INVESTIGATING THE VERTICAL STRUCTURE OF THE SOLAR GRANULATION WITH THE SODIUM D \textsubscript{2} LINE

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ABSTRACT

We present a method to estimate temperature and velocity at different heights in the solar photosphere from fluctuations of intensity and Doppler velocity measured at several positions in the sodium D\textsubscript{2} line profile. Line intensity variations due to small perturbations of temperature and velocity occurring at particular depths in the atmosphere were investigated with the non-LTE radiative transfer code MULTI. The result was used to calculate so-called response functions. As an example we present an application of our method to solar granulation data obtained with MSDP spectroscopy.

The granulation fluctuations (intensity, dynamics) over the solar cycle may reflect a probable interaction between the convection zone and the magnetic field at the global scale of the Sun or possibly to a local interaction between granules and magnetic flux tubes. The variation of the solar granulation, and more particularly of the exploding granule dynamics, provides a direct insight into the change of physical properties in the upper convection zone.

1. INTRODUCTION

Multichannel Subtractive Double Pass (MSDP) spectrograms allow to measure the profile of one or several spectral lines at every point in the two-dimensional field of view. Observed line profiles result from the relative, wavelength-dependent contributions of different atmospheric layers. If those contributions are well determined, one can then in principle extract information on the variation with depth of physical conditions from fluctuations of intensity and velocity measured at different parts of the profile.

The NaID resonance doublet (5890,5896 Å) is particularly interesting for photospheric diagnostics since its extended wings allow to obtain information from a wide range of heights in the solar photosphere. A method to estimate the vertical structure of temperature and velocity from the observed profiles of the D lines have been developed. In this poster we present main results concerning the D\textsubscript{2} line using an example with solar granulation data.

High-spatial resolution images of the solar surface in the visible part of the spectrum show granulation as a continually changing cellular pattern. Nowadays, granulation is known to originate from convection in the photosphere and its basic properties are quite well understood. Numerous works at present are devoted to obtain quantitative information about the dynamical and thermal structure of granules, taking advantage from latest advances in solar instrumentation. Results are of great interest for evaluation of theoretical models of solar granulation.

2. METHOD

The sensitivity of the NaID D\textsubscript{2} line profile to fluctuations of temperature and velocity at different layers was investigated through the numerical calculation of theoretical profiles with the non-LTE radiative transfer code MULTI (Carlsson 1986). We used the VAL C (Vernazza et al. 1981) mean quiet-sun model atmosphere as a reference, which was then perturbed by introducing small amplitude disturbances of temperature and velocity. Resulting profiles led to the calculation of so-called Response Functions (hereafter, RFs). RFs describe the effect that perturbations of a given physical parameter have in the emergent line intensity. They were first defined by Mein (1971) and have since then become extensively used in inversion techniques (Beckers & Milkey 1975; Canfield 1976; Caccin et al. 1977; Ruiz Cobo & del Toro Iniesta 1992; Bellot Rubio et al. 1997). RFs of the D\textsubscript{2} line have been obtained before for temperature and pressure fluctuations under LTE conditions (Kneer & Nolte 1994, Krieg et al. 1999).

Temperature and Velocity RFs of the D\textsubscript{2} line profile calculated as explained above are shown in Figure 1. The wavelength scale in the x axis covers only one side of the profile, for the sake of clarity. But one should keep in mind that RFs are symmetric with respect to the axis...
\[ \Delta \lambda = 0. \] The depth scale (axis $y$) is given in $\log m$ units, where $m$ is the column mass in $g/cm^2$. In general, velocity RFs (RF$_v$) are seen to extend over a wider range of heights than temperature RFs (RF$_T$). With RF$_v$, one can obtain information for heights up to $\log m \sim -2.8$ (geometrical height of 900 km) whereas RF$_T$ become negligible above $\log m = -2$ ($\sim 650$ km). The maximum contribution is found for $\Delta \lambda = 0.108 \, \AA$ at heights close to $\log m = -0.5$ ($\sim 290$ km).

The mapping between given wavelength positions in the $D_2$ line profile and atmospheric height levels is then established through the barycenters of the RFs obtained for those wavelengths. The method performance has been tested with several theoretical models of perturbations and non-linear effects have been investigated. The agreement is good provided that perturbations are small as it is required for a linear treatment to be valid. A more detailed description will be published in a future paper.

