ONE-DIMENSIONAL SPECTROSCOPY OF THE SOLAR PHOTOSPHERE

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Abstract. Data from a time series of spectrograms were used to study correlative relationships between intensity and velocity in the solar photosphere. The variations along the slit of the line parameters from two Fe lines lying in the visible range of the spectrum were used. The formation height difference of these lines is over 300 km. The temporal variations of the correlation coefficients were studied, they showed a strong influence of the 5 min-oscillations.

Key words: Sun: photosphere - Sun: granulation

1. Introduction

A common method to investigate the photospheric structure is the calculation of correlations between characteristic quantities, such as intensity and velocity, in different photospheric heights. A good correlation between continuum intensity and velocity, which decreases with increasing line formation height, was found by Mattig \textit{et al.} (1969), Canfield and Mehltretter (1973), Hanslmeier \textit{et al.} (1990), Komm \textit{et al.} (1990) and Nesis \textit{et al.} (1993). Gadun \textit{et al.} (2000) predicted this result with their model and could confirm it by comparison with observations. They also predicted a decreasing anticorrelation between residual intensity and velocity in the higher photosphere, their observations confirmed this. Canfield and Mehltretter (1973)
also found an inverted correlation of these parameters in the high photosphere. Hanslmeier et al. (1990) and Hanslmeier et al. (2000) studied correlations between velocities depending on the formation height difference. They still found a good correlation even at differences over 300 km.

2. The Data

The data consisted of time series of spectrograms recorded on April 28th 2000 with the German Vacuum Tower Telescope (VTT) at the Observatorio del Teide (Izaña, Tenerife). The recordings were carried out from 09:26:36 to 09:41:36 UT, the target was almost in the centre of the solar disc in the quiet atmosphere near AR 8976. The Adaptive Optics (AO) system of the NSO/SP was allocated on loan for a test deployment at the VTT. The slit width of the Echelle spectrograph was 100 µm, the slit equivalent width 0.5”. The slit was oriented perpendicularly to the horizon. The exposure time was 1 s and the spectra were separated by 3 s. Spatial and spectral samplings were 0.125”/pixel and 2.4096 mÅ/pixel, respectively. The slit-jaw image system was used to record the exact position of the spectrograph slit on the solar disc.

All spectra were then photometrically reduced using the precise reduction procedure of Wöhl et al. (2002). High frequency noise was removed by Gaussian filtering (Gray, 1976), the centre-to-limb darkening was removed, and the spectra were normalized. The spectral line parameters were then calculated, such as the continuum intensity, the residual intensity and the Doppler velocity.

Several Fe lines in the visible range of the spectrum were chosen, here the Fe II line at 4993.358 Å and the nearby Fe I line at 4994.129 Å are used. Some estimated line formation heights and the line’s equivalent widths are collected in Table I. The parameters given are the effective heights of line formation for the line central depth $Hd$ calculated with the depression contribution function and the geometrical height $Htau$ at line centre optical depth $\tau_{X0} = \tau_{X0}^{C+L} = 1.0$. They were obtained using two different atmospheric models: with the MACKKL model (Maltby et al., 1986) and with a 1-D model which was obtained by spatial and temporal averaging of the 2-D models. 2-D models do not consider the chromospheric growth of temperature though, so they can produce wrong formation heights for some lines.
Table I: Estimated line formation heights in km obtained with two models.

<table>
<thead>
<tr>
<th>Eq. width / mA</th>
<th>Fe II</th>
<th>Fe I</th>
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<tbody>
<tr>
<td>(Hd) (MAC)</td>
<td>38.500</td>
<td>105.000</td>
</tr>
<tr>
<td>(Htau) (MAC)</td>
<td>165.9</td>
<td>475.8</td>
</tr>
<tr>
<td>(Hd) (2-D)</td>
<td>108.9</td>
<td>472.2</td>
</tr>
<tr>
<td>(Htau) (2-D)</td>
<td>127.1</td>
<td>392.2</td>
</tr>
<tr>
<td></td>
<td>77.2</td>
<td>449.5</td>
</tr>
</tbody>
</table>

3. Results

The data used here do not consist of the actual two-dimensional spectrograms, but of the one-dimensional variations of the various line parameters along the slit. The line parameters continuum intensity \(I_c\), residual intensity \(I_r\) and Doppler velocity \(v\) are investigated. The velocity is given in \(\text{km s}^{-1}\), positive values for upflows and negative values for downflows are used. The index 1 corresponds to the Fe II line and the index 2 to the Fe I line, respectively. For the next sections, 950 values in spatial (\(\sim 120''\) on the disc) and 300 in temporal direction (15 min) are used.

3.1. Temporal Variation of Correlation Coefficients

The main idea was to study the temporal changes of the correlation between different line parameters. Therefore, the correlation coefficients of the parameter variations have been calculated for each spectrum and were then aligned along the time axis.

