HYDROGEN LINES FORMATION IN FILAMENTARY PROMINENCES

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Abstract - Most of the non-LTE prominence work has been confined to a one-dimensional (1D) slab geometry which approximately describes general behaviour of the radiative transport in quiescent prominences, at least within some line and continuum transitions. Only recently, a few authors have tried to consider schematically the inhomogeneous nature of prominence structures. Here we briefly review this effort and propose some improvements in this direction. In fact, it is rather difficult to reproduce the observed profiles of resonance hydrogen lines without taking into account a prominence porosity. This is particularly evident in the case of Lyman \( \alpha \) and Lyman \( \beta \) lines, which have been detected on OSO-8 satellite. On base of extended numerical simulations, we discuss here in detail mutual effects of the multilevel interlocking, partial-frequency redistribution, prominence porosity and the prominence-corona interface.

1. Introduction

Spectral diagnostics of quiescent prominences is usually based on several simplifying physical as well as geometrical assumptions. It is rather difficult to recognize which of these assumptions can affect our analysis more seriously and, therefore, we have to perform various numerical simulations in order to assess the so-called differential effects produced by a particular assumption. As an example, we can mention our recent results concerning the partial-redistribution (PRD) effects on hydrogen-lines formation in quiescent prominences (Heinzel et al., 1987 – HGV1). Using the same atomic model and prominence geometry (1D homogeneous slab), we have found important differences in the Lyman \( \alpha \) line profiles, as well as in global hydrogen excitation and ionization conditions, if we applied a more exact PRD-approach instead of the classical complete redistribution (CRD). In the present contribution we
Heinzel: Hydrogen lines formation in filamentary ... investigate another important differential effect caused by replacing standard 1D-slab geometry by a more realistic non-homogeneous multithread structure.

It is well known (e.g. Engvold, 1976) that the quiescent prominences are highly structured objects consisting of predominantly vertical thread-like fine structure elements (FSE). The question is to what extent these inhomogeneities affect the radiation properties of prominences and thus the corresponding spectral diagnostics. Hydrogen lines formation in such filamentary prominences was already studied by Morozhenko (1978, 1984), Zharkova (1984, 1990), Fontenla and Rovira (1983, 1985), and Vial et al. (1990). Lyman continuum transfer inside the inhomogeneous quiescent prominences was considered by Orrall and Schmahl (1980). Morozhenko and Zharkova started with 1D multi-slab prominence models, where each slab represents one FSE. All slabs are treated simultaneously, i.e. 1D radiation transfer equation (in the integral form) is solved in this multislab geometry. Each elementary slab is isothermal. CRD is used, together with a simplified hydrogen atomic model ($\text{Li}$ is in detailed balance).

The great advantage of this approach is its ability to account for a mutual radiative interaction between the individual slabs. However, one has to pay for this advantage by the lack of numerical resolution on the depth scale - the depth discretization within individual slabs is not sufficient to treat rather steep temperature and/or pressure gradients in the region between the cold core of FSE and hot interfililar medium - here we shall denote this region as the FSE-interface (in contrast to PCTR which usually means a global transition between the prominence body and the corona - see Vial, 1990).

Another problem is that this multislab geometry doesn't account for a free penetration of the external and diffusive radiation through the prominence body, i.e. between fine-structure elements.

Conceptually different approach is that of Fontenla and Rovira (1985) (FR85), where the non-LTE problem is solved for one representative FSE (1D slab in this case), taking into
account a FSE-interface. Temperature structure is determined by solving the energy-balance equation. Several elements (slabs) are then added together and the formal integration of the radiative transfer equation through all slabs gives the emergent line profiles. Depth-discretization for each FSE is sufficient to describe a FSE-interface, but FR85 don't consider any mutual interaction between FSE's and, moreover, all (identical) elements are irradiated only by the external diluted solar radiation and not by the surrounding plasma elements. They also use CRD for all Lyman lines.

