FINE STRUCTURE OF CONVECTIVE MOTIONS IN THE SOLAR PHOTOSPHERE

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The granulation brightnesses and convective velocities in the solar photosphere between the levels of formation of the continuum radiation and the temperature minimum are examined. The properties of the brightness and velocity are analysed in a sixteen-column model. Four sorts of motions are most typical and efficient. In the first two, only the sign of the relative contrast of the material changes, which occurs, on the average, at a height of 270 km. In the last two motions, both the sign of the contrast and the direction of the motions are reversed near ∼350 km. The convective motions maintain their column structure throughout the photosphere, right to the temperature minimum.

INTRODUCTION

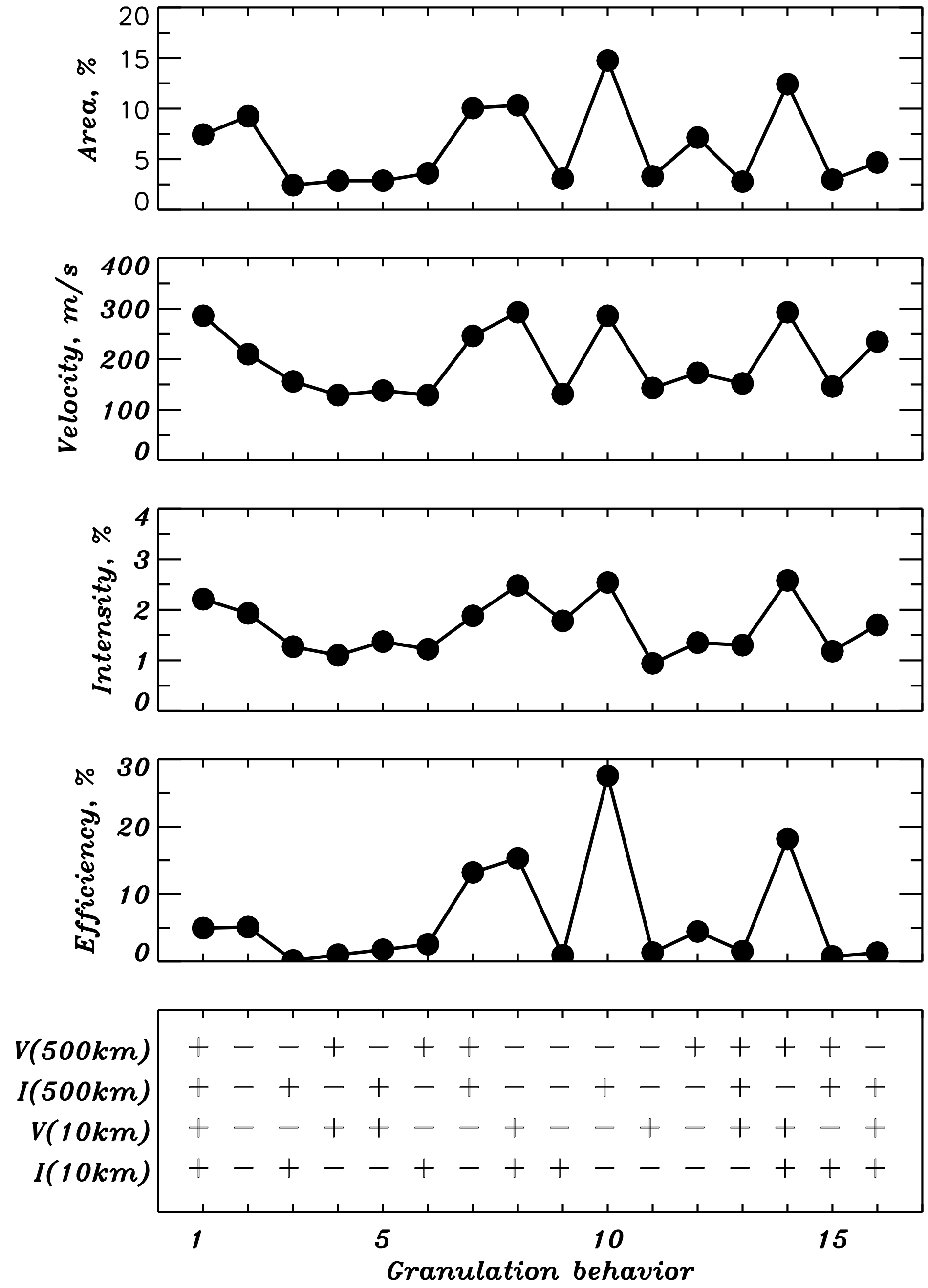
Numerous researchers studied intensities and velocities of motions in the photosphere, using various instruments and applying various data-processing techniques and interpretations. In all these studies the complex intensities and velocities of the motions were analysed with the help of a very simple two-column model. Here, we consider more complicated sixteen-column model. Our study is based on the data obtained with high spatial and temporal resolutions.

