MULTIThread STRUCTURE AS A POSSIBLE SOLUTION FOR THE Lβ 
PROBLEM IN SOLAR PROMINENCES

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ABSTRACT

Following the pioneering works of Heasley, Mihalas, Milkey and Poland (see e.g. Heasley and Milkey, 1983) who built non LTE one dimensional models of solar prominence, much attention has been paid to the spectral signatures of the Lyman lines as observed with OSO 8 (Vial, 1982a). In spite of a better treatment of the frequency redistribution and boundary conditions, one-dimensional low-pressure models lead to Lyman β intensities much lower than observed ones (Heinzel, Gouttebroze and Vial, 1987). Different atomic processes of formation of hydrogen lines (Cooper, Ballagh and Hubeny, 1988, 1989) or the inclusion of a Prominence Corona Transition Region or PCTR (Heinzel, Gouttebroze and Vial, 1988) have been proposed to explain this discrepancy. We present here a different approach where the filamentary nature of prominences which provides the hydrogen lines with different opacities offers their photons different escaping possibilities. The thread models we use derive from an energy equation where radiative losses are balanced by conductive flux (Fontenla and Rovira, 1983, 1985). We show that no superposition of threads gives good values of Lyman α, β and H α intensities for too high and too low pressures. Solutions are found for pressure around 0.05-0.1 dyn cm⁻² and a number of threads between 100 and 400. Two improvements have been performed: first, the inclusion of Partial Redistribution leads to a decrease of Lα (and Lβ) intensity and models now require a higher number of threads; second, the inclusion of the ambipolar diffusion along the steep temperature gradient which changes the hydrogen ionization in the lower regions (Fontenla, Avrett and Loeser, 1989). The new run of temperature and density implies more material at low temperatures and hydrogen lines intensities increase. A solution for the Lβ problem can be found for a pressure of about 0.1 dyn/cm². However the Hα intensity appears to be rather high. Moreover, the number of threads required (about 200) is far larger than the number derived by Zirker and Koutchmy (this issue) and Mein (this issue) from observed Hα profiles. Our neglect of the radiative interaction between threads may explain our results (Heinzel, this issue). To conclude, these computations of non-LTE radiative transfer in realistic geometrical and physical models, appear to be a promising path for the investigation of thermodynamic conditions in solar prominences.

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Introduction

The existence of fine structure in prominences has been evidenced as early as 1960 (Dunn's thesis). However, the diagnostic of thermodynamic parameters such as densities and temperature has concentrated on homogeneous, isobaric, isothermal models. The main reason lies in the nonLTE conditions in prominences due to the strong chromospheric and coronal illumination. Consequently, the first necessary step consisted in solving the right equations for level populations and radiative transfer, but in very simple models.

I. One-dimensional models, problems and tentative solutions

The pioneering works of Heasley, Mihalas, Milkey and Poland who built non LTE one dimensional models of solar prominence, led to low pressure models (Heasley and Milkey, 1983) which were able to explain the then available lines such as Balmer, Ca II, D3. Because of their importance in the radiative losses, more and more attention has been paid to the spectral signatures of the Lyman lines as observed with OSO 8 (Vial, 1982a). As shown by Vial (1982b) emergent radiation is basically determined by the diffusion of the incident radiation and the above models could be considered as successful. However, in spite of a better treatment of the frequency redistribution (Milkey et al, 1979), and of the boundary conditions, one-dimensional low-pressure models lead to Lyman β intensities much lower than the observed ones (Heinzel, Gouttebroze and Vial, 1987).

Possible solutions to this problem have been searched in different directions:

1/ The inclusion of a Prominence Corona Transition Region (PCTR) by Heinzel, Gouttebroze and Vial (1988). Drafting some typical transition regions from VAL chromospheric models, these authors could increase the Lβ emission substantially but also the Lα intensity (although lesser), to unobserved values. This is because the PCTR included a temperature plateau around 2 10^4 K which had moreover the unrealistic feature of conductively isolating the core of the prominence.

2/ Three levels Redistribution: such a disagreement between Lα and Lβ intensities also exists in the Chromosphere-Corona Transition Region (CCTR) and points to an atomic effect in the radiative diffusion. Cooper, Ballagh and Hubeny (1988) have used a complete treatment of the 3 levels frequency redistribution (including Raman diffusion, see Cooper, Ballagh and Hubeny, 1989) and shown that the Lβ emission could be increased by a factor as high as 2. Such a treatment, good for the CCTR, should be tried for the PCTR.

