STUDY OF CHROMOSPHERIC Ca II CLOUD-LIKE STRUCTURES

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ABSTRACT

We present an inversion method to estimate the temperature, electronic density, microturbulence, velocity and emission measure of chromospheric cloud like features observed in the 8542 Å Ca II line. The method involves the computation of a large grid of Ca II models using a multi-level non-LTE transfer code. We compute the necessary photoionization rates by first solving the non-LTE hydrogen case and then we proceed to the calculation of the Ca II line depth-dependent mean intensity inside an isolated, isothermal cloud laying above the photosphere. The inversion of observed profiles with the grid of computed synthetic Ca II profiles is performed with a searching and matching \(\chi^2\) algorithm which is followed by an interpolating algorithm permitting a more accurate determination of the aforementioned parameters. We apply the results to a filament observed with the MSDP instrument on VTT (Tenerife) and discuss through an error analysis the accuracy of the method in determining the physical parameters of the filament. We furthermore compare the results with a corresponding H\(\alpha\) investigation and discuss future extensions of the inversion technique. The determination of the physical parameters of dark cloud-like structures around active regions is crucial to the understanding of the temporal and spatial evolution of such regions and their connection to the solar cycle.

INTRODUCTION

Solar spectral inversion codes that take into account the formation of chromospheric lines under conditions of non local thermodynamic equilibrium (non-LTE) are a powerful diagnostic tool for obtaining information from observed line spectra.

Synthetic profile calculations with multilevel non-LTE transfer codes are usually either based to the linearization or the preconditioning approach. The first approach on which the MULTI code by Carlsson (1986) is based, linearizes all the necessary multilevel transfer equations by neglecting second and higher order terms in the perturbed equations. The preconditioning approach linearizes the original non-linear equations by choosing some quantities from a previous iteration and using an approximate relationship for the radiation field. The latter is used in the one-dimensional multilevel transfer code MALI by Heinzel (1995). The MALI approach has been recently used by Molowny-Horas et al. (1999) - hereafter MH - for the non-LTE inversion of a chromospheric H\(\alpha\) cloud-like filament. Cloud models have been successful for the study of several chromospheric features like filaments, arch filaments and mottles.

In this paper we are interested in the non-LTE formation of the Ca II 8542 Å line in chromospheric cloud-like features. We construct with MALI a large grid of models and afterwards apply the non-LTE Ca II inversion procedure to the same filament that MH studied in H\(\alpha\) to obtain valuable information about inversion in different spectral lines.

MALI PROFILE CALCULATIONS

A thorough description of the MALI code and its boundary conditions is given in Mein N. et al. (1996), Heinzel et al. (1999) and MH. The application to Ca II is worked out in Mein et al. (2000). The cloud-like filament is represented by an isothermal horizontal 1D slab which lays above the solar surface and moves as a whole with a bulk velocity. The input parameters for the synthetic profile calculations are temperature, electron density, microturbulent velocity, macroscopic bulk velocity, geometrical thickness, height above the solar surface and the incident solar radiation.

We first solve the non-LTE problem for hydrogen in order to compute the radiation field in Lyman lines and the continuum used for the evaluation of the Ca II photoionization rates and then we proceed to the Ca II non-LTE calculations. We consider a five level plus continuum Ca II model. We refer the reader to Shine & Linsky (1974) for a summary of the Ca II atomic level structure, transition rates, level broadening parameters and photoionization rates used in the MALI code. The incident solar radiation field is a compilation of various observations made by Gorshkov et al. (1996). The infrared Ca II lines are computed with complete frequency redistribution (CRD). The computed non-LTE level populations as a function of the line-center optical depth are used to evaluate the Ca II line source function. The formal solution of the radiation transfer equation along the line of sight is then numerically calculated where the optical depth\(\tau_l\) is expressed by a Doppler-shifted Gaussian profile. The grid of input parameters for the Ca II MALI synthetic profile calculations is presented in Table 1.