OBSERVATIONAL DATA

We used spectrograms with high spatial ($0.5''$) and temporal (9 s) resolutions obtained in 1996 and 2001 on the German Vacuum Tower Telescope (VTT) in Izana (Tenerife, Spain). Spectral observations of the centre of the solar disc were carried out in an unperturbed region. A CCD camera with 1024×1024 pixels connected in pairs was used. The spatial resolution of a single pair-connected pixel was $0.174''$. The entrance slit of the spectrograph cut off an area of $0.38''\times98''$ on the solar disc. The spectra were recorded for a single point on the solar disc. For the observations in 1996, we chose the Fe I $\lambda\,532.418$ nm line, for which we obtained 31 min recordings. The observations in 2001 were carried out with two cameras, which recorded 158 min of data for the Fe I $\lambda\,639.361$ nm and Fe II $\lambda\,523.462$ nm lines. After the usual preliminary spectral data reduction, we determined the fluctuations in the intensities and velocities of all three lines for each position along the spectrograph slit and for each moment in time at 11 heights in the solar atmosphere using "lambda-meter" technique discussed in detail in [2]. The spatial and temporal variations in the intensities and velocities are due to convective and wave motions. To separate these different types of variations, we constructed a diagnostic diagram that presents the power as a function of the temporal and spatial frequencies. Our further analysis deals only with the convective components. We took motions toward the observer to be positive.

RESULTS OF OBSERVATIONS

If we assume that relatively hot or cool material at two heights $H = 10$ km and $H = 500$ km can move both upward and downward, we find 16 types of convective motions, shown schematically at the bottom of Fig. 1. Ascending material is denoted by a plus sign and descending material by a minus sign. We also used plus and minus signs to denote material whose temperature is higher or lower than the average temperature for a given height. It turns out that all 16 types of convective motions are indeed observed in convective columns on the Sun. The upper plot in Fig. 1 shows the number of cases corresponding to each of 16 convective motions, while the second and third plots from the top show the average absolute values of the velocity and contrast at $H = 10$ km. The fourth plot in Fig. 1 shows a parameter that we have called the "efficiency", and that is the product of five quantities: the number of cases for each type of convective motions, their velocity and intensity with respect to the average values at $H = 10$ km and the same two quantities for $H = 500$ km. This efficiency varies widely, from nearly zero to almost 30%.



V(500km)	+	−	−	+	−	+	+	−	−	−	−	+	+	+	+	−
I(500km)	+	−	+	−	+	−	+	−	−	+	−	−	+	−	+	+
V(10km)	+	−	−	+	+	−	−	+	−	−	+	−	+	+	−	+
I(10km)	+	−	+	−	−	+	−	+	+	−	−	−	−	+	+	+