This second approach seems to us a more flexible one, because it doesn't assume any "rigid" geometry for the spatial distribution of FSE's and, moreover, it allows to treat the physics of a representative FSE in sufficiently great detail. Therefore, we try here to generalize this kind of modelling, in order to account for a mutual interaction between fine-structure elements and including PRD for hydrogen Lyman lines.

2. Iterated Boundary Conditions (IBC) Method

The idea how to generalize the approach of FR85 is rather straightforward, although it is based on certain experience with the behaviour of the radiation transport within the prominences. From our previous non-LTE modelling (see HGV1) we know that inside 1D-slabs, the mean intensities of the radiation field in hydrogen resonance transitions are similar to the corresponding diluted solar irradiation, providing that 1D-slab represents a lower-density isothermal prominence. This is particularly true for those frequencies of \( \text{L_\alpha} \), \( \text{L_\beta} \) and \( \text{L-continuum} \), which are important for determining the corresponding radiative rates. This means that if we select one representative FSE and irradiate it by diluted solar radiation (exactly as in FR85), we will get the output radiation at these frequencies not very different from the incident one. However, this implies that any FSE (we also assume here that all FSE's are identical, as in FR85),

illuminated by both direct solar radiation as well as by the radiation from surrounding elements, will behave — in a first approximation — as it would be irradiated entirely by the diluted solar radiation. In the next step, we can modify — in a heuristic way — FSE's boundary conditions so that the incident intensity will take the form

\[ J_{\text{inc}}(\nu) = \alpha J_e(\nu) + (1-\alpha) J_S(\nu) \]  \hspace{1cm} (1)

where \( J_e \) is the mean intensity of the radiation emergent from an individual FSE, \( J_S \) is the mean intensity of the diluted solar radiation and \( \alpha \) characterizes the prominence porosity. The parameter \( \alpha \) has a probabilistic nature and can vary from zero to unity. Note that the case \( \alpha=0 \) corresponds to models of FR85, which we can now interpret in two different ways: the prominence is a very sparse object \((\alpha=0)\) so that FSE's are indeed irradiated predominantly by \( J_S \), or — in a first approximation discussed above — we assume \( J_e \approx J_S \) for general \( \alpha \approx 0 \) so that \( J_{\text{inc}} \approx J_S \) as if \( \alpha \) would be zero.

The numerical simulation can proceed in a following way:

(i) Select one representative FSE (all are identical in our simulations) and use the boundary conditions with \( J_{\text{inc}} = J_S \) (i.e. \( \alpha=0 \));

(ii) Solve the full non-LTE problem for the representative FSE, accounting in detail for the FSE-interface, PRD, multilevel atomic structure etc. If this solution is not different from that obtained in the previous iteration (see below), go to (v);

(iii) The updated incident radiation is given by Eq.(1), where \( J_e(\nu) \) comes from the previous non-LTE solution. In fact, this mean intensity should represent the radiation field incident from all surrounding elements, where in the line wings (i.e. for a smaller optical thickness) we would get a contribution from several elements. However, for these exploratory simulations, we simply identify \( J_e \) with the output radiation of nearby elements providing that at those frequencies which are important for the
evaluation of radiative rates, these nearest elements are so opaque that our representative FSE cannot see any more distant structure. Our numerical estimates have shown that this is a reasonable approximation, at least for Lyman lines;

(iv) Include $J_{\text{inc}}(\nu)$ given by Eq.(1) into the linearized boundary conditions for FSE and go to (ii);

(v) Perform the formal solution of radiative transfer equation along the line of sight, using previously evaluated atomic level populations inside each FSE and assuming certain stochastic distribution of FSE's. Here we use somewhat simplified picture that all FSE's are centered along the line of integration (line of sight). The emergent intensity is then expressed as (see also FR85)

$$I(\nu, \mu) = I_{e}(\nu, \mu) \sum_{i=1}^{N} e^{-(i-1)\Delta\tau(\nu)/\mu},$$

where $I_{e}$ is the output intensity from one FSE, $\Delta\tau$ is the optical thickness of FSE, $N$ represents the number of elements along the line of sight, and $\mu$ is the directional cosine.

