HD 50896 AND THE COMPOSITION OF WOLF-RAYET ATMOSPHERES

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ABSTRACT

Measurements of the Pickering lines of He II in the spectrum of HD 50896 suggest that the upper limit to the H/He ratio is 0.05 by numbers. Spectral scans from OAO-2 show strong lines, nitrogen being observed most strongly as N IV, but also as N III and N V. Carbon and oxygen are observed dominantly in the triply ionized states. Thus, the degree of ionization of C, N and O are comparable. No indication of extensive selective excitation effects is observed. It is concluded that the differences between the WN and WC stars cannot be explained by selective excitation or ionization effects in the WN stars.

I. INTRODUCTION

Wolf-Rayet spectra are dominated by broad strong emission lines of helium, carbon, nitrogen and oxygen. The spectra are divided into two sequences, the WN spectra, dominated by helium and nitrogen, with little or no evidence of carbon, and the WC spectra dominated by helium, carbon and oxygen with little or no evidence of nitrogen. Ever since the first identification of the lines (Perrin 1920, Beals 1930, Payne 1933) and classification of the spectra (Beals 1938), it has been wondered whether the lack of conspicuous hydrogen lines indicates a real deficiency of hydrogen in the atmospheres and whether there is a difference in the carbon and nitrogen abundance between the

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stars in the two sequences.

Many WR stars are binaries and the presence of the spectrum of the companion greatly complicates analysis of the WR spectrum. HD 50896 is a WR star which does not have a conspicuously composite spectrum and is the only such star bright enough to be observed by OAO-2. The present paper presents ground-based and OAO observations that are relevant to the problem of determining the atmospheric abundances in this star. It is demonstrated that if the atmosphere is optically thin in the Balmer lines, the H/He ratio is no greater than 0.05 by number, and that the relative excitation and ionization of carbon, nitrogen and oxygen are comparable.

II. THE H/He RATIO

Figure 1 shows a graph of the flux in the Pickering lines of He II as a function of n, the principal quantum number of the upper level. The data are taken from Kuhi and Smith (1971) and are derived from spectrograms at 16 Å/mm obtained with the Coudé spectrograph of the 120-inch telescope of Lick Observatory. Conversion to fluxes is made by the use of the continuum fluxes measured by Kuhi (1966, 1968) with an improved estimate of the reddening correction (Smith and Kuhi 1970).

The hydrogen Balmer lines are nearly equal in wavelength and oscillator strength to every second Pickering line. Thus, if hydrogen emission contributes to the spectrum, we would expect that Pickering lines with even values of 'n' would be relatively stronger than lines with odd values of 'n'. Clearly, in Figure 1 this is not the case. The relationship between log (Flux) and 'n' is extremely smooth; hydrogen would appear to make no contribution to the spectrum whatsoever.

In order to place a quantitative upper limit to the amount of hydrogen that may be present, it is necessary to know something about the conditions under which the lines are formed. If the lines are optically thin, the line strengths are dependent only on the numbers of electrons in the upper levels and on the transition probabilities. Due to the similarity of the He II and H I ions the transition probabilities and the Boltzmann factors for the relative populations of the levels are nearly equal. The 'n' values considered here are large enough that the b_n will not differ radically from 1. Hence, the number ratio of H^+ to He^{++} equals the ratio of the flux of the contribution of hydrogen and helium to the Pickering lines. The full equations are given by Castor and Van Blerkom (1970) who find that, for level 14, the ratio of the transition probabilities is 0.94; a 6 percent correction is unimportant in the present context. The assumption that the ratio of the b_n is equal to 1 will not introduce an error greater than 10 percent.

