SECTION II

CHAIRMAN: P. CONTI

CLASSIFICATION AND DISTRIBUTION OF WR STARS AND AN INTERPRETATION OF THE WN SEQUENCE

LINDSEY F. SMITH
*NASA Goddard Space Flight Centre, Greenbelt, Md., U.S.A.**

1. Introduction

In the three years since the Boulder Wolf-Rayet Conference, a great deal of observational material has been collected and processed. That conference was, of course, the stimulus for a great deal of the work, since it made clear where some of the large gaps in our observational knowledge lay. As a result the greatest progress has been in directions which were previously underexplored, and some subjects which were actively pursued before the last conference have been left almost untouched since. Thus, much of what was said in 1968 need not be reviewed again; I can confine my attention to topics which have been significantly changed by new observations. The new observations comprise, in particular, the systematic observation of spectra of many stars at moderately high dispersion, observation of far ultraviolet spectra, and discovery of some WR stars in M33 – the first outside of our own Galaxy and the Magellanic Clouds.

We appear to have achieved one major clarification: I hope to convince you, on almost purely observational grounds, that WN stars are helium stars of 8–14 solar masses with atmospheres that contain only a very low proportion of hydrogen, that the properties of the star are very sensitive to this small amount of hydrogen and that, consequently, this structure explains many of the general properties of the subclasses. However the variety of the subclasses observed is greater than can be explained by variation of the hydrogen abundance alone; which other parameters are vital, and how they operate is not clear at this time.

Data allowing similar specific statements about WC stars are not available. A few general deductions can be made and will be dealt with later in this Symposium.

2. The Atmospheric Abundances

The IAU classification (Beals, 1938) of WR stars recognized that the WR spectra are characterized by emission lines of He and N *or* of He, C and O. Thus, the spectra were classified WN or WC and it was noted that the range of excitation in the two sequences is similar. By omission, it was implicit that H lines are not apparent in the spectra.

There are two controversies that occur repeatedly in the literature:

(1) whether the lack of obvious H lines in the spectra indicates an under-abundance of H in the atmosphere of the stars, and

(2) whether there is a composition difference between stars in the two sequences.

* Present address: Max Planck Institut für Radioastronomie, 53 Bonn, Germany.

M. K. V. Bappu and J. Sahade (eds.), Wolf-Rayet and High-Temperature Stars, 15–41.

2.1. H/He RATIOS

Determination of H/He ratios is made difficult by the near-coincidence of wavelengths of H I and He II lines. With the line widths characteristic of WR spectra, all the hydrogen lines are completely blended with helium lines. However, it has been realized for some time that an estimate of the H/He ratio could, in principle, be obtained from observations of the Pickering decrement. Since the hydrogen Balmer lines coincide with every *second* helium line, the presence of hydrogen in the spectrum would cause a 'bumpy' decrement to be observed.

In the past, it was not possible, due to lack of photometric observations of the continua of the stars and lack of knowledge of reddening corrections, to convert the measured equivalent widths to the fluxes required for the calculation of H/He ratios. Now, both continuum observations (Kuhi, 1966; Kuhi, 1968) and reddening corrections (Smith, 1968c; Smith and Kuhi, 1970) are available. Some knowledge of the conditions under which the lines are formed is also necessary. Fortunately, if the atmosphere is optically thin to the line radiation, the line strengths depend 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 full equations are given by Castor and Van Blerkom (1970) who find that, for level 14 of He II and level 7 of H I, the ratio of the transition probabilities is 0.94; a 6% correction is unimportant in the present context. The 'n' values considered here are large enough that the assumption that b_n is equal to 1 will not introduce an error greater than 10%. Thus, the number ratio of H II to He III equals the ratio of the fluxes of the contributions of hydrogen and helium to the Pickering lines.

Castor and Van Blerkom (*loc. cit.*) have found that the observed line strengths in the spectrum of HD 192163 (Smith and Kuhi, 1970) imply an atmosphere that is optically thin to the line radiation for Pickering lines with the quantum number, n, of the upper level greater than 10. Of the lines satisfying that criterion, λ 3968, upper level = 14, is least affected by blending with nitrogen lines. Using this line, Castor and Van Blerkom derived He III/H II > 2/1.

Figure 1 represents the line fluxes of the Pickering lines for 'single' WR stars from nearly all subclasses of the WN sequence plotted against the quantum number, n, of the upper level. Figure 2 presents similar data for binary stars. The data is from the (imminently to be published) *Atlas of Wolf-Rayet Line Profiles* of Kuhi and Smith (1973), and is based on 16 Å/mm and 32 Å/mm Lick coudé spectrograms. Equivalent widths of the emission lines have been converted to fluxes with the continuum observations of Kuhi (1966, 1968), corrected for a change in the estimated reddening (Smith and Kuhi, 1970). The error bars allow for observational uncertainty in the measurements and for blending with N III and He I lines.