An analysis of the Ca II synthetic profiles for the case of a static \(\dot{V} = 0\) km s\(^{-1}\) cloud shows that:


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Table 1. Parameters used for the calculation of the grid. The total number of computed MALI models is $3 \times 9 \times 11 \times 5 \times 7 = 10395$. Since the source function is symmetric to negative and positive velocities only the three positive points are calculated for parameter $V$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>No of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ (km s$^{-1}$)</td>
<td>5 - 5</td>
<td>3</td>
</tr>
<tr>
<td>$N_e$ (cm$^{-3}$)</td>
<td>$2 \times 10^{10} - 1 \times 10^{11}$</td>
<td>9</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>6000 - 11000</td>
<td>11</td>
</tr>
<tr>
<td>$Z$ (km)</td>
<td>1000 - 5000</td>
<td>5</td>
</tr>
<tr>
<td>$\xi$ (km s$^{-1}$)</td>
<td>3 - 9</td>
<td>7</td>
</tr>
<tr>
<td>Height (km)</td>
<td>20000</td>
<td>1</td>
</tr>
</tbody>
</table>

- An increase in temperature $T$ gives brighter Ca II intensities near the center of the line as a direct result of the increase of the rate of collisions with temperature. Moreover, since the optical thickness of the cloud decreases with increasing temperature we see more background radiation due to the lower line center opacity.

- An increase of microturbulence causes a considerable broadening of the profile and thus a decrease of the line center opacity. As a consequence, we see more background radiation.

- There is a strong dependence of intensity on electron density $N_e$ (see Fig. 1). For low temperatures with increasing $N_e$ the Ca II line center intensity goes through a minimum before increasing again while for high temperatures the line center intensity is monotonically decreasing within the range of used densities. For low temperatures an increase of $N_e$ leads initially to an increase of the optical thickness of the cloud and thus absorption until $N_e$ reaches a high enough value for collisions to dominate and thus give rise to emission. However, as temperature increases Ca II starts ionizing to Ca III. As a consequence for high temperatures larger electron densities $N_e$ are needed in order for Ca II to start emitting.

- As $Z$ increases the Ca II line intensities decrease since the optical thickness of the cloud increases making it less transparent to the incident radiation.

Since ambiguities can occur in the inversion for large uncertainties in the observed profiles, the number of variables is reduced to four by collapsing $Z$ and $N_e$ into a new single parameter, the emission measure $Q$, defined as $N_e^2 Z$.

### THE INVERSION PROCEDURE

The comparison of the observed line profile $I_{\text{obs},\lambda_i}$ with each of the grid model profiles $I_{\lambda_i}(V, T, \xi, Q)$ is done by a minimizing $\chi^2$ function given by

$$
\chi^2 = \sum_{i=1}^{N} \left( \frac{I_{\text{obs},\lambda_i}}{I_{\text{obs},\lambda_i}} - \frac{I_{\lambda_i}(V, T, \xi, Q)}{I_{\text{tab},\lambda_i}} \right)^2
$$

where $I_{\text{obs},\lambda_i}$ and $I_{\text{tab},\lambda_i}$ are the observed and tabulated background profiles, $\lambda_i$ refers to the wavelength-positions used in the line profile and $N$ is the number of these positions which in our case is equal to five. Since this $\chi^2$ procedure gives the minimum at the resolution of the grid's mesh, a more accurate determination of the parameters is further achieved by a parabolic interpolation which takes into account the nearby grid mesh points of the minimum.

We apply the procedure to a filament observed with the MSDP instrument of the German VTT at the Observatorio del Teide on September 25th, 1996 (see Fig. 2). The calibration of the observed and grid calculated profiles is done by comparing the observed and tabulated background profiles $I_{\text{obs},\lambda_i}$ and $I_{\text{tab},\lambda_i}$ and calculating a proportionality factor $K$ which satisfies that $I_{\text{obs},\lambda_i} = K \cdot I_{\text{tab},\lambda_i}$ for all $i$'s. The calibration gives a difference of the observed and the tabulated profile which is always less than 2% and can be attributed to instrumental or observational reasons.

We have inverted a total of 4009 Ca II profiles from the filament region that have a maximum contrast (compared to the background profile) lower than 0.95 excluding thus all border points where the filament is extremely optically thin and we may be observing the background. A first qualitative look of the inversion maps (Fig. 2) shows that the darker center of the filament seems to have lower temperatures than its borders which is in agreement with the results obtained for Hα by MH. We also roughly recognize the same velocity structures seen for Hα and although there is no clear pattern the filament borders seem to have higher values of microturbulence. However, there is no trend at all in the distribution of emission measure $Q$ which is in contrast with the Hα inversion where $Q$ increases from the border towards the center of the filament.
A direct comparison of the inverted parameter values for Ca II and for H\(\alpha\) at every point in the filament is usually not possible because of the different formation depths for H\(\alpha\) and Ca II within the filament as well as to the different refraction indices of the two lines in Earth's atmosphere. However a statistical analysis of the results for the two lines, reveals that:

- The Ca II temperature distribution peaks around 8500 K and then drops dramatically for higher temperatures. This is expected since Ca II is mostly dominant for low temperatures and dramatically drops for higher temperatures where the formation of Ca III is more favorable. The H\(\alpha\) distribution has no clear equivalent peak in temperature and the filament seems to be on average cooler. The different behaviour is explained by the fact that the Ca II line is collision dominated and hence much more sensitive to temperature compared to H\(\alpha\) which is photoionization dominated.