The important requirement for application of this method to

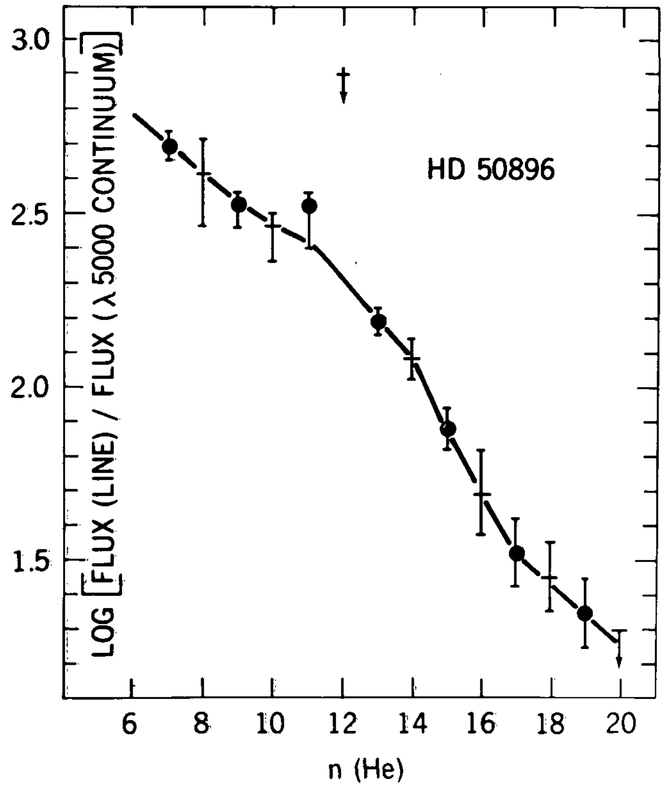

Figure 1.—The logarithm of the observed flux in the Pickering lines, in units of the continuum flux at 5000 Å, plotted as a function of the principal quantum number, n, of the upper level of the transition. Hydrogen Balmer lines coincide with lines with even values of n; these are plotted as crosses. Error bars include possible errors due to the presence of unresolved blends with nitrogen. The line from n = 12 is 4100 Å and is blended with strong lines of N III and Si IV.

the determination of the abundance ratio is that both the hydrogen and the helium lines be optically thin. Castor and Van Blerkom's (1970) analysis of the spectrum of HD 192163 (WN6) indicates that the lines in the Pickering series of He II of that star are optically thin for $n > 10$. The diagram for the fluxes of the Pickering lines in the spectrum of HD 192163 is very similar to that in Figure 1 for HD 50896. The change of slope between $n = 10$ and $n = 13$ appears to correspond to the change from optically thick to optically thin lines, in agreement with Castor and Van Blerkom's analysis. Observation of the Pickering decrements in a large number of WR spectra further supports the assertion that the He II lines with $n > 10$

are optically thin (see Smith 1971). The hydrogen lines have been seen neither in emission nor in absorption at $n \geq 7$. Assuming their absence is due to a real deficiency of hydrogen, then the hydrogen lines are optically thin and we may place an upper limit of 5 percent on the contribution of hydrogen to the emission, and thus an upper limit of 0.05 to the number ratio of H^+/He^{++}.

To obtain the total H/He ratio, the possible presence of other ionization states needs to be considered. The He I lines appear only weakly in absorption and moderately in emission in the spectrum of this star (cf Smith 1955); thus, while there may be a small amount of He^+, neutral H and He can probably be neglected. Thus, the upper limit of the total H/He ratio is also 0.05.

To place this result in perspective, it should be noted that it is an extreme case. Hydrogen emission is found to contribute to the Pickering series in some WN spectra, with relative fluxes that indicate H^+/He^{++} ratios as high as 2.3 (Smith 1971). It should also be noted that this is not a new observation. Many investigators have noted, qualitatively, the smoothness or bumpiness of the Pickering series. However, the higher resolution spectrograms now available allow much more accurate measurements of the equivalent widths of the lines and continuum flux measurements, while the theoretical studies of Castor and Van Blerkom allow equivalent width measurements of optically thin lines to be converted to a quantitative value of the H/He ratio.

III. THE CNO ABUNDANCES

One can, in theory, use the same procedure to obtain number ratios of some ions of carbon, nitrogen and oxygen to helium. In practice, however, this requires observation of lines from high values of 'n' in the CNO spectra; these lines are weak. The spectra are dominated by lines from lower levels of the ions, and a theory for the relative strengths of these lines is not available at this time.

