HYDROGEN EMISSION FROM MOVING SOLAR
PROMINENCES

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Abstract. Brightness variations of the lines arising from a five-level hydrogen model atom, depending upon
prominence velocities, have been investigated using a combination of two non-LTE techniques. The
importance of the Doppler brightening and/or Doppler dimming effects is demonstrated for the lines of the
Lyman and Balmer series.

1. Introduction

Our understanding of the physics of solar prominences has rapidly increased since the
introduction of highly sophisticated non-LTE diagnostic techniques and we could quote
several important papers dealing with elaborated non-LTE models (for a recent review
see Hirayama, 1985). However, most attention was devoted to quasi-static structures
like quiescent prominences (QP), while practically no studies of this kind were done for
active prominences (AP) (as AP’s we shall generally denote here all coronal structures
sufficiently cold to emit Hz and with considerable mass motions). From the radiative-
transfer point of view, the most important difference (and difficulty) is the presence
of strong velocity fields in AP’s, contrary to QP’s where we frequently use a simple
one-dimensional static geometry (i.e., the plane-parallel slabs of the finite thickness).
It is well documented from many observations of AP’s that their macroscopic velocities
in the corona can reach tens to hundreds of km s\(^{-1}\) and also their internal motions
(turbulence) are often of considerable value (see Tandberg-Hanssen, 1974; Engvold,
1980). There is no doubt that such strong velocity fields can significantly influence both
the internal structure of the prominence, as well as its global energy balance. Therefore,
it seems to be highly desirable to advance our knowledge of radiation hydrodynamics
of the prominence plasma moving in the magnetic field. In fact, there exist several papers
dealing with various MHD aspects of such problem (see, e.g., Shibata et al., 1982), but
no detailed investigation was undertaken to estimate possible effects of these velocity
fields on the prominence radiation. Simply speaking, except of a few rather crude
estimates (see below), there is no quantitative answer even to such trivial questions as

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'how the prominence brightness in different spectral lines will depend on the macroscopic velocity, keeping other prominence parameters fixed for the moment?' This question is closely linked with any spectral diagnostics of moving prominences, as well as with a quantitative analysis of the prominence filtergrams as obtained from usual coronographic observations. Therefore, we address the present paper to detailed non-LTE study of the radiation transport in moving prominences, starting with the hydrogen spectrum.

The brightness changes we have in mind above all are those induced by velocity-dependent variations of the atomic-level populations and in the literature they are usually called the Doppler-brightening and/or Doppler-dimming effect (DBE, DDE). DBE occurs when the amount of the photospheric-chromospheric radiation incident on the prominence in the wavelength range of its line absorption profile increases due to the relative motion of the scattering prominence with respect to the solar surface, thus increasing the radiative excitation rate for a given line transition. On the other hand, DDE will take place when the intensity of irradiation falling in the wavelength range of the line absorption profile of a prominence decreases due to the above mentioned relative motion. While DBE occurs for lines having their photospheric-chromospheric counterpart in the form of a Fraunhofer line (e.g., Hα), DDE takes place in the case of incident emission lines such as Lx. However, these rather schematic definitions are strictly valid only for two-level-atom transitions. For the more realistic multi-level case, both DBE and DDE occur simultaneously to determine, through different atomic transitions, the velocity-dependent atomic level-populations from which the brightness variations can be directly deduced. The most important effects occur in the source functions dominated by the scattering of the incident solar radiation. However, especially AP's, can exhibit relatively higher electron densities (Hirayama, 1979) and, therefore, some line source functions become collisionally-dominated thus lowering both DBE and DDE.

Historically, DBE for the solar studies has been defined and qualitatively demonstrated by Rompolt (1967a, b; 1969). Subsequently, Rompolt (1980a, b) made some quantitative estimates of DBE for the first Balmer lines of hydrogen, using a two-level atom model (see following sections). The importance of DDE for the hydrogen Lx line was pointed out by Hyder and Lites (1970) who made a first attempt to interpret quantitatively the calibrated Hα-filtergrams of a moving eruptive prominence, accounting — in a schematic way — for a combined action of DDE in Lx and DBE in Hα on the Hα emission itself. Note that more detailed estimates of possible DDE in Lx have been made by Rompolt (1980c), who computed the incident Lx intensity as seen by the moving prominence and supposed that the incident intensity in the wavelength range of the prominence Lx absorption profile are also representative of Lx radiation inside the prominence.