II. A Prominence as a "forest" of Threads

NonLTE transfer computations of superposed interacting (but isothermal) threads have been performed as early as 1978 (Morozhenko) for a two level atom and more recently for a 5 level atom by Zharkova (1983, and 1989) who addressed the problem of the Lα/Hα ratio (see e.g. Milkey et al 1979 and Heinzel.
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and Vial 1983). More realistic models built by Fontenla and Rovira (1983, 1985) include, for an
elementary thread, an energy equation where radiative losses are balanced by conduction. The central
temperature is fixed to 6500 K, the pressure is constant, and transfer equations are solved for a nonLTE
hydrogen atmosphere. Consequently, the radiative losses are exactly determined even at low
temperatures. An elementary thread being computed (in a 1 D approximation), the intensities of n
threads are simply added according to the formula:

\[ I = \sum_{i=0}^{\infty} e^{-\frac{\tau}{\mu}} \int_0^\tau S(\tau) e^{\frac{\gamma}{\mu}} d\tau \]

which implies that they do not interact radiatively, a reasonable assumption when the distance between
threads far exceeds the size of threads. Results are shown in Table 1.
Here we compare observed intensities (first row) in the L\(\alpha\), L\(\beta\), and H\(\alpha\) lines (and their ratios) with
computed intensities for different models where the pressure of individual threads and their total number
are varied.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Intensities (cgs)} & \text{L\(\alpha\) (10^4)} & \text{L\(\beta\)} & \text{L\(\alpha\)/L\(\beta\)} & \text{H\(\alpha\) (10^4)} & \text{H\(\alpha\)/L\(\alpha\)} \\
\hline
\text{Observed} & 2.8-3.6 & 440-550 & 65 & 1-10 & 0.25-2 \\
\hline
\text{Thread number} & \text{Model A} & p=0.02 \text{ dyn cm}^{-2} & & & \\
\hline
200 & 2.2 & 200 & 111 & 2.5 & 1.14 \\
400 & 2.4 & 237 & 102 & 4.9 & 2.02 \\
\hline
\text{Model B} & p=0.05 \text{ dyn cm}^{-2} & & & & \\
100 & 2.4 & 300 & 83 & 2.4 & 1 \\
200 & 2.7 & 375 & 72 & 4.7 & 1.74 \\
400 & 3.0 & 483 & 62 & 2.7 & 2.9 \\
\hline
\text{Model BC} & p=0.065 \text{ dyn cm}^{-2} & & & & \\
100 & 2.5 & 337 & 75 & 3 & 1.2 \\
200 & 2.8 & 445 & 63 & 5.7 & 2 \\
\hline
\text{Model C} & p=0.1 \text{ dyn cm}^{-2} & & & & \\
20 & 2.64 & 302 & 88 & .86 & 0.3 \\
50 & 2.9 & 390 & 75 & 2.1 & 0.7 \\
100 & 3.2 & 490 & 65 & 4.0 & 1.27 \\
\hline
\text{Model D} & p=0.2 \text{ dyn cm}^{-2} & & & & \\
20 & 5.0 & 1076 & 47 & 1.8 & 0.35 \\
30 & 5.5 & 1309 & 42 & 2.6 & 0.47 \\
\hline
\end{array}
\]

One can notice that a good agreement can be reached for models with a pressure between 0.05 and 0.1
dyn cm\(^{-2}\) and a number of threads between 100 and 400.

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III. Threads with Partial Frequency Redistribution (PRD)

The above computations were performed in Complete Frequency Redistribution (CRD) which is known to overestimate wing intensities, contrary to PRD. So, we started from individual threads where the hydrogen radiative losses are computed in CRD and evaluated the equations of statistical equilibrium and radiative transfer in PRD. We finally added threads intensities according to the above formula. A comparison between PRD and CRD intensities is made in Table 2 for model B (0.05 \text{ dyn cm}^{-2}).

