ISSN 0351–2657
HOBUD7 23(1) 1 (2004)

VELOCITY FIELD IN INTERGRANULAR ATMOSPHERE

A. KUČERA[1], J. KOZA[1], L.R. BELLOT RUBIO[2], A. HANSLMEIER[3], J. RYBÁK[1] and H. WÖHL[2]

[1]*Astronomical Institute of the Slovak Academy of Sciences, SK-05960 Tatranská Lomnica, Slovak Republic*
[2]*Kiepenheuer-Institut für Sonnenphysik, Schöneckstraße 6, D-79104 Freiburg, Germany*
[3]*Institut für Geophysik, Astrophysik und Meteorologie, Universitätsplatz 5, A-8010 Graz, Austria*

UDC 523.985.3-355
Conference paper
(Received October 25, 1999; accepted November 15, 1999)

Abstract. The line-of-sight velocity $v_{\rm LOS}$ and macroturbulent velocity $v_{\rm MAC}$ are studied in the center of the intergranular space in 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 center. The results are presented in the form of the functional dependence of $v_{\rm LOS}(\log\tau_5,t)$ and $v_{\rm MAC}(t)$ on the continuum optical depth τ_5 at 500 nm and time t. A $v_{\rm LOS}$ 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 directing toward the observer were found in deeper layers ($\log\tau_5 > -1.5$). The typical value of $v_{\rm MAC}$ in the center of the intergranular space is found to be $\sim 1.7\,{\rm km\,s^{-1}}$, which is about $0.5\,{\rm km\,s^{-1}}$ 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 $100\,\mathrm{m\,s^{-1}}$ (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.* Espagnet *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_{LOS} in the center 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_{MAC} in the center 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 center of the selected GR at ~ 5 arcsec and IG at ~ 7 arcsec (see Figure 1 in Paper III) were analyzed 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 λ_{S} of these lines were adopted from an FTS atlas (Neckel, 1999). The laboratory wavelengths λ_{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 $\Delta\lambda = \lambda_{\rm S} - \lambda_{\rm lab}$.

The inversion provided the stratification of temperature T and $v_{\rm LOS}$ throughout the atmosphere. It also returned $v_{\rm MAC}$ 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 center of IG. The typical discrepancies between synthetic and observed line profile intensities were smaller than 4%.

Figure 1 shows two instantaneous models of $v_{\rm LOS}$ in the center of IG corresponding to the beginning ($t = 0$ min) and the end ($t = 4$ 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 $v_{\rm LOS}$ indicates flows away from the observer (downflow) and negative $v_{\rm LOS}$ indicates flows toward the observer (upflow). Our results reveal that $v_{\rm LOS}$ 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 $\Delta v_{\rm LOS}$ with respect to the first model at $t = 0$ min (hereafter *reference model*) at selected layers. At a given time t and optical depth $\log\tau_5$, the velocity differences are computed as:

$$\Delta v_{\rm LOS}(\log\tau_5, t) = v_{\rm LOS}(\log\tau_5, t) - v_{\rm LOS}(\log\tau_5, t = 0) \qquad (1)$$

Figures 1 and 2 enable to estimate the value of $v_{\rm LOS}$ at an arbitrary time and optical depth. Figure 2 indicates weak oscillatory and evolutionary variations of $\Delta v_{\rm LOS}$. In the lower layers ($\log\tau_5 \in \langle -0.5, -1.5\rangle$) the $v_{\rm LOS}$ was typically greater than in the *reference model* at $t = 0$ 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 $v_{\rm LOS}$ are noticeable between 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 $t = 0.2$ min to $t = 3$ min.