Some observational evidences support the idea that DBE, together with DDE, can exhibit a pronounced influence on the amount of radiation emitted by rapidly moving objects. Hyder (1968) supports the opinion that DBE can play an important role in the observed brightenings of prominences and of some of the moving features above the solar limb that appear to be brighter than the mean Hα chromosphere. In the opinion
of Beckers (1968), DBE can be significant in explaining the observed brightness of spicules. Ramsey et al. (1975) and LaBonte (1979) suggest that part of the Hα enhancement in the moving material of the macrospicules is caused by the DBE. Similarly, a sudden brightening of an erupting filament observed in Hα in the phase of its rapid rise can be interpreted, according to Roy and Tang (1975) as caused by the DBE, although a sudden change of the physical conditions inside the filament offers an alternative explanation. Finally, Webb and Jackson (1981) interpret the effect of decreasing Hα prominence brightness in eruptive prominences in terms of DDE in Lyman lines.

In a recent paper, Kawaguchi et al. (1984) have interpreted two examples of active prominence brightenings in terms of (i) Doppler shifting of the Hα emission line with respect to the filter pass-band, (ii) DBE, and (iii) intrinsic variations of the physical state of the prominence plasma. In contrast to the case studied by Hyder and Lites (1970), these authors conclude that the observed brightness changes are probably due to intrinsic plasma variations and that the DBE plays only a marginal role. However, also in this study all conclusions are drawn without solving the non-LTE transfer problem.

To evaluate numerically the velocity-dependent brightness variations in all hydrogen lines arising from a five-level model atom, we adopt an approach that Mihalas (1978) calls ‘kinematics’ of radiative transfer in moving media, i.e., given the velocity, prominence location and a physical model, we compute the overall excitation and ionization balance of hydrogen plasma and evaluate the emergent synthetic spectrum. We simulate a monotonic velocity flow by solving the transfer problem for optically-thick transitions (lines and continua) in a one-dimensional slab with prescribed velocity-dependent boundary conditions. As a second approach, we put all optically-thick transitions into detailed balance, and for the remaining optically-thin lines and continua we fix the corresponding radiative rates by the incident photospheric-chromospheric radiation.

2. Non-LTE Hydrogen-Line Formation in Moving Prominences

In the present paper we solve in detail the non-LTE problem of radiative transfer in moving prominences in order to determine the velocity-dependent hydrogen level populations. With these populations we compute the integrated hydrogen-line intensities, which directly reflect the prominence brightness variations caused by the macroscopic velocity changes. However, as mentioned in the introduction, there is an inherent ambiguity due to the unknown prominence geometry. Since this study’s main purpose is to describe the overall behaviour of the prominence brightness variations rather than at explaining the actual observations, we use simplified approximations for this exploratory work to avoid a complicated multidimensional solution.

2.1. Optically-thin Moving Prominence (Case A)

In this first case we assume that the prominence plasma is optically thin in all subordinate hydrogen transitions and that all Lyman lines and continuum are suf-
ficiently thick to ensure the detailed balance in these resonance transitions. Further, we
suppose that the departures from detailed balance near the prominence boundaries do
not affect significantly the formation of optically thin lines (the main contribution to
optically thin emission is assumed to come from the central parts of the prominence
body). We note that a similar approach was widely used for QP's by the Kiev group,
except for assuming that all subordinate lines are optically thin (see, e.g., Yakovkin et al.,
1979). Moreover, Heasley and Milkey (1978) made a direct comparison of their full
non-LTE solution with that assuming detailed balance in all Lyman lines and found that
in order to determine the QP’s emission in the hydrogen lines of subordinate series, it
is not necessary to solve explicitly the transfer problem in Lyman lines.

