LINE BLANKETING IN THE LYMAN-ALPHA WINGS

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SUMMARY.— A schematic study of the formation of lines in the Lyman-alpha wings in A and late B stars is presented. It is demonstrated that lines situated in the Lyman-alpha wings have very complex profiles, and in several cases they can appear strongly in emission. This emission tends to increase with increasing abundance and with decreasing distance from the Lyman-alpha centre. It is tentatively suggested that this effect can explain the anomalous brightness variations in the Lyman-alpha wings of \( \alpha^2 \) CVn and similar stars.

INTRODUCTION

The far ultraviolet spectrum, particularly the region of the broad Ly \( \alpha \) wings, is of considerable interest in studying both normal and peculiar A type stars. The importance of the partial redistribution treatment of the Ly \( \alpha \) line and its role in constructing model atmospheres have been pointed out by Hubený (1980 - Paper I). A thorough analysis of the Ly \( \alpha \) region in normal A stars has been performed by Hubený (1981 - Paper II). Although the approach used in Paper II has been found capable of explaining the overall shape of the observed Ly \( \alpha \) region in Vega (Paderewski, 1981), a detailed interpretation of observed features require a careful treatment of a number of weak lines situated in the Ly \( \alpha \) wings.

This question is interesting from both the theoretical and observational points of view. Methodologically, the Ly \( \alpha \) wings form a strong scattering continuum for weak lines, moreover with strongly frequency- and depth-dependent portions of the continuum scattering. This can be viewed as an interesting example of the classical Schuster mechanism.

An interesting observed feature, besides the apparent asymmetry of Ly \( \alpha \), is the anomalous brightness variation in the wings of Ly \( \alpha \) (1190 < \( \lambda \) < 1250 \( \AA \)) in \( \alpha^2 \) CVn (Leckrone and Snijders, 1979) - this region appears brighter in the phase of minimum brightness of the remainder of the ultraviolet. The latter authors explained this effect qualitatively by means of the presence of a number of Cr III lines (the chromium abundance of \( \alpha^2 \) CVn appears to vary in antiphase with rare-earths - Cohen, 1970).

However, as some results of Paper II show (e.g., a prediction of the emission jump in the C I 2p \( ^3 \) D - continuum, \( \lambda_0 = 1240 \AA \)), a combination of non-LTE effects of line formation with the scattering continuum may give, to some extent, unexpected results.

The aim of this paper is then to give an impression of the behaviour of the archetype lines formed in the Ly \( \alpha \) wings in A and late B stellar atmospheres. As the real spectrum in the Ly-alpha
region is quite complex, we have chosen a very schematic but instructive approach: we consider a "fictitious" line, defined by its opacity, source function, and position, and discuss the changes of its theoretical emergent profile by varying these parameters.

METHOD OF CALCULATION

a) Model Atmospheres

We consider several non-LTE model atmospheres in radiative and hydrostatic equilibrium, with the basic parameters \( (T_{\text{eff}}, \log g) \) equal to \((9660, 4)\) and \((12000, 4)\). The models were computed with the explicit inclusion of the following ions in non-LTE: H I, H II, C I, Si I, S I. The hydrogen lines H\(\alpha\), H\(\beta\), H\(\gamma\), P\(\alpha\), P\(\beta\), B\(\alpha\) were taken into account explicitly; the Lyman lines Ly\(\alpha\) - Ly\(\beta\) were set to be in radiative detailed balance, but the effect of their wing opacities were included, allowing for partial redistribution (see Paper I). For the description of the computational method used and further discussion, see Paper II.

b) Line Opacity

For purposes of demonstration, we consider the simplest model. The fictitious line, with the central frequency \( \nu_0 \), is supposed to have a depth-independent Doppler profile, with prescribed values of the Doppler width \( \Delta \nu_\text{D} \) and oscillator strength \( f \). The line absorption coefficient is written as

\[
\kappa_\nu^L = n(z)\frac{n_e^2}{mc}(f/\Delta \nu_\text{D})\exp(-x^2)/\sqrt{2} = 1.497 \times 10^{-2} \frac{f}{\Delta \nu_\text{D}} \alpha n_\text{OII}(z) \exp(-x^2) \tag{1}
\]

where \( x = (\nu - \nu_0)/\Delta \nu_\text{D} \), \( z \) being the depth. The stimulated emission is neglected. The unknown population of the lower level - \( n(z) \) - is parametrized by means of the depth-independent parameter \( \alpha \), i.e. the population with respect to the population of the ground state of ionized carbon. The latter quantity is given by the model atmosphere considered.

c) Line Source Function

The general form of the line source function is very complex (see, e.g., Mihalas, 1978) and does not allow any simple and unique parametrization. However, an inspection of the list of lines situated in the Ly-alpha wings shows that the lines may be divided into three broad categories:

1) Subordinate lines of ions with ionization potentials much greater than that of hydrogen (\( \chi > 13.5 \) eV). The LTE source function is more or less appropriate here,

\[
S_L = B_\nu_0 \quad \text{(type LTE)} \tag{2}
\]

2) Resonance lines of such ions. We approximate the source function by its two-level-atom value, i.e.

\[
S_L = (1 - \varepsilon) \int J_\nu \varphi_\nu \, d\nu + \varepsilon B_\nu_0 \quad \text{(type RL)} \tag{3}
\]
3) There are many lines of ions with ionization potentials in the range \( 10 < \lambda < 13 \) eV; the lines then connect low-lying levels with levels near the continuum. We write the line source function as \( S_L = (b_\lambda / b_z) B_{\nu_0} \) (\( b_\lambda \) and \( b_z \) being the departure coefficients for the lower and upper levels, respectively; stimulated emission is neglected; complete redistribution is assumed). We can put \( b_z = 1 \), due to strong coupling with the continuum. On the other hand, \( b_\lambda \) is strongly depth-dependent and its actual value depends on the energy-level structure and the transition rates of the ion considered. Nevertheless, one can parametrize the unknown \( b_\lambda (z) \) by means of the departure coefficient of a suitably chosen "level of an archetype ion. In our case, we choose the 2p \( ^0 \) D level of neutral carbon with the departure coefficient \( b_\lambda (z) \). The latter is given by the model atmosphere considered. As explained in Paper II (see also Snijders, 1977), \( b_\lambda (z) < 1 \) in the region of formation of the Ly-alpha wings. We then take the line source function (called "continuum dominated" type - CD) as

\[
S_L = \left( \frac{1}{\beta b_\lambda} \right) B_{\nu_0} \quad \text{(type CD)}
\]

where \( \beta \) is the depth-independent (optional) parameter.

d) Calculation of the Emergent Profiles

The total opacity (source function) is given by the sum (weighted sum) of the line opacity (source function) and the background opacity (source function), respectively. The latter quantities, as well as \( n_{\text{II}} (z) \) and \( b_\lambda (z) \), are given by the model atmosphere considered.

The radiative transfer equation is solved by the Hermitian method (Auer, 1976).

In the subsequent applications, we consider the following values of the line parameters: \( f = 1; \lambda_0 = 1220, 1230, 1250 \) Å; \( \Delta \nu_d = 2 \times 10^6 \); \( \Delta \nu_c = 1, 10^{-2}, 10^{-4}, 10^{-6} \).

We restrict ourselves to the red wing of Ly-alpha; the behaviour of a fictitious line in the violet wing is analogous. We do not consider lines in the near wings of Ly-alpha (\( \Delta \lambda < 4.5 \) Å), because this would require more refined model atmospheres than those considered here (see discussion in Paper II).

For each central wavelength, all values of \( \Delta \nu \) for all three types of the source function are considered. The parameter \( \beta \) for the CD type is taken to be unity; \( \epsilon \) for the RL type is taken according to the Van Regemorter (1962) formula as

\[
\epsilon \approx 7.4 \times 10^{-15} n_e T^{-1/2} \left[ 1 - \exp(-h/kT) \right]
\]

where \( n_e \) and \( T \) being the electron density and temperature, respectively.

RESULTS AND DISCUSSION

The computed emergent profiles of the fictitious line, for various values of the central wavelength \( \lambda_0 \), opacity factor \( \Delta \nu \), and various types of the line source functions, are displayed in Figs. 1a-c. We consider the model atmosphere with parameters (12000, 4) only; the results for (9600, 4) (not displayed here) are analogous. Here we see quite clearly several interesting effects:
Figs. 1a-c. a: Computed emergent profile of the fictitious line with $\lambda_0 = 1220$ Å (on a logarithmic scale), for the atmospheric model (12000, 4). Left panel: LTE source function; central panel: CD source function; right panel: RL source function. Full line: $\alpha = 1$; dashed line: $\alpha = 10^{-2}$; dot-and-dashed line: $\alpha = 10^{-4}$; dotted line: $\alpha = 10^{-6}$. As the lines are nearly symmetric around the line centre, only halves of the profiles are drawn.
b: Same as Fig. 1a, for $\lambda_0 = 1230$ Å.
c: Same as Fig. 1a, for $\lambda_0 = 1250$ Å.
A great diversity of the profiles of the LTE, CD, and RL lines. The most striking effect is the appearance of emission profiles for CD and LTE lines. The shape of the LTE profiles can easily be understood by means of the classical Schuster mechanism (see, e.g., Mihalas, 1978), i.e., the line source function is equal to the thermal value everywhere, while, in the continuum, scattering causes the mean intensity of radiation (and then the source function) to drop below $B_\nu$. Its efficiency is furthermore enhanced by the NLTE atmospheric temperature rise; and decreases when one goes to greater distances from the Ly-alpha centre, as the continuum scattering portion rapidly decreases. For the CD lines, the mechanism is similar but enhanced by an increase of the line source function above $B_\nu$ due to the underpopulation of the lower level. For RL lines one always obtains absorption profiles, even if the line source function is of the collision-dominated type. The reason for this is probably that the adopted value of $A_\nu$ ($10^{-8}$ to $10^{-9}$) is a lower limit rather than an actual value.