Finally, let us mention some details of the non-LTE solution. Within the item (ii) we perform full non-LTE computations for a three-level plus continuum hydrogen atom (an extension to more levels is trivial but more time-consuming). To save the computer time, the H$\alpha$ line is assumed here to be optically thin in FSE (see the models in HGV1, where even the whole prominence is rather thin in this line), and also both subordinate continua (Balmer and Paschen) are optically thin. Subsequently, these transitions have their radiative rates fixed by solar radiation fields. Standard PRD approach is applied to both $\text{I}_{\alpha}$ and $\text{I}_{\beta}$ lines. Although our probabilistic formulation, represented by Eq.(1), as well as the formal solution, are independent on actual geometry of individual elements, we use here 1D-slab geometry for the representative FSE (item ii), instead of a more realistic cylindrical one.
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(see the discussion by Gouttebroze, 1990). Further details of our non-LTE method, together with some information about the numerical code, can be found in HGV1.

3. Numerical Simulations

In order to test the IBC-method and to demonstrate possible effects of a mutual interaction between FSE's on the emergent line profiles, we have performed several numerical simulations starting with simple isobaric structures. As a reference model we adopt the homogeneous isobaric prominence model LP2 introduced in HGV1 (see Tab. 1). An "equivalent" filamentary prominence is then composed of fourty FSE's (with or without a FSE-interface - see models FSE2 or FSE1, respectively), which have together the same column mass M as LP2 - this allows a direct comparison of results obtained for homogeneous and inhomogeneous prominences. Temperature structure inside the FSE-interface (model FSE2) is prescribed, i.e. no energy-balance equation is considered here. Typically 3-5 IBC-iterations are required to get a converged solution. All computational details are exactly the same as in HGV1 (dilution factors, radiation temperatures for continua etc.).

<table>
<thead>
<tr>
<th>Model</th>
<th>M</th>
<th>T_c</th>
<th>P</th>
<th>ΔM</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP2</td>
<td>3.0×10^{-5}</td>
<td>7500</td>
<td>0.02</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>FSE1</td>
<td>7.5×10^{-7}</td>
<td>7500</td>
<td>0.02</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>FSE2</td>
<td>7.5×10^{-7}</td>
<td>7500</td>
<td>0.02</td>
<td>9×10^{-8}</td>
<td>12500</td>
</tr>
</tbody>
</table>

Table 1

Parameters of the prominence models. M is the column mass in g/cm², T_c is the central temperature in K, P is the constant pressure in dyn/cm², ΔM represents a part of M occupied by the FSE-interface, where the temperature rises from T_c to T_c+ΔT.
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Note also that the results obtained here for the model LP2 differ slightly from those in HGV1, where a more complex five-level atomic structure was used.

Our principal results are displayed in Figs. 1-5. In Fig.1 we can see a large discrepancy between 1D homogeneous model and the filamentary one with mutually interacting FSR’s. There is also an important difference between the profiles b and c, where b represents computations similar to those of FR85, but using PRD approach (which considerably changes the line profiles, particularly in the wings — see HGV1). Lower peak-intensity of the c-profile as compared to b-one is caused by the fact that in Eq.(1) J_e also exhibits lower peaks

![Graph of IBC LYMAN-A](image)

**Fig. 1.** \( \lambda \alpha \) profiles emergent from an isothermal prominence. 
- **a** - homogeneous model LP2; 
- **b** - filamentary model with 40 elements FSEI along the line of sight, no mutual interaction (\( \alpha = 0 \)); 
- **c** - same as in b, but with a mutual interaction between the FSE’s (\( \alpha = 0.5 \)). 