In this approximation we need not solve the radiative transfer equation (RTE), and
the only problem is to solve the equations of statistical equilibrium (ESE) with the
radiative rates fixed by the incident solar radiation. We assume that the time-scales of
the prominence-plasma changes are large compared to a mean relaxation time in ESE
and, therefore, we simply use stationary ESE for each (discrete) prominence velocity
separately. For a five-level hydrogen atom, the corresponding ESE for the levels 2–5
and continuum states will be represented by four linearly-independent equations of the
form

$$A \cdot (\bar{n}_3, \bar{n}_4, \bar{n}_5, \bar{n}_e) = B,$$  

(2.1)

where $\bar{n}$’s are defined as

$$\bar{n}_j = n_j/n_2 \quad (j = 3–5), \quad \text{and} \quad \bar{n}_e = n_e/n_2.$$  

(2.2)

In these equations, the $n$’s are the level populations and $n_e$ is the electron density. $A$
represents the rate-matrix and $B$ is a vector containing all upward rates from the second
level. The evaluation of the velocity-dependent radiative rates is discussed in
Section 2.3, all collisional rates are computed according to Mihalas et al. (1975). As the
basic input parameters we use here the kinetic temperature $T$ and the electron density
$n_e$. Therefore, from the solution of the system (2.1),

$$\bar{n} = (\bar{n}_3, \bar{n}_4, \bar{n}_5, \bar{n}_e) = A^{-1} \cdot B,$$  

(2.3)

we can derive immediately all level populations $n_i (i = 2–5)$. Now, for optically thin
transition $i \leftrightarrow j (i < j)$, the integrated intensity can be written in the form

$$E \sim n_j g_i / g_j,$$  

(2.4)

where $g$’s are the statistical weights of the levels involved in this transition. Since our
principal interest is to determine the velocity-dependent brightness variations in different
hydrogen lines, we define the relative intensity (or brightness) $W$ as (see also Rompolt,
1980a)

$$W \equiv E(v)/E(0) = n_j(v)/n_j(0).$$  

(2.5)

Note that from this relation we shall arrive at the same $W$ for the lines H$\beta$, P$\alpha$, and for
the lines H$\gamma$, P$\beta$, B$\alpha$, since both these groups of lines have the common upper state (see
figures in the subsequent section). $W$ is the quantity of most immediate interest in this paper and will be also used in our full non-LTE solution (see next subsection). For a strict two-level atom without collisions, $W$ takes the form

$$W = \frac{n_i(v)}{n_i(0)} \frac{R_{ji}(v)}{R_{ji}(0)} \frac{R_{ji}(0)}{R_{ji}(v)},$$

(2.6)

where $n_i$ is the population of the lower level and $R$'s are the radiative rates. This form was used by Rompolt (1980a, b) for evaluating $W$ for Balmer lines assuming no variations of the lower-level population (i.e., $n_2$) and neglecting stimulated emissions. Under these circumstances, $W$ is simply given by the ratio of upward radiative rates:

$$W = \frac{R_{ji}(v)}{R_{ji}(0)}.$$  

(2.7)

2.2. Optically-thick case (Case B)

As a second approach, we solve the full non-LTE problem of radiative transfer for all relevant hydrogen transitions, using a 5-level atom with continuum and assuming one-dimensional geometry (i.e., vertically-standing slab of finite thickness). The motion of the prominence is simulated by using velocity-dependent boundary conditions (see next subsection). This approach has two-fold significance: (i) by using rather thin slabs to represent one isolated ‘moving’ structure (knot, blob, thread, etc.) we obtain a resemblance with our optically-thin Case A, but with explicit solution for all optically thick Lyman lines and continuum. Therefore, we can test our assumptions made in sub-Section 2.1 simply by comparing the results obtained for the same situations. (ii) We obtain the velocity-dependent level populations $n_i (i = 1-5)$ and electron density $n_e$, depending on the basic input parameters $M$, $T$, $p$, $v_i$, and $y$. $M$ is the total columnar mass along the line of sight, $T$ is the kinetic temperature, $p$ represents the total gas pressure, and $v_i$ characterizes the mean microturbulent velocity. To obtain the density structure, the prominence is assumed to be composed of hydrogen and helium only, with abundance ratio $y = 0.1$. Since we now solve for each of the $n$'s, we can evaluate the brightness variations in Lyman lines, which was not possible in Case A. In this way, we try to answer the question of DDE in L$_\alpha$ line and to demonstrate the behaviour of other Lyman lines.

