THE STATISTICAL EQUILIBRIUM OF H AND He AND THE H/He RATIO IN WR STARS

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INTRODUCTION

The mixed selection of strong emission lines present in the spectra of WR stars suggests that we are observing plasma with an electron temperature of the order of 10^5 K somewhere in the atmospheres of these rare stars. In the spectra of some WR stars emission lines of H are detected; this suggests that plasma with an electron temperature of the order of 10^4 K may be present also. Since the observations made in the last 30 years show that the masses, luminosities, effective temperatures, and general distribution in space of WR stars are similar to those of stars with spectral types in the range from about B2 to O9, a prime question is why are the spectra of WR stars so different from those of the B stars with which they are associated.

In this paper we present some new theoretical results which correct conclusions about the physical state of the atmospheres of WR stars which have been widely accepted even though a careful consideration of the theory used to interpret observed line strengths would have suggested caution. We are particularly concerned with correcting the deduction that the atmospheres of WR stars are deficient in H (Castor and van Blerkom 1970; Willis and Wilson 1978; Smith and Willis 1982, 1983).

The transfer of radiation through an outer atmosphere which contains a velocity gradient and which is optically thin except for the continua and lines of one ion has been studied by Castor (1970). This theory was used by Castor and van Blerkom (1970) to study the statistical equilibrium of He^+ in the atmospheres of WR stars. It has been used by Willis and Wilson (1978) and by Smith and Willis (1982, 1983) to interpret the strengths of He II lines and lines from the C and N ions in the spectra of WR stars. The conclusion reached as a result of these studies is that the composition of the atmospheres of WR stars corresponds to that of material which has been processed by nuclear burning in the center of the star. This has led to the postulate (see Conti 1982 and Maeder 1982) that WR stars are highly evolved objects. Conti has suggested that WR stars are the remnants of massive O stars which have lost their outer layers because of strong mass loss.

The spectrum analyses upon which these conclusions stand suffer from four grave errors: (1) Castor's theory has been applied for such typical lengths and electron densities that the model atmosphere is opaque in electron scattering, a condition contrary to one of the basic assumptions of Castor's theory. (2) No study was done of the statistical equilibrium of H. Instead it was assumed that the relative populations of the levels from which observed lines arise are in LTE ratios with respect to the density of H^+ ions. (3) The model He atom used contains no levels of He I even though He I lines are quite strong in many WR spectra. (4) The statistical equilibrium of the selected C and N ions is studied taking account only of bound-bound transitions.

In the published work, the identification of the model atmospheres with the atmospheres of real stars was done in a cursory manner using only the relative strengths of He II lines in the visible range as criteria of fit. One result of this is that Willis and his colleagues claim that the electron temperatures in the atmospheres of WR stars are of the order of 30000 to 50000 K and that the electron density is of the order of 5×10^{11} cm^{-3}. They assume that hydrogen is completely absent, and they put the number density of He^+ equal to half the electron density.

MODEL ATOMS AND THE EQUATIONS OF STATISTICAL EQUILIBRIUM

We (Bhatia and Underhill 1984) have solved the equations of statistical equilibrium for a 70-level model He atom and for a 25-level model H atom in a plasma at temperature T and electron density N_e irradiated by a photosphere which emits a continuous spectrum $B_\nu(T_\star)$. The model He atom contains singly and doubly excited states of He I; dielectronic recombination of He is considered as well as all the usual bound-bound and bound-free transitons driven by radiation and by electron collisions. We used the radiative transfer theory of Castor (1970) in the manner of Castor and van Blerkom (1970) to iterate to a final set of populations for 80 model atmospheres. We assume a normal composition for the atmosphere, that is N(H) = 10 N(He), and we calculate the fractional population of the levels of both model atoms by solving the equations of statistical equilibrium.

In order to relate our model atmospheres and model spectra to the real spectra of real stars we calculated the relative energies in the lines He I 5876, He II 1640, 3203, 4338, 4686, 5411, and Hα, Hβ, and Hγ, and we compared the theoretical results with observed energy ratios corrected for wavelength-dependent interstellar extinction.

The choice of $T_\star = 2 \times 10^4$ K provides a continuous spectrum in the primary ionization continua of H, He I, and He II approximately like that of a star with $T_{eff} \sim 27000$ K. The choice $T_\star = 3 \times 10^4$ K provides a continuous spectrum which mimics that from a star with $T_{eff} = 3.5 \times 10^4$ K.

It is necessary to restrict the choice of electron density to $N_e < 10^{10}$ cm^{-3} in order that the optical depth in electron scattering may remain negligible, as it must be for Castor's (1970) theory to be valid.

THREE SIGNIFICANT RESULTS

1. The departures from LTE of He I can be large; those of He II are modest. An electron temperature of the order of 10^5 K is required to account for the observed ratio of He I 5876/He II 5411 in HD 191765, HD 192103, and HD 192163. The relative energy in He I 5876 to that in He II 5411 is sensitive to the amount of dielectronic recombination. Only when T is high does the relative energy in He I 5876 approach what is observed. Neglect of the levels of He I in the studies by previous workers prevented the use earlier of this sensitive criterion for determining the electron temperature.

2. No matter what the values of T_* and T (within the range appropriate for WR stars), the departure coefficients of the levels from which the usually observed Balmer lines arise are of the order of 0.04. This fact accounts fully for the difficulty of detecting H emission lines in the spectra of many WR stars because the departure coefficients of the levels of He^+ from which the usually observed blending Pickering lines arise are of the order of or greater than 1 when T is of the order of 10^5 K. Typically at $T \sim 10^5$ K, the predicted energy ratio He II 4338/Hγ is greater than about 4. There is no reason to conclude that the atmosphere of any WR star is deficient in hydrogen. Ratios less than 1 can be obtained if $T < 3 \times 10^4$ K and if $N_e > 10^{10}$ cm^{-3}.

3. The relative energies in He II 4686, 3203, and 5411 are insensitive to the choice of T_*, T, and N_e. The relative energies in He II 1640 and 4686, however, are very sensitive to N_e and slightly sensitive to the choice of T_*. Agreement between observation and theory indicates that $T_* = 2 \times 10^4$ K and an electron density a little larger than 10^9 cm^{-3} is appropriate for the atmospheres of the WR stars HD 191765, HD 192103, and HD 192163.

Numerical results supporting these conclusions can be found in Bhatia and Underhill (1984). A few results are given in Tables 1 and 2.

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Table 1

Predicted Relative Energies in He I 5876/He II 5411
Case $T_* = 2 \times 10^4$ K

T (10^4 K)	Case $N_e = 10^9$ cm^{-3}	Case $N_e = 10^{10}$ cm^{-3}	Observed Ratios
7.5	0.132	0.045	HD 191765: 0.3
10.0	1.07	0.367	HD 192103: 3.1
12.5	3.71	1.30	HD 192163: 0.4

Table 2

Predicted Relative Energies in He II Lines
Case $T_* = 2 \times 10^4$ K, $T = 10^5$ K

Ratio	Case $N_e = 10^9$ cm^{-3}	Case $N_e = 10^{10}$ cm^{-3}	Observed Ratios HD 191765	 HD 192103	 HD 192163
4686/5411	33.7	0.616	10.3	10.2	8.6
3203/5411	10.9	2.39	3.2	2.8	6.5
1640/4686	7.41	1.82 +5	7.4	>0.6*	8.2

*He II 1640 shows a strong central reversal.