Intensities are in ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) Hz\(^{-1}\).
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than $J_0$. For $\alpha=0$, each FSE is irradiated only by the solar radiation $J_0$ and thus the $b$-profile has higher peaks. A similar situation takes place for $\text{I}\beta$ (Fig.2). Triple-peaked $\text{I}\beta$ profiles are typical for isobaric filamentary prominences, as was already demonstrated by FR65. Figs.3 and 4 compare the abovediscussed profiles with those emergent from non-isothermal prominences, where each FSE has its own interface towards the interfililar medium (corona). The line-core intensities of both $\text{I}\alpha$ and $\text{I}\beta$ are higher due to a higher temperature in the region of their formation (compare profiles $b$ and $c$ in these figures). Finally, the line wings of $\text{I}\alpha$ (and also $\text{I}\beta$) are more extended if the number of FSE’s along the line of sight increases (Fig.5). However, the line cores are almost independent on the number of FSE’s, as was previously assumed.

Fig. 2. The same as in Fig. 1, but for the $\text{I}\beta$ line.
Fig. 3. Effect of a FSE-interface on $\lambda \alpha$ profiles emergent from an inhomogeneous prominence. a – isothermal homogeneous model LP2; b – filamentary model with 40 elements FSE1 (no interface) along the line of sight, $\alpha=0.5$; c – same as in b, but with 40 elements FSE2 (i.e. the FSK – interface).

4. Conclusions

IBC-method proposed in this paper was developed to account for a mutual non-LTE interaction between fine-structure elements inside the filamentary prominences. The advantage of such a method is that it is capable of treating a stochastic nature of highly inhomogeneous media to which prominences belong. Although our approach here is rather heuristic (a more rigorous mathematical treatment is now under development), we were able to demonstrate some differential effects of the filamentary structure on radiation properties of prominence.
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**Fig. 4.** The same as in Fig. 3, but for the $\text{H}\beta$ line.

**Fig. 5.** $\text{H}\alpha$ profiles emergent from an isothermal prominence with N elements FSE1 along the line of sight ($\alpha=0.5$). $a - N = 10$; $b - N = 40$; $c - N = 80$.
plasmas, accounting in detail for the multilevel atomic structure, PRD and FSE-interface. A few prospects for the future work are worth to be mentioned:

Development of a more exact mathematical treatment;

Relaxation of the assumption that all FSE's are identical (both from the point of view of their irradiation, as well as their physical structure);

Replacement of 1D-slab geometry for FSE by a more realistic cylindrical one;

Triple-peaked $I\beta$ profiles seem to be unrealistic and thus we probably have to change the pressure and/or temperature structure in order to get double-peaked, strongly reversed $I\beta$ profiles observed on OSO-8 satellite (Vial, 1982).

Quite recently, Jefferies and Lindsey (1988) have proposed a new formulation of the radiative transfer in stochastic media, assuming that the source function in particular elements is already known (e.g. the LTE-case). This or similar approach can be used in our iterative scheme for determination of a non-LTE source function, i.e. as the formal solution in steps (iii) and (v) to evaluate more precisely the boundary conditions and the emergent intensities, respectively.

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STVARANJE VODIKOVIH LINIJA U FILAMENTARNIM PROMINENCIJAMA

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izlaganje

Sažetak: do sada su ne-LTE tretmani zračenja prominencija uglavnom bili ograničeni na jednodimenzionalnu (1D) geometriju koja približno opišu opće ponašanje prenosa zračenja u mirnim prominencijama barem za neke linijske i kontinuumske prelaze. Tek nedavno je nekoliko autor-a pokušalo shematski uzeti u obzir nehomogenu prirodu ustrojstva prominencija. Opisuju se ti postupci i predlažu njihova poboljšanja. U stvari, vrlo je teško reproducirati opažane profile rezonantnih linija vodika, a da se ne uzme u obzir šupljikavost prominencija. To je naročito očigledno za linije Lyman α i Lyman β zabilježene sa satelita OSO-8. Na temelju iscrpnih numeričkih simulacija detaljno se raspravljaju uzajamni efekti međusobnog povezivanja nivoa, djelomične redistribucije frekvencija, šupljikavosti prominencija i svojstva prostora između prominencije i korone.