Possible errors due to blending are indicated by extension of the error bars in the direction of reduced intensity. Estimates of the amount are based on degree of deformation of the profile of the helium line, and the strengths of other lines of N III and

He I in the spectrum. Blending is the most serious in the WN6 spectra. In lower excitation subclasses the lines are moderately well resolved; in higher excitation subclasses, the strengths of N III and He I lines are much less than in the WN6 spectra. It is believed that the error bars given represent realistic upper limits to the possible

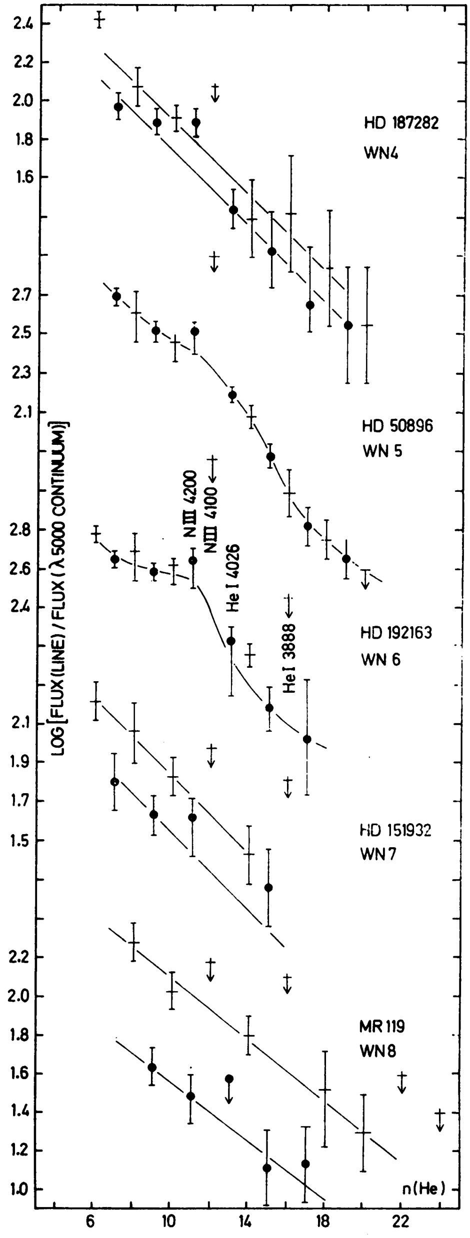


Fig. 1. Graphs of the flux in the Pickering lines vs. the principle quantum number, *n*, of the upper level of the transition, for apparently single WN stars.

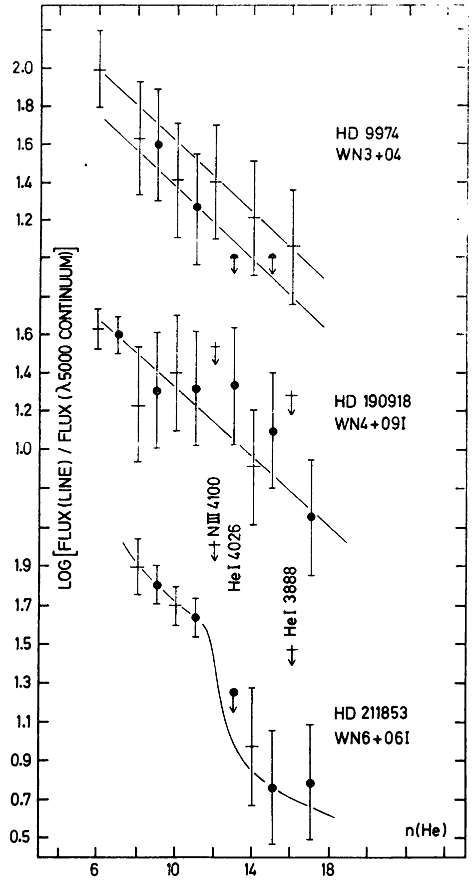


Fig. 2. As for Figure 1, for binary WN stars.

errors; confirmation of this will, of course, only be possible when models for the atmosphere can be constructed and the relative strengths of the blended lines predicted. In spectra in subclasses other than WN5 and WN6 the H+He lines are consistently stronger than the pure He lines, and the ratio of line strengths appears to be independent of the strength of the lines. This strongly implies that, in these spectra, all lines of the series are optically thin.

In the graph for HD 192163 the H+He line that corresponds to $n=14$, is relatively stronger than the two pure helium lines on either side, however, the stronger, low-n members of the series show no contribution from hydrogen to the even-n lines. This is most simply explained if the strong, low-n lines are optically thick so that the contribution due to hydrogen has little effect on the line strength. Since He II lines in WN5 and WN6 spectra are about five times stronger than in other subclasses, optical thickness of the strongest lines is not surprising.

On the other hand, the fact that the He I contribution to the $n=16$ line is quite clearly visible indicates that the high-n members of the series are, even in this star, optically thin. (It should be noted that the same logic cannot be applied to the increased strength of the $n=12$ line at λ 4100 since the N III and Si IV lines do not coincide closely in wavelength with the He II line, and the blend is very broad.) The rate of increase of the line intensities with decreasing n falls off for n less than 11. This is probably also due to optical thickness of the strong lines of the series, their intensities being reduced by self absorption. Thus the observations appear to be in accord with the calculations of Castor and Van Blerkom which suggest a transition from optically thick to optically thin at about $n=10$.