Figure 1. Motions in the solar atmosphere according to the 16-column model. The upper plot shows the number of cases corresponding to each of 16 types of convective motions. The second and third plots from above show the average absolute values of the velocity V_c and contrast I_c for the motions at $H = 10$ km. The signs of I_c and V_c are shown in the diagram at the bottom of the figure. The fourth plot shows the "efficiency" of the motions, which is the product of five quantities: the number of cases, the velocity and contrast at $H = 10$ km, and the velocity and contrast at $H = 500$ km

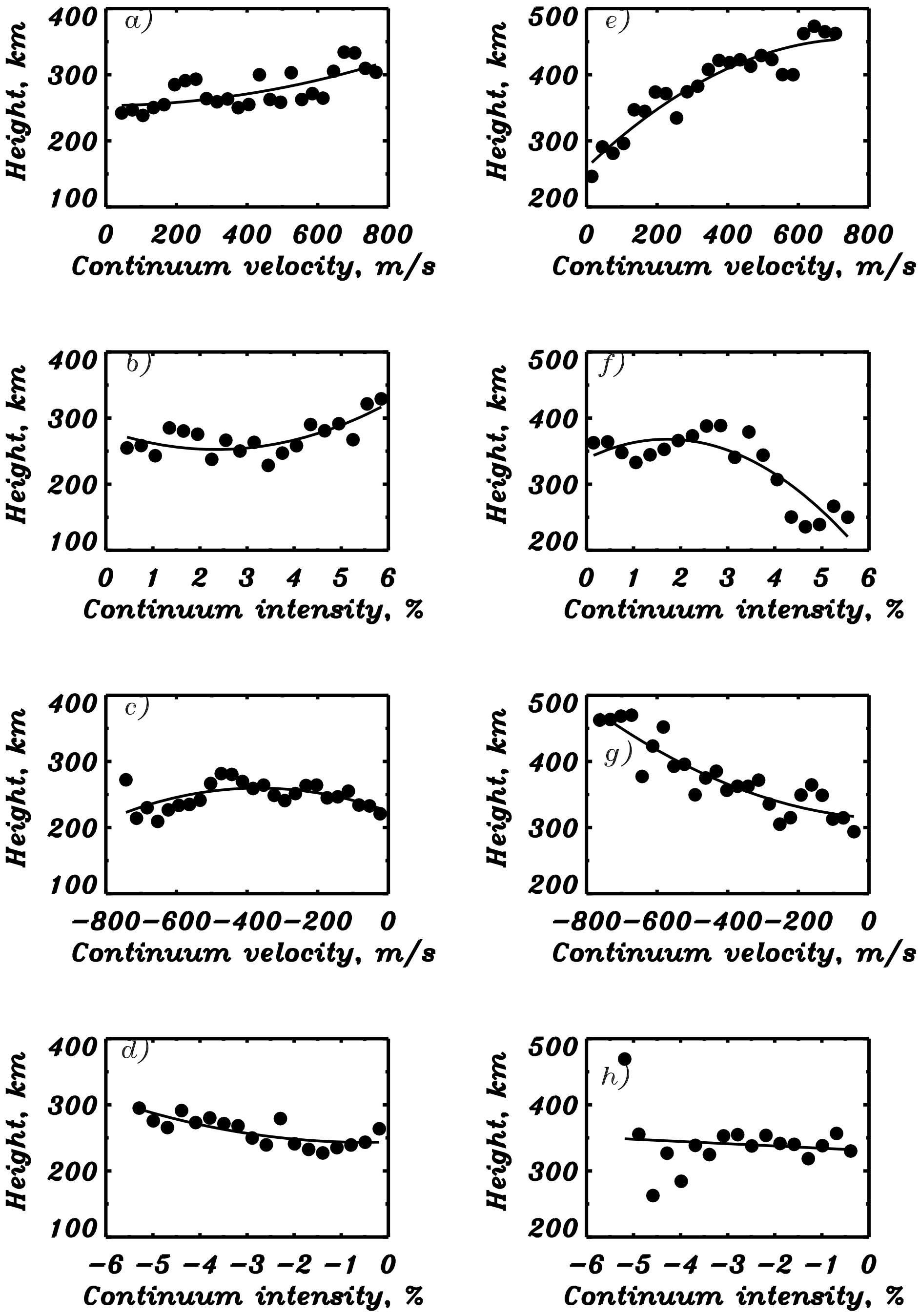


Figure 2. The heights at which ascending material that is hot near the continuum height becomes comparatively cool as a function of continuum velocity (a) and continuum intensity (b). The heights at which descending material that is hot at the temperature minimum becomes comparatively cool as a function of continuum velocity (c) and continuum intensity (d). The heights separating hot ascending material and cool descending material near the continuum height as a function of continuum velocity (e) and continuum intensity (f). The heights separating cool descending material and hot ascending material near the continuum as a function of continuum velocity (g) and continuum intensity (h)

Four types of motions are most efficient. In two of them, the material changes only the sign of its relative contrast, while both the sign of the contrast and the direction of the motion change with height in two others. In detail, these four motions are the following:

- material that is hot at the continuum height and cool at the temperature minimum ascending at all heights in the photosphere (motion 14, with an efficiency of 18%);
- material that is hot at $H = 500$ km and cool at $H = 10$ km descending at all heights (motion 10, 28%);
- hot material ascending at the continuum height and cool material descending at the temperature minimum (motion 8, 15%);
- cool material at $H = 10$ km descending and hot material at $H = 500$ km ascending (motion 7, 13%).

The total efficiency of these four motions is 74%. Thus, we can understand that two-column models for the solar photosphere with hot ascending (motion 1) and cool descending (motion 2) materials cannot explain the observed asymmetry and shifts of the Fraunhofer lines, since the total efficiency of these motions does not exceed 10%. At the same time, the semiempirical four-column model (see [1]), which admits both upward and downward motions of cool and hot materials, can successfully explain almost all features of the fine structure of the absorption lines observed in the solar spectrum, and has predicted some features of the fine structure of the Fraunhofer lines that have been verified by observations.

