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LETTER

Letter to the Editor

Dependence of the photospheric vertical flow characteristics on the granule dimension*

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Abstract. The first high spectral resolution and white–light images obtained at the THEMIS telescope with the Italian Panoramic Monochromator (IPM), are analyzed to study intensity and velocity fluctuations in the photosphere of the sun. Monochromatic images, in two spectral ranges around 538.03 nm (C I line) and 557.61 nm (Fe I line), are used to characterize the vertical structure of the photosphere. Granulation cells and granules are obtained by segmentation of white-light images using suitable finding algorithms.

We observe the height dependence of velocity vs. intensity fluctuations, and we found a dependence of velocity and intensity on granule dimension. Our results show that granules increase their intensity with dimension in the lower solar photosphere. In the higher photosphere, on the contrary, the intensity decreases with the dimension.

Key words: Sun: photosphere – Sun: granulation – techniques: image processing

1. Introduction

Small scale motions on the surface of the sun, known as solar granulation, and due to the overshoot of convective elements into the photosphere, yield a pattern of bright granules surrounded by dark intergranular lanes. These motions overturn in about 10 minutes and are roughly 1500 km across. The analysis of the penetration of the granulation into the solar photosphere, and in particular the height dependence of intensity and velocity fields, give us insights about the role of the convective overshoot, the structure of velocity patterns and the generation of 5–minutes oscillation (cf. Nesis et al. 1996).

Moreover, the geometrical approach in the definition of the properties of granules and granular cells (Roudier & Muller 1986, Title et al. 1989, Noever 1994, Hirzberger et al. 1997, Schrijver et al. 1997) and the study of small–scale features (Rast 1995, Roudier et al. 1997, Hoekzema et al. 1998), would be extremely rewarding for the understanding of the physical processes taking place in this region, and to check hydrodynamic models of solar granulation (cf. Gadun & Pikalov 1996, Stein & Nordlund 1998).

Spectroscopy allows us to investigate different layers of the solar photosphere, and in particular two–dimensional techniques can improve the approach to the definition of the dynamics of this atmospheric region.

In this work we analyze intensity and velocity properties of the solar photosphere in relation to continuum structures. We extract from white–light (WL) images the granules and the granulation cells (Florio & Berrilli 1998) to investigate co-located intensity and velocity fluctuations in the lower and higher photosphere.

2. Observations and image processing

The monochromatic and simultaneous WL images (48 series) were acquired with the IPM (Cavallini 1998) at the THEMIS telescope (Teide, Tenerife) on August 20, 1997. The sequence consists of about 1h time series (between 7:21 and 8:24 U.T.) and refers to a quiet solar region at disk center. The telescope set-up limited the image quality to about 0.7 arcsec.

Two 512×512 CCD cameras (Berrilli et al. 1997), binned to 256×256, were used to record images with an exposure time of 200 ms. The image scale was 0.134 arcsec/pixel, for a total field of view (FoV) of about 34×34 arcsec. This FoV was reduced to 25×25 arcsec because of the telescope tracking loss.

The 48 series of monochromatic images refer to 7 and 9 spectral points, with a bandwidth of about 2.1 pm, respectively

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* Based on THEMIS/CNRS-INSU/CNR telescope observations