A further complication arises from the fact that C, N and O can each exist in many ionization states, the relative populations of which are certainly variable through the atmosphere and are not known. Some of the ions do not have strong lines in the visual region of the spectrum; thus their presence or absence cannot be unequivocally determined from ground-based observations. At this point observations from OAO become pertinent. Within the range 1000-6000 Å all ions have some strong lines, and we may, therefore, make firm statements regarding the presence and relative strengths of lines from all ions.

Figures 2 and 3 show OAO spectra of HD 50896 obtained by Bless. Figure 2 is a sum of seven scans, Figure 3 is a sum of

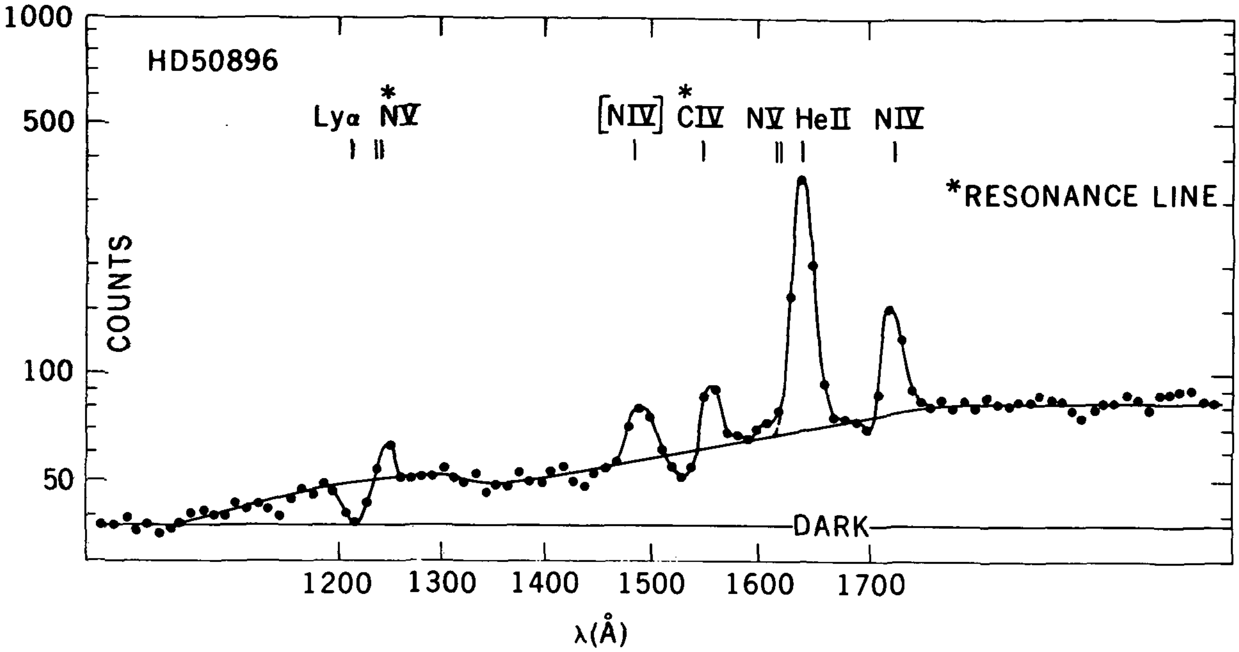

Figure 2.—Sum of counts from seven OAO scans of the wavelength region 1000-2000 Å. The most probable identification of the strong features are shown.

