USING THE NaI D RESONANCE LINES TO PROBE THE SOLAR PHOTOSPHERE

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ABSTRACT

Observational techniques in Helioseismology are often based on measurements made in the NaI D resonance lines. A good knowledge of their spectral profiles is crucial for the purposes of calibration and interpretation of data. Here we explore their diagnostic properties by calculating response functions of the D1 and D2 line profiles to temperature and velocity perturbations in the atmosphere. We propose a method to transform spectral line intensity fluctuations measured at several wavelengths into temperature and velocity disturbances at different height levels. The possibilities of such a procedure to trace the vertical structure of the photosphere are discussed.

1. INTRODUCTION

Two-dimensional high resolution spectroscopic observations of the solar surface are now available. Intensity and velocity maps of the observed field of view can be produced at high spatial resolution. High spatial resolution in the vertical direction may be also achieved by measuring the spectral line profile at various wavelength positions simultaneously. To exploit such high quality data a good knowledge of the spectral line formation is required. Lines are not formed at single precise heights but do involve different levels in the atmosphere. An accurate determination of those layers which are responsible for intensity variations at the observed wavelengths is essential for a correct interpretation of data.

The NaI D resonance doublet is a good diagnostic of the solar photosphere. Both D1 and D2 lines are very strong and show well extended wings, allowing us to probe a wide range of atmospheric heights. They are commonly used in Helioseismology (Snider 1970; Fossat & Roudier 1971; Brookes et al. 1978, Gabri & al. 1995.1997).

We have investigated the mapping between given wavelengths in the profiles of the D lines and atmospheric height levels. Our approach involves calculation of Response Functions, which are classical tools for inversion techniques. We aim to convert fluctuations of intensity and Doppler velocity as measured from spectrograms into atmospheric disturbances of temperature and macroscopic velocity, respectively, at characteristic heights. This kind of analysis is very important to clarify the structure and dynamics of photospheric layers. Results can also be used to evaluate theoretical models of solar granulation. In addition, physical properties of deep convective layers are often used as boundary conditions in the study of solar interior phenomena.

2. FORMULATION

The calculation of so-called Response Functions to temperature and macroscopic velocity for the D line profiles constitutes the essential part of this method. Response Functions (hereafter, RFs) describe the effect that perturbations of a given physical parameter have in the emergent line intensity (Mein 1971; Beckers & Milkey 1975; Canfield 1976; Caccin et al. 1977). If RFp is the response function for a certain parameter, p, the intensity fluctuation that corresponds to a small disturbance Δp, can be written as

$$\Delta I(\lambda) = \int_{0}^{\infty} RFp(\lambda, s) \Delta p(s) \, ds$$  \hspace{1cm} (1)

where s is the coordinate associated to atmospheric height.

Synthetic line profiles for different models of atmospheric perturbations were computed 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. Perturbed atmospheres were then obtained by introducing small amplitude disturbances of temperature and velocity into the reference model. In the case of temperature, relative perturbations $\delta T/T$ were considered whereas for velocity we used absolute perturbations, $\delta V$.

Table 1. $\Delta \lambda$ and $\lambda$ barycenters in log m and height (km) coordinates for the Na ID$_2$ line.

<table>
<thead>
<tr>
<th>$\Delta \lambda$ (Å)</th>
<th>RF$_T$ barycenter</th>
<th>RF$_V$ barycenter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>log m</td>
<td>height</td>
</tr>
<tr>
<td>0.072</td>
<td>-0.31</td>
<td>260</td>
</tr>
<tr>
<td>0.108</td>
<td>-0.09</td>
<td>206</td>
</tr>
<tr>
<td>0.120</td>
<td>-0.04</td>
<td>192</td>
</tr>
<tr>
<td>0.144</td>
<td>0.05</td>
<td>170</td>
</tr>
<tr>
<td>0.180</td>
<td>0.14</td>
<td>145</td>
</tr>
<tr>
<td>0.216</td>
<td>0.21</td>
<td>127</td>
</tr>
<tr>
<td>0.252</td>
<td>0.25</td>
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<tr>
<td>0.288</td>
<td>0.29</td>
<td>103</td>
</tr>
<tr>
<td>0.324</td>
<td>0.32</td>
<td>95</td>
</tr>
<tr>
<td>0.360</td>
<td>0.34</td>
<td>89</td>
</tr>
<tr>
<td>0.432</td>
<td>0.37</td>
<td>79</td>
</tr>
</tbody>
</table>