- The Ca II microturbulence distribution shows a peak around 5 km s\(^{-1}\). Since temperature is well defined by the Ca II inversion it leads to a better definition of the microturbulence from the profile width which depends on temperature and microturbulence. The coupling of temperature and microturbulence is stronger in the case of H\(\alpha\) which is a much lighter element than Ca IIand as a result there are several couples of values for temperature and microturbulence that correspond to a specific H\(\alpha\) line width.

- The velocity distribution of Ca II is almost Gaussian like while the equivalent velocity distribution for H\(\alpha\) shows an excess of blue shifted velocities (filament moving upwards). However, we should take into account that for the optically thinner Ca II where the optical thickness is on average less that one, velocity structures of the background play an important role for the velocity determination in the filament itself.

The uniqueness and precision of the inversion procedure can be checked by exploring the whole parameter space. In Fig. 3 we present for an observed filament profile plane cuts of the 4-dimensional \(\chi\) distribution. They show that temperature is always well defined and that the inversion gives only one solution within the range of parameters and defines quite accurately the global minimum of the \(\chi\) distribution for velocity, temperature and microturbulence. It fails however to define \(Q\) since small fluctuations of temperature result to a wide range of values for \(Q\), contrary to the case of H\(\alpha\) where the emission measure is always well defined. As MH demonstrated there is a clear relationship between the integrated H\(\alpha\) intensity emitted by the slab itself and \(Q\) while the corresponding Ca II one shows no correlation at all, something related to the different nature of the two lines. The almost unique correlation found for H\(\alpha\) means that for a given \(Q\), the integrated intensity is almost insensitive to kinetic temperature. The reason is that H\(\alpha\) is photoionization dominated line. The Ca II line is, on the other hand, coupled to kinetic temperature via collisions.
The calculation of the standard deviation for each of our inverted parameters \((V, T, \xi, Q)\) by considering all solutions with an intensity which is within 2% of the observed profile intensity gives an average standard deviation value of 0.45 km s\(^{-1}\) for velocity, 0.61 km s\(^{-1}\) for microturbulence, 918 K for temperature and 1.75 \(\times\) \(10^{10}\) cm\(^{-5}\) for emission measure. Even for such a large error the average standard deviation is quite low for velocity, microturbulence and temperature but very high, comparable to the actual range of values, for emission measure.

A parameter that can always be inverted is the maximum line-center optical depth \(\tau_{c, \text{max}}\), which is proportional to the line-center absorption coefficient. The latter depends on the lower level population, microturbulence and temperature. The lower level population is strongly coupled with \(N_e\) and \(T\). As \(\xi\) increases the values of \(\tau_{c, \text{max}}\) slightly decrease. The inversion shows (see Fig. 2) that \(\tau_{c, \text{max}}\) is generally higher in the center of the filament than its borders which is in absolute agreement with previous observations.

**DISCUSSION**

The inversion strategy for the Ca II filament with the use of a grid of models permits a quick and quite accurate search for the best fit to a large amount of observational data. Future investigations in Ca II should probably include a grid extended to lower densities and also consider a filling factor for the filament. The inversion of velocity suggests that a more careful consideration of the background intensity should be taken into account.

Since the background in Ca II is quite structured below cloud-like features, as Fig. 2 clearly shows, that influences the optically thin observed Ca II profiles by introducing modifications to the line profile through different illumination conditions and possible Doppler shifts existing to the incident radiation profiles. A future extension of the inversion code will include the incident radiation as a free parameter, something that should definitely lead to a more accurate determination of the actual velocity structure within cloud-like features. An extension of the grid to higher velocities combined with the inclusion of incident radiation as an input parameter would enable the investigation of a wide range of chromospheric cloud-like features apart from filaments.

**REFERENCES**

Gorshkov A.B., Heinzel P., Vial J.-C., 1996, unpublished