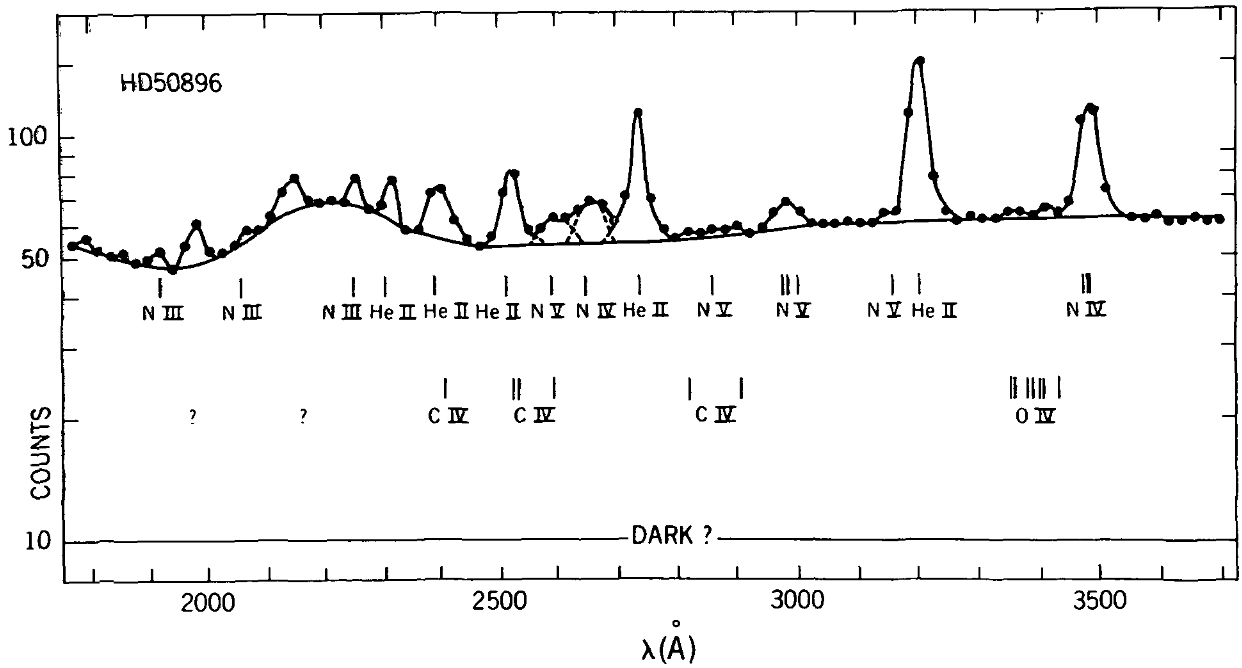

Figure 3.—Sum of counts from two OAO scans of the wavelength region 2000-4000 Å. Background is assumed to be 5 counts for each scan.

two. Background counts in Figure 1 are estimated from the region shortward of 1000 Å where the detectors are insensitive. In Figure 2 the background is taken to be 10 counts, representing 5 counts per scan, in accordance with the estimate given by Savage (private communication). No correction has been made for the sensitivity functions of the receivers, since these are poorly known at the present time. The continua that have been drawn are, however, of the same shape as the preliminary sensitivity functions.

Several points in these figures are of obvious interest.

(1) C IV lines are clearly present. It should be recalled in this context that C IV 5806 Å is a strong line in most WN spectra. Clearly the spectrum of C IV is quite well developed, and 5806 Å is not an isolated line.

(2) O IV is observed at 3400 Å. That wavelength is accessible from the ground. However, because of the presence of ozone absorption in ground-based spectra, OAO spectra provide as accurate a measurement of this line as is obtained from higher dispersion ground-based spectrograms.

(3) The forbidden line, N IV] 1488 Å is clearly present. This is the analogue of C III] 1909 Å observed in the spectrum of γ^2 Vel by Stecher (1968).

Measurement of equivalent widths of all features in the spectrum, together with tentative identifications, are given in Table 1. The equivalent widths are obtained by numerical integration of the observed counts over the line. It should be noted that the results for the lines 3480 and 3203 Å differ by nearly a factor of 2 from the values, 94 and 100 Å, respectively, obtained by Kuhi and Smith from ground-based spectrograms. It seems most likely that this is due to an underestimate of the background count level at these wavelengths. However, it does not seem possible that the background counts are much higher than 10 at the shortest wavelengths, and the reason for the discrepancy remains uncertain. Fortunately, we are mostly interested in the presence or absence of lines, and a factor of two will not invalidate any of the qualitative conclusions to be drawn from these data.

