ON THE HYDROGEN ABUNDANCE IN WOLF-RAYET STARS

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ABSTRACT

With a semiempirical NLTE-model in spherical geometry we investigate the hydrogen abundance in Wolf-Rayet stars. We find that the flux contribution of the H-Balmer to the He-Pickering lines lies between the usually applied approximate formulae for the optically thin and optically thick case. This result can be understood with our finding that there are no optically thin helium and hydrogen lines. The influence of the temperature structure on the relative intensity of the hydrogen-helium blends to the helium lines is vanishingly small, even for peculiar temperature laws. The conclusion is that Wolf-Rayet stars are hydrogen deficient objects.

1. INTRODUCTION

The majority of Wolf-Rayet specialists are convinced that the elemental abundances in Wolf-Rayet stars are abnormal, especially that they are hydrogen deficient. However, up to now there have been no elaborate investigations of the formation of the helium and hydrogen lines in the extended atmospheres of Wolf-Rayet stars. To analyse the Balmer and Pickering lines the approximate formula of Castor and van Blerkom (1970, henceforth CB) for the optically thin case has usually been applied

$$\Delta \log(W_\lambda) \approx \log\left(\frac{N[H^+]}{N[He^{++}]}\right) \approx \log\left(\frac{N[H]}{N[He]}\right),$$

where $\Delta \log(W_\lambda) = \log(I(He+H)/I(He))$ is the ratio of the intensity of a Balmer-Pickering blend to the estimated intensity of the Pickering line alone. The optically thin approximation has been justified by CB, who showed that the Pickering lines from the upper level $n > 10$ are optically thin. However, the model used by CB is a one point model. This was criticised e.g. by Underhill (1982) or by Sahade (1981), who writes: *"(...) at least we ought to be cautious and not state so firmly that WR stars are H-deficent objects."* The approximation of Massey (1980) for the optically thick case takes into account the different emitting volumes of the lines. But the lines used to derive the hydrogen abundance are not expected to be optically thick.

The purpose of this paper is to investigate the formation of HI and HeII lines in a spherically extended atmosphere and the influence of the temperature structure on these line intensities.
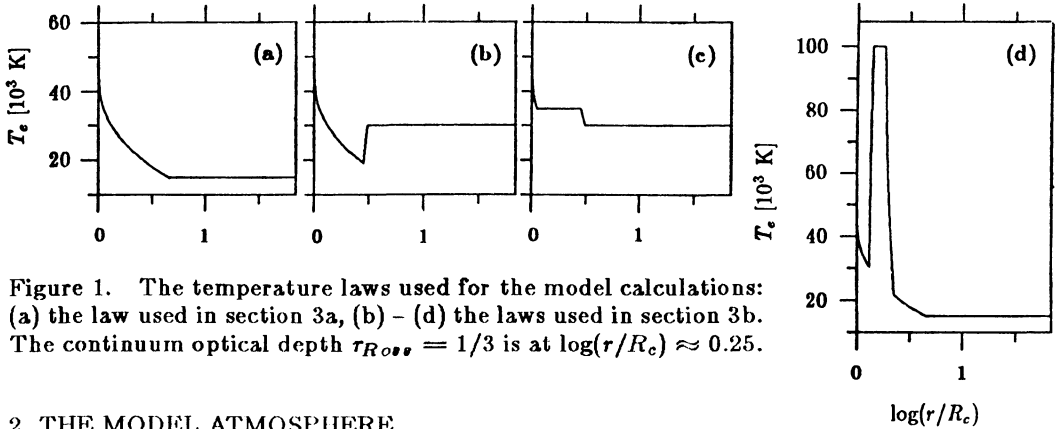
Figure 1. The temperature laws used for the model calculations: (a) the law used in section 3a, (b) – (d) the laws used in section 3b. The continuum optical depth $\tau_{R_{oss}} = 1/3$ is at $\log(r/R_c) \approx 0.25$.

2. THE MODEL ATMOSPHERE

The model is semiempirical, i.e. the velocity law $V(r)$ and the temperature law $T(r)$ are free input parameters. Further physically important input parameters are the mass loss rate and the abundances. The elements included in the calculation are hydrogen and helium. The calculation of the continuum radiation field and the level populations are performed alternately until convergence of the level populations ('Λ-iteration'). The NLTE level populations are calculated with the Sobolev approximation of Castor (1970), modified to treat the diffuse radiation field. Interaction between the helium and hydrogen lines of the same wavelength are taken into account by using the same combined escape probability for both elements. We set the inner boundary R_c where the velocity field is $V(R_c) = V_\infty/100$; we do not include deeper layers because the validity of the Sobolev approximation would break down. At the inner boundary we assume the outgoing radiation field to be $I^{out}(\nu, R_c) = B(\nu, T(R_c))$ and LTE level population. For the models presented here the inner boundary lies at $\tau_{R_{oss}} \approx 8$, therefore the observable quantities are not very sensitive to the boundary conditions.