**TABLE 2**

<table>
<thead>
<tr>
<th>Intensities (cgs)</th>
<th>L\alpha (10^{4})</th>
<th>L\beta</th>
<th>L\alpha/L\beta</th>
<th>H\alpha (10^{4})</th>
<th>H\alpha/L\alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>2.8-3.6</td>
<td>440-550</td>
<td>65</td>
<td>1-10</td>
<td>0.25-2</td>
</tr>
<tr>
<td>Thread number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model B (CRD)</td>
<td>p=0.05 dyn cm^{-2}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2.47</td>
<td>300</td>
<td>83</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>2.7</td>
<td>375</td>
<td>72</td>
<td>4.7</td>
<td>1.74</td>
</tr>
<tr>
<td>Model B (PRD)</td>
<td>p=0.05 dyn cm^{-2}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1.5</td>
<td>192</td>
<td>78</td>
<td>1.6</td>
<td>1.09</td>
</tr>
<tr>
<td>200</td>
<td>1.6</td>
<td>228</td>
<td>70</td>
<td>3.1</td>
<td>1.95</td>
</tr>
</tbody>
</table>

We notice again the typical effect of PRD as compared to CRD : L\alpha and L\beta intensities decrease, because of lower wings (see Milkey et al 1979, Heinzel and Vial 1983 and Heinzel, Gouttebroze and Vial 1987). Consequently, still more threads are needed, although their number may appear not very realistic.

IV. AMBIPOLAR DIFFUSION (AD)

This process of neutrals (ions) penetration in hot (cool) regions respectively, is at work wherever a strong temperature gradient exists. As shown by Fontenla (1987) and Fontenla, Avrett and Loeser (hereafter FAL, 1990), it changes significantly the hydrogen ionization in the lower parts of the Chromosphere-Corona Transition Region (CCTR). Figure 1 taken from FAL displays a smooth variation of the electron density when ambipolar diffusion (AD) is taken into account; moreover, there is now no more temperature plateau, needed in previous modeling in order to fit the observed Lyman lines profiles.
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Fig. 1: Hydrogen density as a function of height in the PCTR, computed with (---) and without (— —) ambipolar diffusion (from Fontenla, Avrett and Loeser 1990).

1/Ambipolar diffusion and thread structure:
We compare in Figures 2 the density and temperature structures of a thread with and without AD. We notice the same features found in the CCTR: less steep gradients which lead to an increase of material at low (around 2 $10^4$ K) temperature. For a given model (central temperature, pressure) and the same atomic physics, we should obtain increased hydrogen lines intensities.

Fig. 2: Hydrogen density as a function of radial distance in the thread (model B) computed with (---) and without (— —) ambipolar diffusion. (Fig. 2.a). The same for temperature (Fig. 2.b)


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2/ Ambipolar diffusion and radiative transfer with PRD:

We compute again the radiative transfer for different thread models (the previous ones, modified by AD) and we add the specific intensities in the way described above. We compare in Figures 3 the Lα profiles emerging from one thread (model B with p=0.05 dyn cm⁻²) at 3 different angles (cos θ= 0.2, 0.6 and 1) without (Fig. 3a) and with AD (Fig. 3b)

Fig. 3: Emergent Lα profiles computed for model B without (Fig. 3a) and with (Fig. 3b) ambipolar diffusion (AD) for 3 angles defined by cos θ= 1 (___), 0.6 (—..) and 0.2 (..)

At normal incidence, AD profiles are slightly higher, an effect which is stronger at skew angles since the line-of-sight then scans rather tangentially the region where the material is increased (see above). As far as absolute intensities are concerned, results are summarized in Table 3.


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The effect of AD is evident when one compares Table 3 with Table 2 for Model B (100 or 200 threads). With AD, Lα and Lβ intensities increase by a few per cent while the Hα intensity increases by a factor 3 to 4. As far as the Lβ problem is concerned, the situation is worse with AD. This is exemplified when one compares the full sets of computations contained in Tables 1 and 3. The implementation of AD and PRD decreases Lα and Lβ intensities, while the ratio Lα/Lβ remains quite constant. We now need more threads but the Hα intensity also increases up to unrealistic (unobserved) values.

V. CONCLUSION

When all possible macroscopic (particles) and radiative processes are fully taken into account, as we did here with AD and PRD, we obtain a possible solution for the Lα/Lβ problem with about 200 threads with a pressure of about 0.1 dyn cm⁻² (model C).