The numerical procedure for solving this non-LTE problem for AP's is the same as that used by Heinzel et al. (1987) for quiescent prominences. We solve simultaneously RTE's in all Lyman transitions and in H$_\alpha$ (the radiation field in other lines and in subordinate continua is fixed by the incident solar irradiation) together with ESE and particle and charge conservation equations. As a basic iteration loop we use the linearization scheme similar to that of Mihalas et al. (1975), supplemented by several equivalent-two-level-atom (ETA) iterations to accelerate the convergence. Hydrostatic equilibrium is treated iteratively. We use all relevant opacity sources for hydrogen in prominences, hydrogen atomic data were compiled from several different sources (inelastic collisional rates are computed in the same way as in Case A). For all technical details concerning these non-LTE computations see Heinzel et al. (1987). Note that we
use here the complete frequency redistribution for all lines, in order to simplify the non-LTE solutions. In fact, partial redistribution affects mainly the resonance-line profiles and to a lesser extent the integrated intensities – at least for thinner structures (see Heinzel et al., 1987). Moreover, since we deal entirely with the ratios of integrated intensities, complete redistribution seems to be a good starting approximation.

2.3. INCIDENT PHOTOSPHERIC AND CHROMOSPHERIC RADIATION FIELDS

Photospheric and chromospheric radiation incident on the prominence at a given height $H$ (see Figure 1) determines (i) the velocity-dependent radiative rates for all optically-thin transitions and (ii) the velocity-dependent surface boundary conditions for optically-thick slabs treated in the Case B. Both these quantities have been carefully precomputed for a representative grid of radial velocities, heights, and line Doppler widths, using the technique described by Heinzel (1983) (see also Rompolt, 1967a, b). The line radiative rates depend directly on the mean integrated incident intensity

$$\overline{J} = \int_{0}^{\infty} \phi(v)J_{0}(v) \, dv,$$  \hspace{1cm} (2.8)
where $\phi(\nu)$ is the line absorption profile (Gaussian for optically-thin lines) and $J_0(\nu)$ represents the mean incident radiation intensity as seen by the prominence moving relatively to the radiation field coming from the solar surface. $J_0(\nu)$ is expressed as the integral

$$J_0(\nu) = \frac{1}{4\pi} \oint I_0 \left( \nu + \frac{\nu_0}{c} \nu ', \nu' \right) d\nu', \quad (2.9)$$

with $I_0(\nu, \mathbf{n})$ being the specific intensity of the incident photospheric and chromospheric line radiation (see Figure 1). In Case A, $\bar{J}$ appears directly in the rate matrix $A$ and the vector $B$. For optically thick case (case B), we use to advantage the symmetry properties of the slab, which is irradiated symmetrically from both sides by the same radiation field, and solve the transfer problem for one half only. In this situation, the corresponding second-order boundary conditions require the knowledge of $J_0(\nu)$ at the surface.

Fig. 2. Mean intensities of the incident Lα emission profiles as seen by a moving prominence (at the height $H = 50,000$ km). The profiles are displayed for the velocities ranging from 0–280 km s$^{-1}$. 

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boundary of the slab (see Heinzel et al., 1987). Moreover, since we use here the complete frequency redistribution for the scattering of line photons, we symmetrize $J_0$ to obtain

$$\tilde{J}_0(v) \equiv \frac{1}{2} [J_0(v_0 + \Delta v) + J_0(v_0 - \Delta v)].$$

(2.10)

This frequency-symmetrization simplifies the solution of RTE, which is performed by using the Fautrier method. In Figures 2–4, we display $\tilde{J}_0(\lambda)$ for the lines L$\alpha$, L$\beta$, and H$\alpha$. Note that the radiative rates for all subordinate transitions, including continua, are computed in the same way (except of H$\alpha$) in both approaches A and B, which partly ensures a compatibility of both these approximations. In fact, the only difference between A and B lies in the way the Lyman transitions and H$\alpha$ are treated. Moreover, in both these approaches we use no explicit dilution factors for the lines since the dilution of the radiation field is automatically inherent in $J_0$ or $\tilde{J}_0$, which are precomputed for a given height $H$ using the limb-darkened incident profiles (see below). The continua

Fig. 3. Mean of the incident L$\beta$ emission profiles as seen by a moving prominence. The profiles are displayed for the velocities ranging from 0–280 km s$^{-1}$.
are treated in two different ways: optically thick Lyman continuum transfer requires the specification of the mean intensity at the surface (for suitably chosen grid of continuum frequency points) – this is done by using the ‘incident’ radiation temperatures equivalent to the intensity on OSO-6 satellite (Vial, 1982). For subordinate continua we use one mean $T_{\text{rad}}$ at the head of the continuum: for Balmer, Paschen, Brackett, and Pfund continua we specify $T_{\text{rad}} = 6300, 6060, 6610, 6360$ K, respectively (without a dilution factor which is accounted for as an additional parameter for the continua, depending on $H$). The treatment of optically thin continua with fixed rates is the same as in Mihalas et al. (1975). $T_{\text{rad}}$ specified above are very similar to those used by Heasley et al. (1974) and correspond to the values observed near the head of the continuum. However, as pointed out by Gouttebroze (1986), these values neglect the line blanketing effect in determining the mean continuum intensity and, therefore, they are overestimated, particularly in the region of Balmer continuum where a lot of Fraunhofer lines exists.

