotina metara na sekundu u gornjoj fotosferi (\( \log \tau_5 \leq -1.5 \)) gdje plazma teče u suprotnom smjeru od opažača. Nasuprot tome, u dubljim slojevima (\( \log \tau_5 > -1.5 \)) opažana su uzgonska gibanja prema opažaču. Tipična vrijednost \( v_M \) u središtu međugranularnog prostora iznosila je oko 1.7 km s⁻¹, što je za oko 0.5 km s⁻¹ više nego u susjednoj granuli.

Ključne riječi: Sunce - fotosfera - granulacija - međugranularni prostor