Following Klein and Castor (1978) we write for the equivalent widths

$$W_\lambda = \frac{h\nu}{L_\nu^c} \int 4\pi r^2 \left[\beta^{out} N_u A_{u,l} - (N_l B_{l,u} - N_u B_{u,l}) J^{out}\right] e^{-\tau_\nu^c(r)}\, dr = \int E(r) + A(r)\, dr,$$

where β^{out} is the escape probability of a line photon to leave the atmosphere and J^{out} is the mean outgoing continuum radiation seen by the line at the position r.

For this investigation only the abundances and the temperature law (given in figure 1) are varied. The assumed mass loss rate is $\partial M/\partial t = 4 \cdot 10^{-5}\ M_\odot/year$ and the velocity law is

$$V(r) = 3000 \left(1 - \frac{R_c}{r}\right)^1\ [km/sec]\,,$$

with $R_c = 5.5 R_\odot$. Though we have no particular star in mind we notice that the resulting flux and line strengths resemble the LMC WN4 star FD13 (Smith and Willis, 1983).

$N[H]/N[He]$	opt. thin	opt. thick	Model
2.0	0.47	0.32	0.41
1.0	0.30	0.20	0.24
0.5	0.18	0.12	0.15
0.1	0.040	0.027	0.030

Table 1. Intensity ratio $\Delta \log(W_\lambda) = \log(I(He + H)/I(He))$ of the Pickering-Balmer blends to the Pickering line intensity.
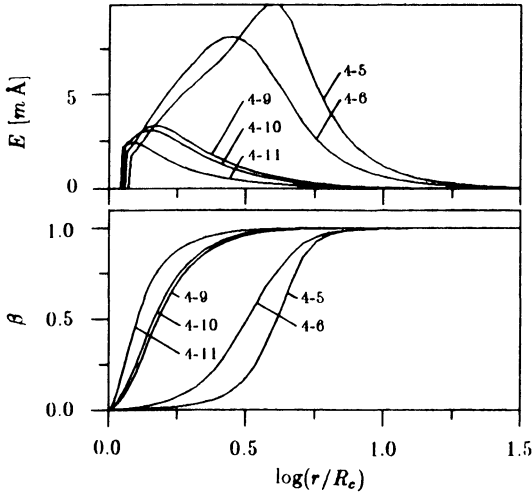
Figure 2a. He II and combined H I and He II line emission $E(r)$ (see text) as a function of radius for a model with $N[\text{H}]/N[\text{He}] = 1$. The labels on the curves refer to the He II transitions. The curves 4-6 and 4-10 include the contribution from H I 2-3 respectively 2-5.

Figure 2b. The escape probability $\beta(r)$ as a function of radius for the same transitions as in figure 2a.

3. RESULTS OF THE MODEL CALCULATIONS

(a) The Balmer-Pickering line strengths for different abundances

In Table 1 we give the calculated contribution of the Balmer to the Pickering lines for four different hydrogen abundances. Also given are the corresponding values of the two approximate formulae. It is interesting to note that our value lies between the two approximations. To understand this result we present figure 2a, where the quantity $E(r)$ from the formula above is plotted as a function of radius. In figure 2b we give the escape probability $\beta(r)$. A comparison of these two graphs shows that the main contribution to the line strength arises from the region where $\beta \approx 0.5$. This is true for all lines (except for optically thick ones), even for those from higher n. Hence, *there are no optically thin He lines*; the result of CB was an effect of the one point approximation.

The figures of Conti et al. (1983) give an idea of the quality of the observations: the detection limit is $N[\text{H}^+]/N[\text{He}^{++}] \approx 0.3$.

(b) The influence of the temperature structure

For the calculations reported in section 3a the temperature law of figure 1a was used. To analyse the influence of the temperature law, we ran the three different temperature structures given in figures 1b, 1c and 1d. Though the absolute line strengths are dependent on the laws *we do not find any measurable change of* $\Delta \log W_\lambda$. This is due to H$^+$ and He^{++} being isoelectronic. If both hydrogen and helium are fully ionized, line emissivities of H I and He II react practically in the same way to variations in N_e and T_e. This implies also that an inhomogenious atmosphere, as suggested by Underhill (1983), would have no influence on the relative line strengths of hydrogen to helium.

4. CONCLUSION

We found that there is no mechanism to suppress the H I/He II line ratio. Neither optical thickness, i.e. density structure, nor a peculiar temperature law changes the relative emission. An upper and a lower limit on the $N[\text{H}^+]/N[\text{He}^{++}]$ ratio can be set by the approximate formulae. As under all conditions He^{++} will recombine before H$^+$, the Pickering and Balmer line intensities will give an upper limit for the hydrogen abundances.

ACKNOWLEDGEMENTS

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DISCUSSION

Kudritzki: Did you include the HeII-resonance lines in your rate equations
and did you encounter then convergence difficulties within the Λ-iteration
scheme?

Schmutz: Yes, I include the HeII-resonance lines and I got indeed problems
namely that the convergence is very slow. On the basis of a few tests
I think that it is a real convergence.