![Graph](image)

**Fig. 4.** Mean intensities of the incident Hα profiles as seen by a moving prominence. Otherwise the same as in Figure 2.
A more realistic set of $T_{\text{rad}}$ leads to somewhat different $n_e$, but the qualitative behaviour of our results is unchanged. Finally, we shall mention our sources for hydrogen-line incident radiation fields – the results of all computations depend sensitively on the accuracy with which these quantities can be specified. All data used here have been taken from observations. Limb-darkened profiles of David (1961) are used for the first four Balmer lines, $P_x$, $P_\beta$, and $B_x$ lines have been determined according to Zelenka (1976, see references therein). All line profiles have been adjusted to limb-darkened continuum levels by using the polynomial expansions (Pierce and Slaughter, 1977; Pierce et al., 1977). Disc-center intensities for continua are taken from Pierce and Allen (1977). Lx and L$\beta$ profiles come from OSO-8 observations (see Vial, 1982), L$\gamma$ and L$\delta$ were assumed to have the same profile as L$\beta$ but are scaled by the ratio of the total intensities L$\gamma$/L$\beta$ and L$\delta$/L$\beta$. Integrated L$\gamma$ and L$\delta$ intensities have been taken from Vernazza and Reeves (1978).

3. Numerical Results and Discussion

3.1. Optically-thick Case

We start our discussion with the results obtained for Case B. Note that some preliminary results were reported by Heinzel and Rompolt (1986). Since the complete non-LTE solution for several values of macroscopic velocity is time-consuming, we have selected only one representative model in order to show the general behaviour of optically-thick lines and to make a comparison with optically-thin Case A. As the basic input parameters for this model we have used the set $M = 1.2 \times 10^{-5}$ g cm$^{-2}$, $T = 6500$ K, $p = 0.1$ dyn cm$^{-2}$, $v_t = 0$ km s$^{-1}$. This model represents an isothermal-isobaric moving prominence structure with a higher value of the total gas pressure, corresponding to an

<table>
<thead>
<tr>
<th>Velocity (km s$^{-1}$)</th>
<th>$n_1(c)$</th>
<th>$n_2(c)$</th>
<th>$n_3(c)$</th>
<th>$n_4(c)$</th>
<th>$n_5(c)$</th>
<th>$n_6(c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.48 + 11</td>
<td>0.81 + 4</td>
<td>0.77 + 2</td>
<td>0.24 + 2</td>
<td>0.20 + 2</td>
<td>0.28 + 11</td>
</tr>
<tr>
<td>40</td>
<td>0.55 + 11</td>
<td>0.67 + 4</td>
<td>0.27 + 2</td>
<td>0.96 + 1</td>
<td>0.11 + 2</td>
<td>0.24 + 11</td>
</tr>
<tr>
<td>80</td>
<td>0.46 + 11</td>
<td>0.88 + 4</td>
<td>0.12 + 3</td>
<td>0.41 + 2</td>
<td>0.31 + 2</td>
<td>0.29 + 11</td>
</tr>
<tr>
<td>160</td>
<td>0.55 + 11</td>
<td>0.61 + 4</td>
<td>0.57 + 2</td>
<td>0.20 + 2</td>
<td>0.17 + 2</td>
<td>0.24 + 11</td>
</tr>
<tr>
<td>240</td>
<td>0.51 + 11</td>
<td>0.57 + 4</td>
<td>0.86 + 2</td>
<td>0.31 + 2</td>
<td>0.24 + 2</td>
<td>0.26 + 11</td>
</tr>
<tr>
<td>320</td>
<td>0.55 + 11</td>
<td>0.55 + 4</td>
<td>0.84 + 2</td>
<td>0.30 + 2</td>
<td>0.22 + 2</td>
<td>0.24 + 11</td>
</tr>
</tbody>
</table>