As depth scale we have chosen the logarithm of column mass, i.e. $s \equiv \log m$. The adopted atmospheric models start at $\log m_0 = 0.75$ and run up to $\log m\nu = -3.28$ ($m$ is in units of g cm$^{-2}$). It is assumed that perturbations occurring at depths larger than $\log m_0$ have no effect at all in the profile. The advantage of using column mass as the depth variable is that, in conditions of hydrostatic equilibrium, it is directly related to pressure. In this way the vertical stratification is preserved, even after temperature or velocity disturbances have been introduced. The geometrical height, however, would vary according to the way perturbations affect opacity and would need to be recalculated specifically for each perturbed atmosphere. The geometrical height scale that is used for reference in the plots is calculated for the static unperturbed atmosphere so that the origin $h = 0$ corresponds to the level at which standard optical depth is 1, increasing outwards.

Barycenters of RFs for different wavelengths, $G_\lambda$, give an indication for depths at which relevant perturbations occur. They are defined as:

$$G_\lambda = \frac{\int_0^{+\infty} RF(\lambda, s) s \, ds}{\int_0^{+\infty} RF(\lambda, s) \, ds}$$ (2)

Barycenters are also of interest because they allow to estimate perturbation amplitudes at different levels in the atmosphere. If we assume that perturbations vary linearly with depth, then the observed intensity (or velocity) fluctuations at wavelength $\lambda$, together with the barycenter of the RF for that wavelength, $G_\lambda$, will provide the perturbation value at the barycenter height.

3. RESULTS AND DISCUSSION

RFs of the D$_2$ line have been obtained before for temperature and pressure fluctuations under LTE conditions (Kneer & Nolte 1994, Krieg et al. 1999). Results from the present calculation of temperature and velocity RFs for the D lines are shown in Figure 1. The barycentres, calculated as in Equation 2, can be found in Tables 1 and 2. The behaviour of temperature RFs is similar for both lines. They tend to shift towards lower heights for D$_1$. This is consistent with the fact that D$_2$ shows weaker, higher-intensity wings by comparison to D$_1$. The highest sensitivity to temperature fluctuations is always found in the wings of the profile, which are formed in deeper layers. Temperature fluctuations above $log m = -2$ (650 km) will have no influence in the profiles.

Velocity RFs cover a wider range of heights, extending up to $log m \sim -2.8$ (900 km) for the line cores. An absolute, narrow maximum is found for $\Delta \lambda = 0.108$ at heights close to $log m = -0.5$ (∼290 km). A second, not so well defined maximum occurs at $log m \sim -0.4$ (∼276 km) for $\Delta \lambda = 0.120$. This is more clearly seen for the D$_1$ line. Velocity RFs for positions close to line centre show a larger width than those for the wings. This has important consequences for definition of formation heights, as discussed below.

The method performance was tested with several theoretical models of perturbations. We use some of the results obtained with the D$_2$ line for illustration in Figure 2. The assumed models are plotted using solid lines. Values predicted with this method are indicated by crosses (perturbations linear with depth) and points (exponential models of perturbations).

In the ideal case, RFs at a given wavelength would be $\delta$-functions centred at one characteristic height. Assignment of atmospheric heights to measurements made at particular wavelengths would then be immediate. In practice, because RFs have a finite width, the observed fluctuations are actually weighted sums of contributions from several depths. For wide RFs as those found for velocity at the core of the D lines (Figure 1) physical perturbations in the atmosphere will be smeared out and height determinations will be more uncertain. In consequence, large deviations between predicted and real values of perturbations are going to be expected at larger heights. The method will fail in the case of large amplitude perturba-
Figure 1. RFs of the Na ID$_1$ (upper panel) and D$_2$ (bottom panel) lines for temperature (left) and for velocity (right). The 'x' axis of wavelength position with respect to the line centre covers only one half of the profile, for clarity. Depth is indicated in the 'y' axis as log $m$, where $m$ is column mass in g cm$^{-2}$ (see text).
Figure 2. Temperature (upper panel) and velocity (lower panel) fluctuations obtained with our method for assumed models of perturbations (solid lines). Each model is labeled in the plot with the parameter that determines the variation with height: the slope, $b$, for linear models ($b \log(m_0/m)$) and the factor $\alpha$ that defines natural exponential functions ($e^{\alpha \ln(m_0/m)}$). The corresponding values predicted with our method are indicated as crosses for linear models and points for exponential models. Departures between curves and points increase for large values of $|\alpha|$, reflecting the fact that perturbations are no more in the linear regime.

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