Let us consider in detail these four most efficient motions. Figure 2 (left panels) presents heights where the material changes the sign of its relative contrast in convective columns with motions 14 and 10. We can see in Fig. 2a and Fig. 2b that the height where ascending (at all heights) material that is hot, near the continuum height becomes cool (motion 14), depends only slightly on the velocity and contrast in the continuum. On the average, this height is $H_{14} = 280 \pm 105$ km. This is also true for descending material; namely, the height where material that is hot, near the temperature minimum becomes cool is almost independent of both velocity and contrast in the continuum. The contrast sign reversals occur, on the average, at $H_{10} = 260 \pm 100$ km.

Figure 2 (right panels) presents the heights in columns with motions 8 and 7, in which there is a sign reversal of both the contrast of the material and the velocity of the convective motions. In contrast to the previous case, the corresponding heights depend significantly on the velocity at the continuum height and, in a less degree, on the contrast in the continuum. Figure 2e shows that the higher the velocity of ascending hot material is, the larger is the height of the sign reversals for the contrast and direction of motion. This height is $H_8 = 360 \pm 130$ km, on the average. We would expect this behaviour based on general reasoning. However, it is difficult to understand the behaviour in Fig. 2f: the lower is the contrast of the granule in the continuum, the larger is the height for the sign reversals of both the direction of motion and the relative contrast of the material. Figures 2g and 2h show the heights of layers separating cool descending material and hot ascending material near the continuum height. These heights depend on velocity at the continuum height, and are virtually independent of the contrast in the continuum.

CONCLUSIONS

There are various combinations of the direction of motion and relative brightness of materials in the solar photosphere. We have analysed 16 cases and shown that four motions are most typical and “efficient”. In the first two cases, the material reverses only the sign of its relative contrast at the mean height $H = 270$ km. In the last two cases, both the sign of the contrast and the direction of the motions are reversed near the height $H = 350$ km. Our study shows that the convective motions maintain their column structure in the lower photosphere right to the height of the temperature minimum.

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