0.48 + 11 = 0.48 \times 10^{11}$ cm$^{-3}$.
active prominence (see, e.g., Hirayama, 1979). However, the value of \( M \) corresponds to a geometrical thickness of only 650 km and, consequently, the moving structure is optically-thin in all subordinate transitions. The numerical computations were done for the radial velocities in the range 0–240 km s\(^{-1}\) and for a height of 50000 km (radial motions exhibit most pronounced effects of velocity-dependent brightness variations, i.e., DBE or DDE). One-half of the symmetrical slab is stratified into 33 layers, 2–3 linearization iterations, supplemented by a few ETA-iterations, are sufficient to achieve a global convergence for all transitions and level populations at all depths. As a result, we obtained the velocity-dependent hydrogen level populations from which we computed the integrated line intensities, \( E(v) \), and the relative brightness \( W(v) \) defined by Equation (2.5). Level populations for model B are summarized in Table I.

As pointed out by Rompolt (1980c), the population of the second level generally decreases with increasing velocity, except for a small rise at the surface, caused by the peaked incident L\( \alpha \) line radiation – see also \( J_0 \) in Figure 2. Consequently, the L\( \alpha \)-brightness decreases as demonstrated in Figure 5. A much more complicated

![Graph](image)

**Fig. 5.** Relative brightness variations versus radial velocities, as calculated for case B (full lines). Dotted-dashed line corresponds to Hz as computed for case A. Dashed-line corresponds to Hz emission arising from a two-level atom.
situation takes place for the third level. Its population depends on three factors: (i) DDE in Lα, (ii) a similar effect in Lβ, and (iii) an important DBE in Hα line. The rate of radiative excitation in these lines is roughly proportional to $\tilde{J}_0(0)$ indicated in Figures 2–4 (near the surface for Lα and Lβ and everywhere for optically-thin Hα). In this way, the third-level population increases markedly for velocities up to about 150 km $s^{-1}$ (DBE in Hα is dominant), and then decreases due to action of DDE in Lα and Lβ. Since the third level represents a common upper state for both Lβ and Hα, the behaviour of brightness variation of these two lines is similar except for higher velocities, where optically thin Hα still exhibits DBE while the surface emission of Lβ is strongly affected by DDE in Lβ itself (see Figure 5). DBE in Hα takes place for velocities up to about 160 km $s^{-1}$, which is in good agreement with an estimate made by Hyder and Lites (1970) and by Rompolt (1980c). Note that Lγ and Lδ behave quite similarly to Lβ. The remaining subordinate lines, which are optically thin, vary as $n_j(v)/n_j(0)$, where $n_j$ is the population of their upper level (see Equation (2.5)). The brightness variations of these lines as obtained from the present model are shown in Figure 6 for a comparison with the results obtained for Case A (see below). Finally, in Figure 5 we compare our exact Hα brightness with that following from a two-level-atom approximation, represented by Equation (2.7). Significant difference between these two curves results from multi-level interlocking and DDE in Lα and Lβ, neither of which is accounted for by two-level atom model.

Since our model hydrogen atom was truncated at the fifth level, the population of this level together with the intensities of all lines arising from it can be somewhat unspecfic. We have also made some tests with a 3-level hydrogen atom for which $E$(Hα) was found

![Figure 6](image-url)  
Fig. 6. The results obtained for case B are displayed by dashed lines for comparison (for Hα see Figure 5). Relative brightness variations versus radial velocities, as computed for the optically thin case A, are shown for the same model parameters as in Figure 5 (full line).
to be about 13% lower than that corresponding to 5-level case, simply due to omission of cascades from higher levels populating the third level. However, the quantity $W$ is practically unchanged, with difference only 1–2% and, therefore, it seems to be possible to use only 3-level atom representation to determine $W$ for Lα, Lβ, and perhaps Hα. The effect of the number of hydrogen levels used in the model on Balmer-line intensities was also demonstrated by Heasley and Milkey (1978), who found an increase of Balmer-lines intensity for an atom with more levels taken into account.