Table 2 contains line strengths from Table 1 and from Kuhi and Smith (1971) arranged in groups of iso-electronic ions. When a line is not observed, an upper limit has usually been estimated. Very strong lines of O III occur at 3759, 3774 and 3791 Å but these lines are not observed in HD 50896. An upper limit of 3 Å is estimated for their equivalent widths.

From the similarity of iso-electronic ions we expect, *a priori*, that relative line strengths of corresponding transitions will be similar. It is easily seen that this is the case and, further, that the lines which are observed are, in general, those that are observed to be the strongest in the laboratory spectra. The strengths of C IV lines appear to be comparable

Table 1. Equivalent Widths of Lines in the Ultraviolet Spectrum of HD 50896

Identification*		E.W.(Å)	Identification	E.W.(Å)
§ H I 1215 }	a	22.9	He II 2520 }	
§ N V 1240 }			C IV 2524 }	26
§ N V 1240		15.7	C IV 2530 }	
N IV 1486		34.8	N V 2591 }	10
§ C IV 1549	a	9.0	C IV 2595 }	
C IV 1549		19.6	N IV 2646	18
N V 1618		3.6	He II 2740	48
He II 1640		183.0	C IV 2819?	1
N IV 1718	a	2.0	N V 2859	1
N IV 1718		39.7	C IV 2906	1
N III 1805		2	N V 2974 }	
N V 1860		1	N V 2981 }	8
N III 1921		2	N V 2998 }	
? 1980		9	N V 3160	3.5
N III 2064		1.5	He II 3203	61
? 2150		7.5	† O IV 3400	4.5
N III 2248		3.5	† N IV 3480	46
He II 2300		6.5		
He II 2390 }		18		
C IV 2405 }				

* 'a' indicates an absorption line
† blend of two multiplets
§ resonance line

Table 2. Equivalent Widths in the Spectrum of HD 50896

Lab Int (N)	C II	N III		O IV		Transition
10	Resonance	1751.7		1338.6		
9	lines	1747.8	< 2Å	1343.0	< 3Å	$2p^2\ ^2P - 2p^3\ ^2D^o$
6	λ1335.7	1751.2		1343.5		
	λ1334.5					
8	not	1184.5	?	923	-	$2p^2\ ^2P - 2p^3\ ^2P^o$
7	observed	1183.0				
10		1885.2	<2Å	1068	-	$3d\ ^2D - 4f\ ^2F^o$
10		2064.0		1164.3		
10		2063.5	1.5Å	1164.5	-	$3d\ ^2F^o - 4f\ ^2G$
6		2068.2				
10		4097.3	≤30Å	3063.5	< 1Å	$3s\ ^2S - 3p\ ^2P^o$
9		4103.4	(HeII,	3071.7		
			?SiIV)			
10		4640.6		3411.8		
9		4634.2	7Å	3403.6		$3p\ ^2P^o - 3d\ ^2D$
7		4641.9		3413.7		
7		4510.9		3381.3		
6		:	3Å	:	4Å	$3s'\ ^4P^o - 3p'\ ^4D$
4		4534.6		3409.8		
10		4379.1	5Å			$4f\ ^2F^o - 5g\ ^2G$

?( ) Possibly blended with

Table 2, continued

Lab Int (N)	C III		N IV		O V		Transition
2	1909	?(NIII) <2Å	1486.5	35Å	1218.4	?(Lyα)	$2s^2\ ^1S - 2p\ ^3P^o$
20	2296.9	?(HeII) <3Å	1718.6	40Å	1371.3	<6Å	$2p\ ^1P^o - 2p^2\ ^1D$
15 14 13	4647.4 4650.2 4651.4	?(NIII) <4Å	3478.7 3483.0 3484.9	91Å	2781.0 2787.0 2789.9	?(HeII) <2Å	$3s\ ^3S - 3p\ ^3P^o$
10 11 12	4067.9 4068.9 4070.3	?(NIV) <12Å	2645.6 2646.2 2647.0	18Å	1643.7	?(HeII)	$4f\ ^3F^o - 5g\ ^3G$
8	5695.9	<1Å	4057.8	23Å	3144.7	?(NV) <3Å	$3p\ ^1P^o - 3d\ ^1D$