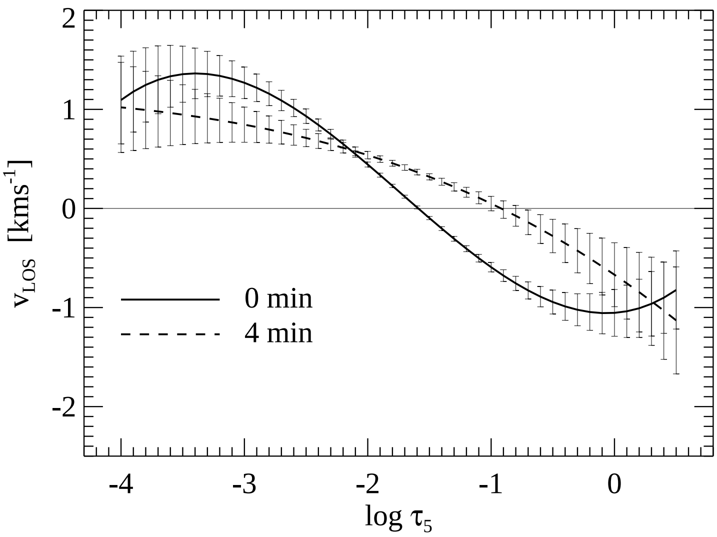

Figure 1: Line-of-sight velocity stratification in the intergranular space center at $t = 0$ min (dashed – *reference model*) and $t = 4$ min (dotted). Positive $v_{\rm LOS}$ indicates downflows and negative $v_{\rm LOS}$, upflows. The velocity has been corrected for gravitational redshift by subtracting of $636\,{\rm m\,s^{-1}}$.

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

4. Discussion

The goal of our study was a modeling of the temporal evolution of $v_{\rm LOS}$ and $v_{\rm MAC}$ in the intergranular space center 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 $v_{\rm LOS}$ values of the order $100\,{\rm m\,s^{-1}}$ and the plasma receded from the observer (see

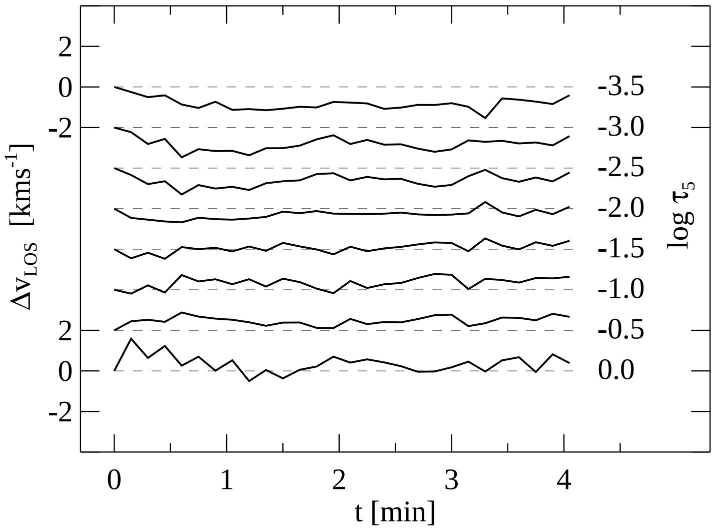

Figure 2: Evolution of the line-of-sight velocity differences $\Delta v_{\rm LOS}(\log\tau_5, t)$ with respect to the *reference model* $v_{\rm LOS}(\log\tau_5, t=0)$ which is represented by horizontal dashed lines at indicated optical depths.

Figures 1 and 2). In turn, we found a plasma upflow in the lower layers ($\log\tau_5 > -1.5$). This non-typical behavior of $v_{\rm LOS}$ 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 center 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 $v_{\rm LOS}$ 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

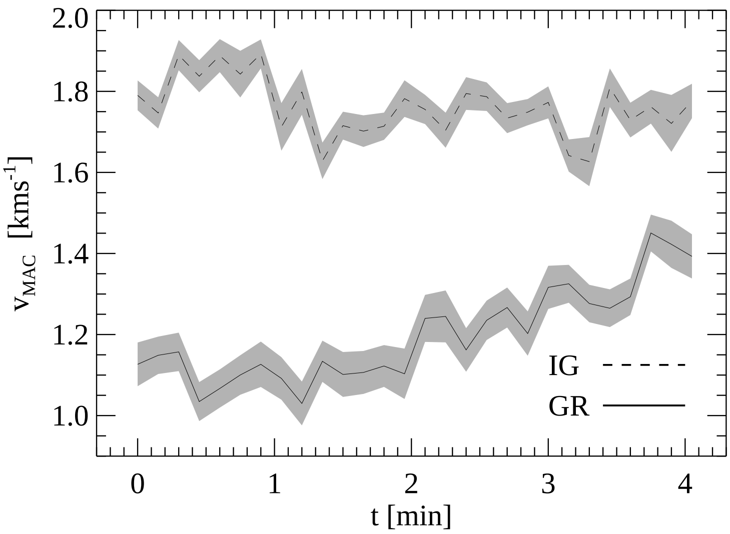

Figure 3: Evolution of the macroturbulent velocity $v_{\rm MAC}$ in the center of granule (solid) and intergranular space (dashed).