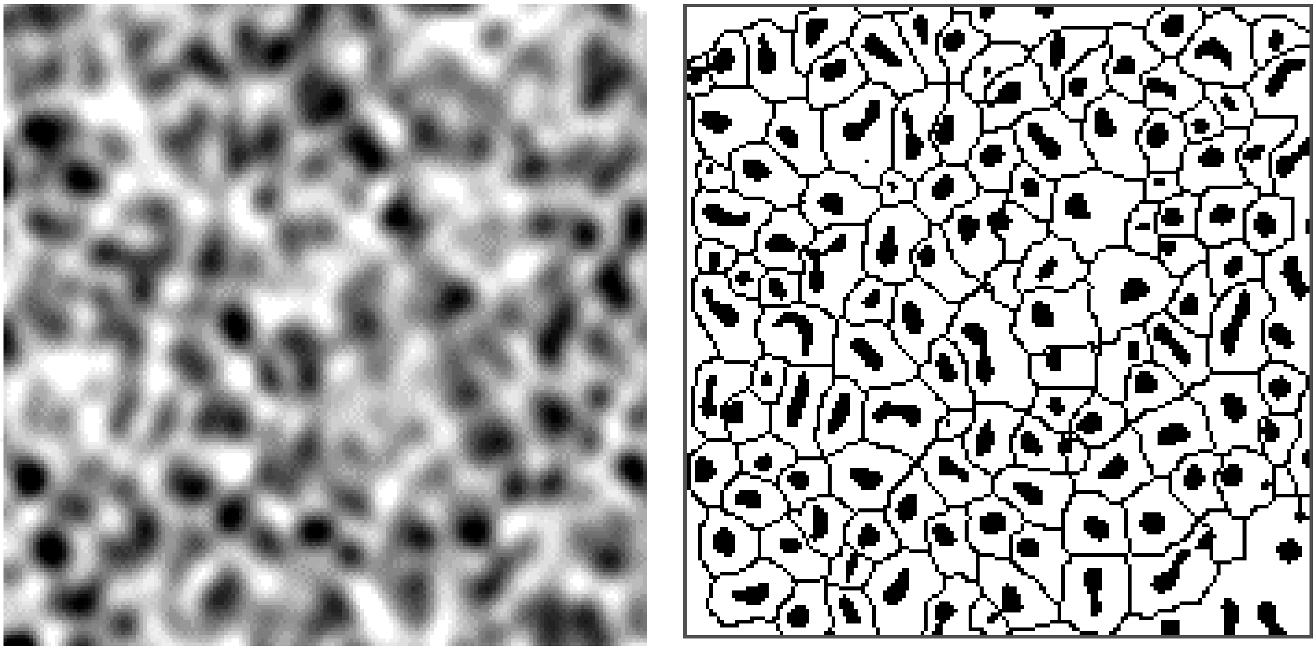

Fig. 1. Granulation field (34 square arcsec). *Left Panel:* Wiener filtered WL negative image of 07:42:49 U.T. August 20, 1997. *Right Panel:* The skeleton defining the cell boundaries (lines), and the binary field defining the granules (spots) corresponding to the same WL image.

within the C I 538.03 nm and Fe I 557.61 nm photospheric lines and near continua. The C line images represent the lower photosphere ($\simeq$ 60 km) while the Fe line images represent the higher photosphere ($\simeq$ 370 km) above $\tau = 1$, as reported in Komm et al. (1991). The time separation between two subsequent images was about 2.5 s.

After the standard corrections for atmospheric transparence variations, dark current and flat field, we applied a "phase opposition" filter (Espagnet et al., 1993) to remove the 5–minute acoustic waves (p-modes) and separate granular and oscillatory fluctuations. The telescope tracking failure, occurred during the observations, does not allow us the use of a more sophisticated filter.

From any cube of corrected monochromatic images we produce a cube of line–profiles using a Lorentz–profile fit. To measure the radial velocities we derive, from pixel by pixel fitted lines, a center line intensity image and a corresponding velocity field. Selecting the frames acquired during the best seeing intervals we derive four center line images, and the corresponding velocity fields, both for C and Fe lines.

A Wiener filter is applied to the WL images, contemporaneous to the Fe and C intensity and velocity frames, in order to correct the degradation (i.e. blur) due to instrumental transfer function, and to reduce the noise (Fig. 1, left). In the parametric Wiener filter we use a gaussian, with σ = 0.4 arcsec, as point spread function and we set the signal–to–noise ratio to a value of 15.

After all the corrections, we apply a finding process to WL image to calculate geometrical properties of granules and cells, the latter being defined as containing both a granule (or more) and its corresponding part of the intergranular lane. We extract (Fig. 1, right) the skeleton of dark intergranular lanes and assume this one as definition of cell boundaries (Berrilli et al., 1998). The granules (Fig. 1, right) are identified using a dynamical threshold (Florio & Berrilli, 1998).

3. Height dependence of intensity and velocity fields

There are good reasons to think that the granules present convective characteristics, if we consider the convection in terms of upflows and downflows. The upward moving fluid diverges and overturns as it rises into lower density layers. The ascending fluid that reaches the surface radiates its energy and produces higher density material that is pulled down by gravity (cf. Stein & Nordlund, 1998).

To study the velocity and intensity fluctuations associated to WL cell boundaries and granules, we superimpose these "zero" level features to C and Fe velocity and line center intensity frames.

