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A PHYSICAL ANALYSIS OF WOLF-RAYET SPECTRA

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In the last few decades numerous studies made of Wolf-Rayet stars, give us a fairly representative picture of the nature of the Wolf-Rayet atmosphere. The pioneering work of Beals, Miss Payne, and Edlén provides a complete list of wavelength identifications and a thorough survey of most of the Wolf-Rayet stars brighter than the tenth photographic magnitude. In recent years, the discovery of numerous spectroscopic binary systems with Wolf-Rayet components by O.C. Wilson, W.A. Hiltner and Otto Struve, together with the demonstration by S. Gaposchkin, G. E. Kron and others of the eclipsing nature of some of them, has given a vast impetus to the development of diverse methods of analysis whereby one can gain an insight into the fundamental processes operative in a Wolf-Rayet atmosphere.

On the basis of different postulates concerning the mechanism of emission-line formation, temperatures have been derived for some Wolf-Rayet stars. Beals assumed the Zanstra-Menzel mechanism, of photoionization with subsequent recombination, to be the source of emission lines and has derived temperatures of 90,000° for HD 192103 and 70,000° for HD 184738 (Campbell's hydrogen envelope star). Aller (1) has obtained excitation temperatures for several of the brighter northern Wolf-Rayet stars. In the case of HD 192103 he derives temperatures ranging from 28,000° to 75,000° depending on the kind of ion used in the analysis. The lines of higher excitation potential like those of C IV are assumed to originate lower in the atmosphere than those of He I, implying a decrease of excitation with increasing distance from the centre. Thomas (2) considered the case wherein microscopic motion alone in the form of a $T_e > T_r$ is sufficient for atmospheric support.

T_e and T_r here, are the kinetic and radiation temperatures respectively. An increase in excitation with increasing distance from the centre is a direct consequence, a suggestion independently made by Münch (³) in his study of the Wolf-Rayet eclipsing binary V444 Cygni.

A basic characteristic, of Wolf-Rayet atmospheres in general, is the large width of the emission lines, implying a large scale motion in the emission envelope. When such motion exists, one may reasonably assume that collisional excitation plays an appreciable role. The general conditions in the atmosphere are also such that in addition we may have other processes like line radiation exciting the higher levels, as well as some photoionization with subsequent recombination. Observationally, therefore, our approach has to be towards the derivation of a set of values for certain parameters which, when fitted to theoretical models, will enable us to isolate the nature of the excitation in these atmospheres. One of these parameters appropriate to our present discussion is the ratio between the actual population of the n^th^ level of an ion and the population under conditions of thermodynamic equilibrium. A knowledge of this ratio b_n for different values of n would aid greatly in the development of a model with the relative contributions of the different sources accounted for correctly.

Consider the case of two emission lines that are the result of transitions $n' \rightarrow n$ and $n'' \rightarrow n$. We have

$$\frac{I_{n'n}}{I_{n''n}} = \frac{N_{n'} A_{n'n} h\nu_{n'n}}{N_{n''} A_{n''n} h\nu_{n''n}} \tag{1}$$

where $N_{n'}$ and $N_{n''}$ represent the population of levels n' and n'' respectively and $A_{n'n}$ the Einstein coefficient for spontaneous transition $n' \rightarrow n$. For level n we have

$$N_n = b_n N_i N_e \frac{h^3}{(2\pi m k T_e)^{3/2}} \frac{\bar{\omega}_n}{2\bar{\omega}_i} \exp\left(\frac{\chi_n - \chi_i}{kT}\right) \tag{2}$$

From (1) and (2) we obtain

$$T = \frac{(\nu_{n'} - \nu_{n''}) \frac{h}{k}}{\ln\left(\frac{I_{n'n}}{I_{n''n}}\right) - \ln\left(\frac{A_{n'n}\,\nu_{n'}\,\omega_{n'}}{A_{n''n}\,\nu_{n''}\,\omega_{n''}}\right) - \ln\left(\frac{b_{n'}}{b_{n''}}\right)} \cdot \qquad (3)$$

In equation (3) we identify T, the excitation temperature, with the kinetic temperature T_e in the limiting case. Contrary to the case of the solar chromosphere we have no means of measuring directly the kinetic temperature of the Wolf-Rayet atmosphere. A derivation of this value from the observed line intensities would be possible only if we know the factor $b_{n'}/b_{n''}$.

The calculations of b_n values by Thomas (4) and Chamberlain (5) show that for large values of n, $b_n \rightarrow 1$. It follows, therefore, that when n' and n'' are both large, $b_{n'}/b_{n''}$ should be nearly unity. Also Thomas (2) has shown that b_n for any n at a particular value of T_e, decreases rapidly with large nuclear charge. If, therefore, we consider line intensities of any ion having a larger nuclear charge than hydrogen or helium, we can assume with confidence that when n' and n'' are both larger than, say, 8 or 9, the ratio $b_{n'}/b_{n''}$ is 1.