$\log \tau_5 = -3$ 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 $v_{\rm MAC}$ 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 $v_{\rm MAC}$ into 1D stellar atmosphere analyse is necessary to account for missing line broadening mechanisms (*i.e.* representation of real velocity field), limited spatial resolution and some other phenomena hampering observations (stray light, instrumental degradation *etc.*). We conclude that the inferred values of $v_{\rm MAC}$ are those needed for additional broadening of synthetic line-profiles to compensate the line profiles degradation induced by seeing, spectrograph and limited spatial resolution.

Acknowledgements

This research is part of the European Solar Magnetism Network (EC/RTN contract HPRN-CT-2002-00313). J.K. is very grateful to IAC for substantial support provided in summer 2001. A. H. thanks the "Austrian Fonds zur Förderung der wissenschaflichen Forschung" for support. A. H., A. K. and J. R. thank the Slovak Academy of Sciences and Austrian Academy of Sciences for support. This work was supported by GA SAV (grant VEGA 2/3015/23).

References

Asplund, M., Nordlund, A., Trampedach, R., Allende Prieto, C., Stein, R.F.: 2000, *A&A* **359**, 729

Domínguez Cerdeña, I., Sánchez Almeida, J., Kneer, F.: 2003, *A&A* **407**, 741

Espagnet, O., Muller, R., Roudier, Th., Mein, P., Mein, N., Malherbe, J.M.: 1996, *A&A* **313**, 297

Gingerich, O., Noyes, R.W., Kalkofen W., Cuny, Y.: 1971, *Sol. Phys.* **18**, 347

Kostyk, R.: 2003, private communication

Koza, J., Bellot Rubio, L.R., Kučera, A., Hanslmeier, A., Rybák, J., Wöhl, H.: 2002a, in: Proc. Euroconference and IAU Coll. 188 *Magnetic Coupling of the Solar Atmosphere*, ed. H. Sawaya-Lacosta, ESA-SP 505, 457, **(Paper I)**

Koza, J., Bellot Rubio, L.R., Kučera, A., Hanslmeier, A., Rybák, J., Wöhl, H.: 2002b, in: Proc. 10^{th} European Solar Physics Meeting: *Solar Variability: From Core to Outer Frontiers*, ed. A. Wilson, ESA-SP 506, 443, **(Paper II)**

Koza, J., Bellot Rubio, L.R., Kučera, A., Hanslmeier, A., Rybák, J., Wöhl, H.: 2003, *Astron. Nachr.* **324**, No. 4, 349, **(Paper III)**

Kučera, A., Rybák, J., Hanslmeier, A., Wöhl, H.: 2003, *Hvar Obs. Bull.* **27**, 25

Nave, G., Johansson, S., Learner, R.C.M., Thorne, A.P., Brault, J.W.: 1994, *ApJS* **94**, 221

Neckel, H.: 1999, *Sol.Phys.* **184**, 421

Rodríguez Hidalgo, I., Ruiz Cobo, B., del Toro Iniesta, J.C., Collados, M., Sánchez Almeida, J. 1995, in: JOSO Annual Report 1995, ed. M. Saniga, Astronomical Institute, Tatranská Lomnica, The Slovak Republic

Ruiz Cobo, B., del Toro Iniesta, J.C.: 1992, *ApJ* **398**, 375

Stein, R.F. a Nordlund, Å.: 1998, *ApJ* **499**, 914

Steiner, O., Grossmann-Doerth, U., Knölker, M., Schüssler, M.: 1998, *ApJ* **495**, 468