3.2. Optically-thin case

The numerical computations for Case A are extremely fast because we have to evaluate only the radiative rates for a given velocity and then to invert the $4 \times 4$ rate matrix $A$. The linearization procedure requires the same rates, but the size of matrices to be inverted at each depth is $66 \times 66$ (60 frequency points, 5 + 1 levels). Fortunately, as we have found from our previous computations, the electron density $n_e$ varies only very slowly with velocity and remains practically unchanged for velocities up to about 160–200 km s$^{-1}$ (see Table I). For higher $n_e$, which can be met in AP’s, the electron density should be even more constant because the collision-dominated rates do not depend on the velocities. Using this nearly-constant behaviour of $n_e$, we have first computed the level populations and subordinate-line brightness variations to allow a comparison with the corresponding values obtained from the optically-thick model. With $n_e = 2.43 \times 10^{10}$ cm$^{-3}$, which is consistent with the electron density in the center of the slab for zero velocity (see Table I), we obtained the results similar to those indicated in Table I. Corresponding $W$’s are displayed in Figure 6. The agreement between both approaches is very promising, at least for the velocity range 0–150 km s$^{-1}$. Certain differences for high velocities are caused by a decrease of $n_e$, which is neglected in the optically-thin case (in fact, taking $n_e = 2.32 \times 10^{10}$ cm$^{-3}$, one recovers quite well the level populations for $v = 240$ km s$^{-1}$). As supposed, the overall agreement is achieved for central values of level populations and not for the surface values. Note also that Hα is the only optically-thin line explicitly treated in Case B (i.e., RTE is solved for it), while in Case A it is evaluated only approximately as other subordinate lines. The good agreement indicated in Figures 5 or 6 justifies the assumptions made in Case A. Thus, for optically-thin subordinate transitions in moving prominence structures having $n_e \gtrsim 10^{10}$ cm$^{-3}$, the brightness variations can satisfactorily be determined using approach A, at least for the velocities below 200 km s$^{-1}$.

Having established the validity of approach A, we subsequently computed – at low cost – several model examples, indicating the dependence of subordinate-lines brightness variations on the basic parameters $n_e$, $T$, $v$, and $H$. All results thus obtained are displayed in Figures 7–12, where three curves correspond to three sets of lines having a common upper state: (Hα), (Hβ, Pα), (Hγ, Pβ, Bα). Figure 7 with the model parameters indicated there should represent a reference for a comparison with other cases. First, we have studied the influence of the electron density. As expected, for lower $n_e$ (Figure 8), DBE in all lines is more pronounced because the velocity-independent collisional rates play a negligible role in determining the line source function. On the
Fig. 7. Relative brightness variations versus radial velocities, as computed for the optically thin case A, are presented for the model parameters indicated.

Fig. 8. The same as in Figure 7, but for another set of model parameters as indicated.

other hand, when increasing $n_e$ up to the values found in very bright AP’s or limb flares, DBE is diminished since the line source function becomes collision-dominated (Figure 9). The effect of increasing the kinetic temperature is two-fold: (i) the broadening of the line absorption profile leading to a higher value of $E(0)$ while $E(\nu)$
for large velocities remains unchanged (absorption in a flat continuum). As a consequence, $W$ exhibits less pronounced variations even when $E(0)$ is higher than for a lower temperature (see Figure 10)! In a sense, the line broadening causes an additional DBE. (ii) A higher temperature also strengthens the collision rates thus lowering DBE. Next sample, Figure 11, shows DBE in the case of a strong turbulent broadening, which
Fig. 11. The same as in Figure 7, but for another set of model parameters as indicated.

can take place during some stages of AP's development (see Tandberg-Hanssen, 1974). As for higher temperature, \( E(0) \) is higher when turbulence is present, but again \( W \) is lower for higher velocities when compared with the case without turbulence (see Figure 11). Note also that other kinds of internal prominence motions like rotation, expansion, etc., can also give rise to DBE (see Rompolt, 1975 or 1976; Ciurla and

Fig. 12. The same as in Figure 7, but for another set of model parameters as indicated.
Rompolt, 1975, 1977; Rompolt and Ciurla, 1976). The last example, Figure 12, demonstrates the height variation of DBE: since we use the limb-darkened incident profiles (see Section 2.3), the dilution of radiation depends on the height in a rather complex manner and cannot be approximated simply by one dilution factor for all lines. Note that detailed analysis of Hα and other Balmer lines variations was undertaken by Rompolt (1980a, b) for the range of heights 0–700 000 km, for the velocities ranging from 0 to 300 km s⁻¹ and for various directions of the prominence motion relative to the solar surface. However, all these results were obtained for a two-level-atom model and thus can be viewed only as a rough estimate of the general behaviour of such variations.