Edlén (6) has identified recently, in Wolf-Rayet stars of the carbon sequence, strictly hydrogen-like transitions in C IV. This important work aids greatly an analysis of Wolf-Rayet atmospheres using the arguments outlined above. The transitions 7-10, 7-12, 7-15, 7-16, having wavelengths 5470.8 Å, 4229.2 Å, 3566.9 Å and 3450.5 Å respectively can be seen well on spectrograms of the WC stars. Since n and n'' range from 10 to 16, we may assume that $b_{n'}/b_{n''} = 1$. The line intensities would then give a value of the excitation temperature if we have a knowledge of $A_{n'n}$ and $A_{n''n}$. For hydrogen-like transitions in C IV we calculate the $A_{n'n}$ values from the equivalent hydrogen case treated by Menzel and Pekeris (7).

The results obtained from such an investigation of the stars

HD 192103 and HD 184738 are reported herewith. The line intensities in HD 192103 were measured on direct intensity microphotometer tracings, of spectra obtained with the 100-inch Coude spectrograph (10A/mm dispersion). For HD 184738 the line intensities were taken from an unpublished investigation of the star by O.C. Wilson and the author. One difficulty in the measurement of the line intensities proved to be the separation of blends. To avoid complications due to interstellar reddening, I measured only those lines which were in a narrow wavelength region. The temperature derived from line intensities of 4229 Å (7-12), 3567 Å (7-15) and 3451 Å (7-16) are given in Table 1.

TABLE 1

$\frac{\lambda (n'\ n)}{\lambda (n''\ n)}$	Equivalent width ratio $W_{n'n}/W_{n''n}$		Excitation temperature	
			HD 192103-WC 7	HD 184738-WC 8
	HD 192103	HD 184738		
$\frac{I(3451)}{I(3567)}$	0.842		68,400°	
$\frac{I(3451)}{I(4229)}$	0.523	0.406	40,600°	30,300°
$\frac{I(3567)}{I(4229)}$	0.622	0.681	37,400°	24,500°
		Mean	48,800°	27,400°

I thus obtain a mean values of 48,800°K and 27,400°K for the WC 7 and WC 8 stars respectively. The temperatures are estimated to be accurate within a range of + 10,000° about the mean value for

HD 192103 and within ± 8000° for HD 184738. These estimates are made on the basis of the accuracy of the emission-line equivalent widths. Temperatures derived in a similar fashion for other representatives of the WC 7 and WC 8 subgroups should yield a mean temperature for each subgroup of temperature classification.

Having derived the excitation temperature, which I consider is representative of the region emitting the C IV lines, we proceed next to consider the helium intensities. The excitation potentials of the helium lines of the Pickering series are comparable with those of the C IV lines from which an excitation temperature has been derived. I, therefore, assume that the helium lines originate from the same region of the atmosphere. This does not imply that we have a stratification in the Wolf-Rayet atmosphere or that we have to assume the existence of such a case in order to proceed further with the argument. We also avoid those members that are likely to be contaminated by Balmer emission, if such an emission exists. This, along with the tendency to avoid comparing lines having large wavelength separations, confines us to the lines 4686Å (3-4), 4542 Å (4-9) and 4200 Å (4-11). Of these I omit 4686 Å because of its abnormally low intensity. The line ratio $\frac{\text{I (4200)}}{\text{I (4542)}}$ gives us the ratio b_9/b_{11} as shown in Table 2.

TABLE 2

Star	W 4200/W 4542	Excitation Temperature	b_9/b_{11}
HD 192103	0.543	48,800°K	1.073
HD 184738	0.592	27,400°K	1.025

The accuracy of the $b_{n'}/b_{n''}$ ratio is dependent wholly on the precision with which the intensities can be determined. Apart from the errors inherent in photographic spectrophotometry, blending of lines in Wolf-Rayet spectra presents the major difficulty. We are, therefore, forced at present to apply these methods of analysis to the narrow lined stars. HD 192103 and HD 184738 studied here are extremely good examples of objects that are amenable to such study. Even so, 4542 Å in HD 192103 is blended to some extent and the value of b_9/b_{11} derived for this star may be considered to indicate the order of magnitude of this ratio.

A single value of $b_{n'}/b_{n''}$ that I have derived, will not suffice for comparison with theoretical models. A few more such ratios will facilitate greatly such comparison. For the present the positive value of this ratio, and its magnitude, indicates on the basis of an analogy with the case of hydrogen as calculated by Chamberlain (5) and Thomas (4), that collisional excitation plays a very important role in the production of emission lines in Wolf-Rayet atmospheres.

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