* First, we must question the high values of the computed Hα intensity. We suggest that they could result from our neglect of radiative interactions between threads. Although it is difficult to predict the way the basic 3 radiations (Lα, Lβ and Hα) would change when closest threads replace the illuminating chromosphere (see Heinzel, in this issue), we can build the following scenario : the Lyman thread emerging profiles being narrower than chromospheric ones, the Lyman source functions within any particular thread will be smaller when actual incident radiation is taken into account. Consequently, level
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2 of hydrogen will be less populated and the Hα opacity smaller. Assuming that the Hα source function did not change much (because levels 2 and 3 were "equally" increased), the decrease of Hα opacity leads directly to a decrease of intensity, as wished. Moreover, the results of Zharkova (1983) show that a strong fragmentation of material (i.e. an increase of radiative interaction) increases the Lα/Hα ratio.

* Second, the number of superposed threads appears to be high as compared to the numbers derived by Zirker and Koutchmy (around 10, this issue) and Mein (around 20, this issue) with independent data and methods. As for the PCTR, Schmahl and Orrall (1986) also found a number of "sheaths" close to 10. We can only state here that the mentioned observations have been made (in Hα) with a resolution that did not allow a direct evidence of very small structures, and that our computations compare with the full set of Lα, Lβ and Hα lines. Let us add also that in the range of our models, we easily obtained solutions for flat-topped Lα profiles, such as the ones obtained by Fontenla, Reichmann and Tandberg-Hanssen (1988) with UVSP/SMM.

* Third, the validity of the One Dimension approximation for the computation of individual threads can be questioned too (see Gouttebroze, this issue). 2 or 3 D effects have been shown to be marginal in the case of large structures (see Vial 1982b who used the 2D code of Mihalas, Auer and Mihalas 1978, or Gouttebroze, Vial and Tsiofoloua, 1986) but are certainly important in our situation.

* Fourth, results will certainly change also when all aspects of ambipolar diffusion are taken into account: actual changes of populations, macroscopic velocities, etc...

Our conclusion points to many improvements that must be done in our computations (interaction of threads, 2D computations, full account of AD) but from our work we can stress the importance of the Hydrogen lines (including Lyman) as a powerful, difficult but necessary tool for prominence diagnostic including the PCTR.

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Discussion:

Fang Cheng: Instead of the isothermal model (each thread has the same temperature) if one reduces the temperature in the central part of the prominence, the intensities in Hα wings may decrease and this could fit the observations better. Is this true or not?

Vial: The threads are not isothermal since the temperature goes from a low central value to about 10^5 K. Reducing the temperature may actually decrease the Hα intensities.
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VIŠEVLAKNASTO USTROJSTVO KAO MOGUĆE RJEŠENJE PROBLEMA SPEKTRALNE LINIJE Hβ U SUNČEVIHM PROMINENCIJAMA

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izlaganje

Sažetak: Nakon pionirskih radova autora Heasley, Mihalas, Milkey i Poland,(vidi Heasley i Milkey, 1983) koji su razradili jednodimenzionalne non-LTE modele Sunčevih prominencija, posebna pažnja je bila posvećena oblicima profila Lymanovih linija vodika opažanih satelitom OSO-8. (Vial et al. 1982). Unatoč boljoj obradi redistribucije frekvencija i rubnih uvjeta, jednodimenzionalni modeli s niskim tlakom daju intenzitete linije Hβ koji su mnogo niži od opažanih (Heinzel, Gouttebroze i Vial, 1987). Da bi se objasnila ta neslaganja predloženi su razni atomski procesi formiranja li-
nija vodika (Cooper, Ballagh i Hubeny, 1988, 1989) ili pak uključivanje prelaznog područja između prominencija i korone PCTR (Hein-
zel, Gouttebroze i Vial, 1988). Ovdje prikazujemo jedan drugačiji pristup u kojem filamentarna priroda prominencija stvarajući vodi-
kove linije različitih opaciteta omogućuje fotonima različite mo-
gućnosti za bijeg. Model vlakana koji koristimo potiče iz jedna-
dže energete u kojoj su radijativni gubici uravnoteženi konvektij-
skim tokom (Fontenla i Rovira, 1983, 1985).