Figure 1 shows the variation of the correlation between the residual intensities (solid line) and the velocities (dotted line), respectively. Although the lines are formed in atmospheric layers separated by more than 300 km, both correlations are quite good and fluctuate about a mean value of 0.6. Both correlations fluctuate due to the 5 min-oscillations, the amplitude of the velocity correlation is larger. The maxima of the \(I_r\)-correlation do not always occur at the same times as the maxima of the velocity correlation.

The variation of the correlation between \(I_c\) and velocity is displayed in Figures 2 and 3. The correlation for the Fe II line is positive and shows quite large fluctuations about a mean value of 0.6. The same correlation for the Fe I line shows similar variations with time, though the mean correlation
Figure 1: The temporal variation of the correlation between $I_{r1}$ and $I_{r2}$ (solid), and between $v_1$ and $v_2$ (dotted).

The coefficient is much lower. The large fluctuations in Figure 2 are due to the 5 min-oscillations. The Fe I line shows oscillations with shorter periods, because the frequency changes from the photosphere to the chromosphere.

The correlation between $I_r$ and respective velocity show a similar temporal behaviour (Figures 4 and 5). For Fe II, there is a low anticorrelation, the coefficient fluctuates about $-0.35$. For the Fe I line, the coefficient fluctuates about zero, the curve’s maxima are positive. Again the influence of the 5 min-oscillations is clearly visible.

3.2. MEAN CORRELATION COEFFICIENTS

Table II shows the averaged correlation coefficients over all 300 spectra. As can be seen from the previous figures, these mean values are not capable of representing the real physical situation. The correlation between line parameters can fluctuate strongly with amplitudes of over 0.4 during a time series. The strong influence which the the 5 min-oscillations have on the correlation coefficients has to be taken into account.
Figure 2: The temporal variation of the correlation between $I_c$ and $v_1$.

Figure 3: The temporal variation of the correlation between $I_c$ and $v_2$. 
Figure 4: The temporal variation of the correlation between $I_{r1}$ and $v_1$.

Figure 5: The temporal variation of the correlation between $I_{r2}$ and $v_2$. 
Table II: Mean correlation coefficients.

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<tbody>
<tr>
<td>$&lt; I_c, v_1 &gt;$</td>
<td>$0.63 \pm 0.07$</td>
</tr>
<tr>
<td>$&lt; I_c, v_2 &gt;$</td>
<td>$0.16 \pm 0.11$</td>
</tr>
<tr>
<td>$&lt; I_{r1}, v_1 &gt;$</td>
<td>$-0.36 \pm 0.08$</td>
</tr>
<tr>
<td>$&lt; I_{r2}, v_2 &gt;$</td>
<td>$-0.05 \pm 0.16$</td>
</tr>
<tr>
<td>$&lt; I_{r1}, I_{r2} &gt;$</td>
<td>$0.59 \pm 0.05$</td>
</tr>
<tr>
<td>$&lt; v_1, v_2 &gt;$</td>
<td>$0.57 \pm 0.09$</td>
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4. Discussion

The resulting mean correlation coefficients correspond well to the findings in the literature. The correlation between $I_c$ and velocity is good for the low to mid-photosphere and decreases with height. This decrease shows that the intensity fluctuations (and therefore the temperature fluctuations) become less coupled with height, in the upper photosphere the material is not necessarily ascending above the bright granules. The good, but not perfect correlation in the lower photosphere indicates the asymmetry of the the granular flow (Nesis et al., 1993). They found that the intensity maxima do not coincide with the velocity maxima. The good correlation of about 0.6 which decreases with height was also found by Mattig et al. (1969), Canfield and Mehtlretter (1973), Hanslmeier et al. (1990) and Komm et al. (1990), to name a few. Gadun et al. (2000) compared theoretically derived correlations with data from observations. Their model predicts a decrease of the correlation between $I_c$ and velocity with height, which is also confirmed by their observations. The correlation between $I_r$ and velocity is predicted to be positive in the low photosphere, decrease steeply with height and become negative in the mid-photosphere, and then show decreasing anticorrelation in the upper regions. Their observations confirmed the decrease of anticorrelation in higher regions, which is also found in here. Hanslmeier et al. (1990) calculated correlations between the line centre velocities depending on the height difference. For height differences larger than 300 km, they found values of about 0.65, which is in accordance with the results presented in here. Hanslmeier et al. (2000) again studied the correlation between velocities of different lines. They found a linear decrease with increasing height difference. Their largest height difference is 250 km, and the correlation is still about 0.76. For $I_r$, they also found a high value of 0.7 at
this height difference.

References

JEDNODIMENZIONALNA SPEKTROSKOPIJA
SUNČEVE FOTOSFERE

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Izlaganje sa znanstvenog skupa

Sažetak. Pomoću serija spektrograma istražuju se korelativne sveze intenziteta i brzina u Sunčevoj fotosferi. Korištene su promjene parametara dvaju spektralnih linija željeza koje se nalaze u vidljivom dijelu spektra uzduž pukotine spektrograфа. Razlika u visini nastajanja tih dvaju linija iznosi preko 300 km. Istražene vremenske varijacije koeficijenata korelacije pokazuju snažan utjecaj 5 minutnih oscilacija.

Ključne riječi: Sunce: fotosfera - Sunce: granulacija