We observe that the relation between the vertical velocity and the brightness is reversed passing from the lower photosphere (Fig. 2) to the upper photosphere (Fig. 3). In the lower layers we calculate a mean velocity $< V_g >$=–171 m s^{-1} for granules, and a mean velocity $< V_{cb} >$=+57 m s^{-1}, for cell boundaries. The rms is approximately the same and it is of the order of 300 m s^{-1}. In the upper layers we found $< V_g >$=–93 m s^{-1} and $< V_{cb} >$=+81 m s^{-1}, the rms is about 190 m s^{-1}. The observed peak-to-peak amplitude of the velocity is of about 2 km s^{-1} in the lower layers, and it is of about 1 km s^{-1} in the upper layers. This result is related to the decrease of the velocity amplitudes with height (cf. Stein & Nordlund 1998).

The distribution of mean granular intensities (Fig. 4) shows an asymmetric shape, for lower layers, that disappears when we go up of about 300 km. A similar asymmetry is reported, for

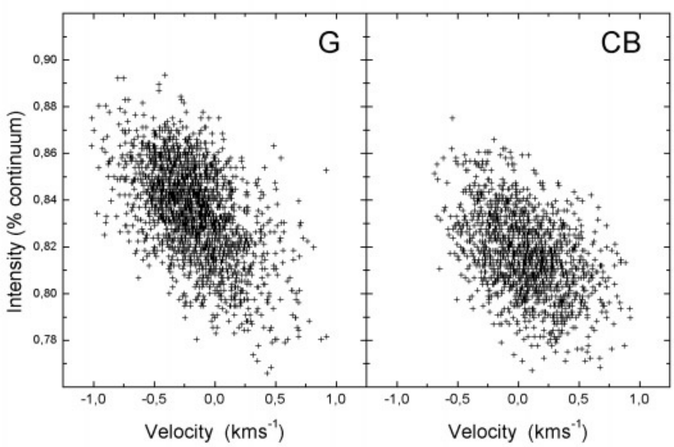

Fig. 2. Scatter plot of center line intensities and velocities derived from C I 538.03 nm frames. Upflows have negative velocity to respect to the mean that is set to zero. In the *left panel* we report the values of intensities and velocities associated to pixels belonging to granules (G). In the right panel we report values relative to pixels belonging to granular cell boundaries (CB).

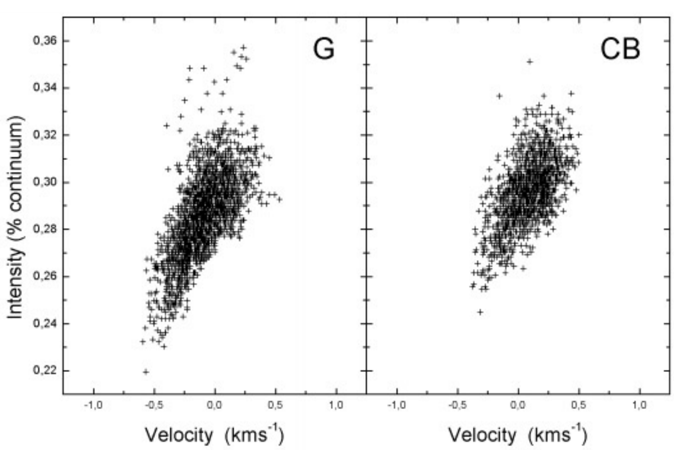

Fig. 3. Scatter plot of center line intensities and velocities as derived from Fe I 557.61 nm frames. The meaning of the panels is the same as in Fig. 2.

maximum granular intensities in WL images, by Hirzberger et al. (1997). In the upper layers the intensity of granules spreads, because of diverging horizontal motions, producing a more uniform bright distribution.

4. Vertical flow characteristics and granule dimension

It is well established that photospheric features observed in white light images are associated with photospheric velocity field. Nevertheless, this simple picture thickens when we cross the over–shooting region (cf. Nesis et al. 1997, Espagnet et al. 1995). In the previous section we showed the transition from a velocity–intensity negative correlation to a positive one when we go up in height. Moreover we can expect a further dependence of velocity and temperature (intensity) fluctuations on granule dimension, and this dependence can change with height (Steffen et al., 1989). Some experimental evidence derives from