The height of the emission peaks decreases with increasing $\alpha$, due to the reasons explained above.

The last effect offers a possibility of an alternative explanation of the anomalous behaviour of the Ly-alpha wings in $\alpha^2$ CVn. To demonstrate it, let us consider the equivalent width of the fictitious line as a function of wavelength, for each type of the source function (see Table 1.).

<table>
<thead>
<tr>
<th>Type of source function</th>
<th>Parameter</th>
<th>$\alpha$</th>
<th>$\lambda_\alpha=1220$</th>
<th>$\lambda_\alpha=1230$</th>
<th>$\lambda_\alpha=1250$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE</td>
<td>1</td>
<td>-69.9</td>
<td>3.80</td>
<td>8.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-2}$</td>
<td>-49.9</td>
<td>3.76</td>
<td>7.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$</td>
<td>-21.7</td>
<td>3.99</td>
<td>5.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-6}$</td>
<td>-1.1</td>
<td>3.16</td>
<td>3.97</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>1</td>
<td>-1768</td>
<td>-101.9</td>
<td>-1.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-2}$</td>
<td>-1496</td>
<td>-88.0</td>
<td>-1.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$</td>
<td>-1205</td>
<td>-75.4</td>
<td>-2.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-6}$</td>
<td>-468.8</td>
<td>-45.8</td>
<td>-1.72</td>
<td></td>
</tr>
<tr>
<td>RL</td>
<td>1</td>
<td>6.41</td>
<td>8.21</td>
<td>8.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-2}$</td>
<td>5.19</td>
<td>6.93</td>
<td>7.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$</td>
<td>3.32</td>
<td>5.38</td>
<td>5.87</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-6}$</td>
<td>0.44</td>
<td>2.94</td>
<td>3.78</td>
<td></td>
</tr>
</tbody>
</table>

We see that for $\lambda_\alpha=1220$ Å, the greater the abundance, the brighter the lines for LTE and CD type of the source function appear. For $\lambda_\alpha=1230$ Å, the LTE line remains roughly unchanged, while for the CD type the same as for $\lambda_\alpha=1220$ Å is valid. For $\lambda_\alpha=1250$ Å, the CD lines are weak for all abundances, while for
other types lines are darker for greater abundances.

In other words, the otherwise identical CD lines, which cause more darkening, for \( \lambda > 1250 \, \text{Å} \), when abundance increases, may cause brightening for \( \lambda < 1250 \, \text{Å} \). The analogous "critical" wavelength for the LTE lines is situated near 1230 Å.

A rough inspection of possible opacity sources in the Ly-alpha wings suggests that the above mechanism can really operate in the case of the actual spectrum. Most of singly ionized rare-earths have the ionization potentials in the range 10.5 - 13 eV (see Leckrone and Snijders, 1979). The lines of these elements, situated in the Ly-alpha wings, have then source functions which can be described by type CD (or intermediate case between CD and LTE). An enhancement of the rare-earths abundances can thus cause brightening in the Ly-alpha wings for \( \lambda < 1250 \, \text{Å} \), simultaneously with a darkening for \( \lambda > 1250 \, \text{Å} \), in agreement with the observations.

CONCLUSION

From this limited study, devoted rather to the demonstration of the problem than to its systematic investigation, we come to the following conclusions:

i) For the realistic treatment of the line blanketing in the Ly-alpha wings, it is necessary to take carefully into account partial redistribution in Ly\( \alpha \), as well as the line source function.

ii) The appearance of a great diversity of computed theoretical line profiles indicates that an identification of observed weak line features in the wings of Ly\( \alpha \) should be performed with caution.

iii) We found that the brightness of emission lines generally increases with increasing abundance and with decreasing distance from the Ly\( \alpha \) centre; this allows us to suggest an alternative explanation of the anomalous brightness variation in the Ly-alpha wings observed for \( \lambda > 1250 \, \text{Å} \).

iv) However, our calculations rest on several crude simplifications (e.g., a very simple parametrization of the line opacity and source function), which prevent our conclusions to be viewed as definite. More detailed calculations would then be needed before a suitable interpretation of the far ultraviolet spectra becomes possible.

REFERENCES