3.3. DISCUSSION

Our approach B belongs to a class of 'exact' solutions of highly nonlinear non-LTE problems and its drawback, from the radiative transfer point of view, is the planar geometry used here. More complex geometry, in connection with the linearization technique, would require extremely large computer memory and long execution times. A more economical approach may be to use an equivalent two-level atom following a technique developed recently by Mihalas et al. (1978) and applied, for example, by Vial (1982) for QP's. Another procedure which seems to be promising for the future work of this kind is that described by Carlsson and Scharmer (1985) who use approximate radiative transfer operators. Our optically-thin approach is, on the other hand, computationally very convenient, apart from considerations of geometry. However, it requires the knowledge of the electron density. We have found in the present study that the electron density $n_e$ varies only slowly with velocity and for the velocity range of approximately 0–150 km s⁻¹, $n_e$ is nearly constant. Therefore, we conclude that the actual variations of $n_e$ are mainly due to changes of the gas pressure caused by an expansion or compression of the prominence plasma. To assess these variations, we should include more realistic MHD equations into our approach B where the gas pressure appears as one of the basic parameters. In summary, a suitably chosen combination of both methods A and B can serve as a useful tool for a first quantitative analysis of the observed brightness variations. Moreover, approach A can be somewhat generalized leaving the assumption of optically-thin lines (at least for some lines) and assuming only a constant source function for subordinate-line transitions.

Detailed computations of radiative transfer in static slabs using the partial-frequency redistribution (PRD) in Lα and Lβ were performed by Heinzelt al. (1987). Although we suppose here that the complete redistribution (CRD) is a good starting approximation for the purpose of this exploratory work, certain effects of PRD are to be expected for moving prominences. The reason is that for higher velocities most of the incident Lα and Lβ radiation is absorbed in the wings and the quasi-coherent penetration of this incident radiation into the prominence body will lead to different excitation of hydrogen inside the prominence as compared to the CRD case (see Heinzelt al., 1987). In this way, DDE will also be changed. On the other hand, the optically-thin emission lines seem to be unaffected by PRD. This situation was studied by Heinzelt (1983) for the
static case, and his results indicate that for a moving structure possible departures from PRD are even less pronounced.

When solving the PRD transfer problem in $L\alpha$ and $L\beta$ lines formed in homogeneous slabs, Heinzel et al. (1987) arrived at significant controversy between theoretical and observed $L\beta$ intensities. It seems that a lateral radiation transport through the prominence filamentry structure could be responsible for such discrepancy, although other mechanisms cannot be ruled out at present. However, in our case of the AP we deal rather with one isolated structure (knot, blob, thread, etc.) so that the $L\beta$ emission should be correct, providing that the actual reason for the discrepancy met in QP's is the lateral transfer. Nevertheless, we cannot exclude a possibility that even such well isolated structures are composed of many unresolved threads.

4. Conclusions

Using a combination of two non-LTE techniques, we have investigated in the present paper the general behaviour of the prominence brightness variations in all hydrogen lines arising from a five-level atom model, depending on the prominence motion in the corona. We have quantitatively shown the actual importance of DBE and DDE in different lines and, more generally, we demonstrated how the prominence intensity varies due to the changes of various macroscopic parameters. Our formulation of optically-thin and optically-thick models is in some sense similar to that of Gouttebroze et al. (1986), who computed $L\alpha$ emission emergent from static coronal loops. It can be equally used also for other coronal structures defined in the introduction as AP’s, i.e., for various types of ejecta, limb-flares, cool coronal loops, edge-ejecta in QP’s, jet-like structures and coronal transients. This formulation also recovers the whole class of problems discussed by Loughhead et al. (1985). The general aim of this paper was to establish a basis for a more sophisticated analysis of these active phenomena, particularly for an adequate spectral diagnostics of plasma variations and a deeper understanding of the relevant radiation-hydrodynamical processes. From the observational side we need simultaneous spectral measurements in as many as possible different lines, including also such line transitions which are less sensitive to velocity changes (e.g., $D_3$ line of HeI) and which can help us to separate different mechanisms leading to the observed brightness variations. We plan to do such observations by using a multi-channel solar spectrograph with sufficient temporal resolution.

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