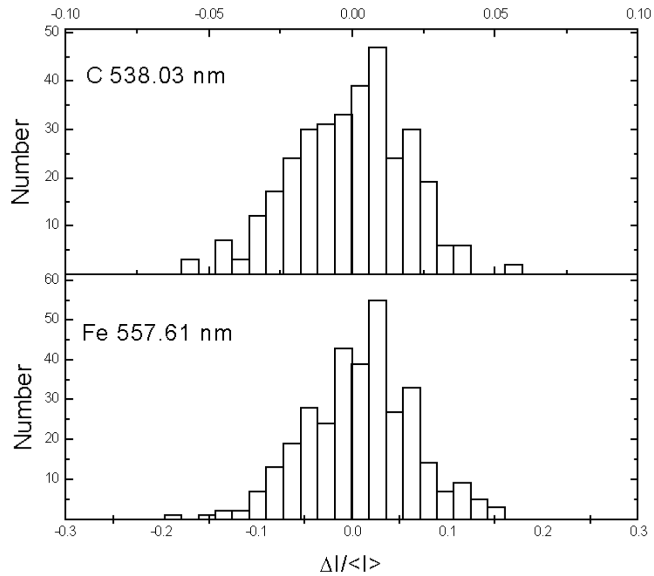

Fig. 4. Distribution of granule intensity fluctuations with respect to the mean granule intensity, for the C line core (*upper panel*) and Fe line core (*lower panel*).

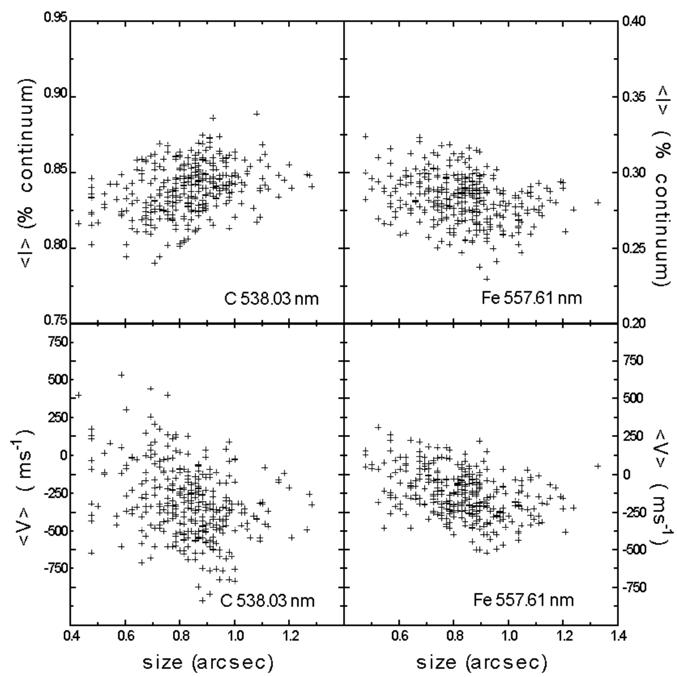

Fig. 5. In the upper panels we report the center line mean intensities of granules against their size (diameter of the circle of same area) for C (*left box*) and Fe (*right box*) lines. In the lower panels we report the mean velocities of granules against granule sizes for C (*left box*) and Fe (*right box*) lines.

the analysis of spectrograms (Wiehr & Kneer, 1988) or from the analysis of WL images (Hirzberger et al., 1997). To study the characteristics of vertical flow in regard to the granule dimension we plot mean velocities and intensities with respect to the area of associated "zero" level granules. We use over 400 identified granules whose sizes are in the range 0.4–1.3 arcsec.

As it is shown in Fig. 5 (lower panels), we observe that the upflow velocities (negative) of the granules increase with granule size both for C and Fe lines.

Instead, the intensity fluctuations of the granules show different behaviors at the two considered levels (Fig. 5, upper panels). In fact, for thermodynamic reasons, we expect that temperature fluctuations of granules have different sign in the lower and upper layers. Near the basis of the photosphere granules are hotter (brighter) with respect to the surroundings, and the fluctuations increase with their dimensions. Large elements result brighter than smaller ones because they extend deeper into the convection zone, and have less radiative loss in the horizontal direction (Steffen et al., 1989). In the upper photosphere (overshooting region) fluctuations change in sign, a super-cooling effect and a smaller radiative losses produce a negative correlation between temperature (i.e. intensity) and granule sizes.

We have presented preliminary results showing that the dynamical and thermodynamic properties of the observed photospheric structures depend on their vertical position and horizontal scale. This is due to the convective overshooting into stable atmospheric layers.

We are extending this analysis to a larger sample of images obtained in a recent observation campaign with the IPM. With the new data base, including also images obtained in the Na D I and Mg I b_1 lines, we will explore more carefully the height dependence, the magnetic field effects and the time evolution of photospheric structures.

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