3. ANALYSIS OF DATA

Analysis of solar granulation data with the RFs presented above allowed to recover information about the evolution of exploding granules through the photosphere. A complete investigation was carried out by Roudier et al. (2000) and Espagnet et al. (1995). For a more detailed description we refer the reader to those works.

The time series consists of 64 2D spectrograms in the NaI $D_2$ line covering a quiet area of the solar surface. The effective field of view after images processing is $172'' \times 8''$. The total duration of the sequence is 16 min, with consecutive frames separated by 15 s. The 5-min oscillations were filtered out as part of the reduction process.

We present results from the most representative example among the nine exploding granules that were detected in the field of view. Observations allowed to trace them during most of their lifetime. Intensity and Doppler velocity fluctuations for every point of the field were calculated at ten different positions in the $D_2$ line profile, as described in Espagnet et al. (1995). An example of the two-dimensional maps for intensity and velocity fluctuations obtained at $\Delta \lambda = 0.144 \, \AA$ and $\Delta \lambda = 0.288 \, \AA$, respectively, is shown in Figure 2. RFs for these wavelengths yield as most representative heights those of 202 km in the case of temperature (intensity) and 170 km in the case of velocity. Brightest and darkest areas in the velocity frames correspond to Doppler velocities of -0.7 and 0.6 $km/s^{-1}$, respectively. We have applied the method described above to derive the height variation of local disturbances of temperature and velocity in the photosphere.
at every time during the series.

The height variation of temperature fluctuations derived for selected frames during the sequence is shown in Figure 3 (left panel). An absolute maximum of $\Delta T/T$ is always found in the low photosphere, followed by an approximately linear decrease with height in the immediate overlying layers up to $\sim 175$ km. The maximum amplitude as well as the slope (absolute value) of the following decay are seen to increase progressively before the explosion. Approximately 1 min after the explosion the absolute maximum is reduced by half. A reversal of temperature is clearly seen at about 150 km in the atmosphere all the time before explosion. After explosion, $\Delta T/T$ remains negative at almost all heights.

The temporal evolution of velocity at different heights can be seen in Figure 3 (right panel). Contrary to what is found for temperature fluctuations, the height variation of velocity in the low photosphere would not be consistent with a linear model of perturbations. The largest velocity perturbations tend to occur at heights around 150 km in the mean photosphere during the entire lifetime of the granule. Decay after maximum is generally smoother than in the case of temperature. Only around explosion time we see a sharper decrease of velocity with height in the immediate layers above maximum. On the other hand, velocity disturbances are always positive. By the time of explosion the absolute maximum shows an increase of 70% over its initial value. After a time interval of 4.5 min, the maximum amplitude goes back to half its value. Effects in the velocity structure due to granule explosion seem to persist for a longer time than they are seen in temperature.

4. CONCLUSIONS

In this work we have calculated Response Functions of the NaD$_2$ resonance line profile to temperature and velocity disturbances in the solar photosphere. It is found that they probe quite different layers in the atmosphere, with $RF_T$ extending over larger heights than $RF_V$. On this basis we have developed a method to estimate the vertical structure of temperature and velocity from the observed D$_2$ line intensity at several wavelengths.

By way of illustration, we used an example with a time series of MSDP spectrograms to study the height variation of solar granulation. The temporal evolution of exploding granules in temperature and velocity was investigated. We conclude that granulation velocities are seen to penetrate higher in the atmosphere than the associated temperature disturbances. The birth of granules is accompanied by a temperature increase and strong upflows at some levels. The maximum of velocity fluctuations is always located at about 150 km in the mean photosphere, followed by a progressive decay. In the case of temperature, however, the maximum is always found in the low photosphere. Effects due to explosion are seen for both velocity and temperature as a change in their gradients with height. After explosion, the velocity structure is recovered in a longer time scale than that for temperature.

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Figure 3. Temporal evolution of temperature (left) and velocity (right) disturbances in the centre of the exploding granule as estimated from the measured fluctuations of line intensity and Doppler velocity. The interval of time with respect to explosion (in seconds) is annotated in each plot.