?( ) Possibly blended with

Table 2, concluded

Lab Int (N)	C IV		N V		O VI		Transition
20	1548.2	20Å	1238.8	>16Å	1031.9	-	2s ^2S - 2p $^2P^o$
19	1550.8		1242.8		1037.6		
12	5801.5	28Å	4603.3	34Å	3811.4	?(HeII) <<1Å	3s ^2S - 3p $^2P^o$
10	5812.1		4619.1		3834.2		
9	2524.2	?(HeII)	1616.3	?(HeII) ~4Å			4d ^2D - 5f $^2F^o$
12	2530.0		1619.7				4f $^2F^o$- 5g ^2G
6	4647.0	?(HeII)	2974.5	8Å			5d ^2D - 6f $^2F^o$
8			2980.8				5f $^2F^o$- 6g ^2G
10	4668.3		2981.3				5g ^2G - 6h $^2H^o$
9	7726.2	§yes	4944.6	6Å			6h $^2H^o$- 7i ^2I
6	2906.3	1.5Å	1860	1Å			5g ^2G - 7h $^2H^o$
6	2404.4	?(HeII)	1548	?(CIV)			4p $^2P^o$- 5d ^2D
	2405.1		1549.3				

§ Kuhi (private communication) confirms the presence of this line from scanner observations

?( ) Possibly blended with

in all cases to those of the corresponding lines in N V. The single band of O IV that is observed corresponds to two of the strongest bands in the spectrum of N III. The great strength listed for N III 4100 Å is a high upper limit owing to unresolved blending with He II 4100 Å and possibly with Si IV 4088 Å and 4116 Å.

In general, it is confirmed that when an ion is present in the spectrum of a WR star, the spectrum of that ion is well developed; selective excitation processes are relatively unimportant.

Table 3 gives the ionization potentials of each of the ions, and indicates, qualitatively, by the number of slashes, the relative strength of the spectrum of the ion in the spectrum of HD 50896. Nitrogen is observed most strongly as N IV, but N V is also strong and N III is present. Carbon appears strongly as C IV; C III is not observed, but many of the lines are blended. Smith (1955) has seen C III 5696 Å weakly in this spectrum; it certainly is not present on our spectrograms.

Table 3. Summary - Relative Equivalent Widths / Ionization Potential /

	C	N	O
II	24.3	29.6	35.1
III	?47.9?	//47.4//	54.9
IV	///64.5///	////77.4////	/77.4/
V	392	///97.9///	113.8
VI	490	552	138.1
VII	-	668	739
Cosmic Abundance	45	13	100

Oxygen occurs weakly as O IV, while Smith has seen O V. Clearly the ions of O and C that are observed are those with ionization potentials closest to that of N IV, the strongest nitrogen ion. This is certainly what one would, _a priori_, expect, and it demonstrates that there are no peculiar ionization conditions in the atmosphere of this star. The failure to observe strong lines of carbon and oxygen in the visual spectra of WN stars is repeated in the ultraviolet region longward of 1200 Å, and no evidence is found for these atoms being present in ionization states that do not contribute strongly to the visual spectrum.

IV. CONCLUSIONS

It has been demonstrated that hydrogen may be essentially absent from the spectrum of HD 50896. This implies that all of the hydrogen-rich envelope has been removed at some time after a pure helium core has been created.

All the observed emission features of C, N and O arise from similar levels of excitation and ionization and can be produced under conditions approximating thermodynamic equilibrium. Of course, the differences between WC and WN spectra may be due to peculiar conditions in the WC atmospheres. However, it should be emphasized that since the atmosphere of HD 50896 contains no hydrogen, it has obviously been processed by thermonuclear reactions, and there is no reason to expect that the relative abundances of C, N and O should have their primordial value. The obvious conclusion is that nitrogen is grossly overabundant with respect to C and O in WN atmospheres, and that C and O are overabundant with respect to N in WC atmospheres. It is to be hoped that a theory adequate to predict line strengths of some of the observed transitions will soon be forthcoming so that the ratios of C, N and O may be placed on as quantitative a basis as the H/He ratios now are.

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