The similarity of the graph for HD 50896 to that for HD 192163 suggests that, in this star also, the Pickering lines become optically thin for $n>10$. (He I is essentially absent from this spectrum, thus the argument used above cannot be applied.)

The spectra of the binary stars appear to have similar properties to those of the single stars of the same subclass.

TABLE I

H/He abundances in WN atmospheres and their correlation with T_{eff}

HD	Sp. Type	Δ Log F	N(H II)/ N(He III)	W(He I4471)/ W(He II4541	$N(H)/N$(He)	T_{eff} (K)
50896	WN5	0.00 ± 0.02	0.00 ± 0.05	0.8/25	0.0 ± 0.05	53000
187282	WN4	0.15 ± 0.10	0.40 ± 0.30	0.0/5.7	0.4 ± 0.3	46000
192163	WN6	0.16 ± 0.06	0.45 ± 0.20	7.2/33	$\lesssim 0.4 \pm 0.2$	29000
151932	WN7	0.30 ± 0.15	1.00 ± 0.60	1.4/3.6	< 1.0	
MR 119	WN8	0.52 ± 0.10	2.30 ± 0.70	3.4/3.7	$\leqslant 2.3$	23000
9974	WN3 + 04	0.24 ± 0.10	0.75 ± 0.35	0.0/3.2	0.8 ± 0.4	
190918	WN4 + 09I	0.00 ± 0.05	0.00 ± 0.12	0.0/1.5	0.0 ± 0.1	
211853	WN6 + 0B	0.13 ± 0.10	0.35 ± 0.25	1.0/4.9	$\lesssim 0.3 \pm 0.2$	
COSMIC					10.0 ± 0.1	

Table I summarizes the numerical results. For subclasses other than WN5 and WN6, the mean difference, $\Delta \log F_{\lambda}$, was taken from the graphs, as indicated. For the WN6 stars the value depends only on the $n=14$ line. The number ratio of H II/He III ranges from 0 to 2.3. To obtain values for the total H/He ratio we need to consider the possible presence of singly ionized helium. The relative strengths of He I and He II lines are indicated in Table I by the equivalent widths of He I 4471 and He II 4541. He I makes no contribution whatsoever to the visible spectra of WN3 and WN4 stars; thus, for these subclasses He II may be neglected. In WN5 and WN6 spectra He I lines are very weak, and we probably make little error by again neglecting He II. However, in WN7 and WN8 spectra He I lines are strong. In the WN8 atmospheres, in particular, most of the helium may be singly ionized. We have no method for determining the ionisation balance. In Table I, therefore, for the lower excitation classes, the values are given only as upper limits. Neutral hydrogen and helium should have low abundances out to regions of the atmosphere where densities are too low to greatly concern us and may probably be safely neglected.

We conclude that there is essentially no hydrogen in the atmospheres of WN5 stars, that there is a little hydrogen in WN4 and WN6 atmospheres, and that the H/He ratio may get as high as 1/1 in the atmospheres of WN8 and WN3 stars. The H/He ratios are an order of magnitude less than the cosmic abundance of 10/1 (Popper *et al.*, 1970). They are also much less than the value, 5/1, derived by Aller and Heap (1971) for HD 45166 using the same method, and the values between 4/1 and 14/1 derived by Oke (1954) for Of stars. Thus, severe underabundance of hydrogen in the atmosphere appears likely to be a necessary (though not a sufficient) condition for a WN star.

I emphasize that nothing has been assumed in the H/He derivations other than that the lines are optically thin and that the b_n are near one. It should be noted, in particular, that the temperature dependence of the strengths of the He II and H I lines are identical and thus the (unknown) temperature of the WR atmospheres does not enter the calculation. The assumption of optical thinness in is accord with the calculations of Castor and Van Blerkom (1970) and is substantiated by the observations as discussed above. The assumption that the $b_n = 1$ is not likely to be in error by more than 10%.

2.2. 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. This possibility deserves further attention; at the present time it has not been attempted because it requires observation of lines due to transitions from high energy levels of the CNO ions and 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 ionisation 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. However, at this time, OAO-II observations are available for HD 50896, an apparently-single WN5 star (Smith, 1972). Thus we now have observations of the spectrum from 1000–6000 Å, and within this spectral range all ions have some strong lines; we may, therefore, make a firm statement regarding the presence and relative strength of lines from all ions.

Figures 3 and 4 show spectra obtained by Bless; the line identifications are due to the present author. I present the raw data; information on the sensitivity functions of the satellite instruments are still tentative; however, their shapes are qualitatively similar to those of the continua that have been drawn on the diagrams. Figure 3 is a sum of two scans in the wavelength range 2000–4000 Å. The resolution is about 25 Å; data is taken every 21 Å. No simultaneous measurement of the background is available for spectra in this wavelength range; in Figure 3 the background is taken to be 10 counts, representing 5 counts per scan, in accordance with the estimate given by Savage (private communication). Figure 4 represents the sum of seven scans in the wavelength region 1000–2000 Å. Care was taken to line the spectra up as well as

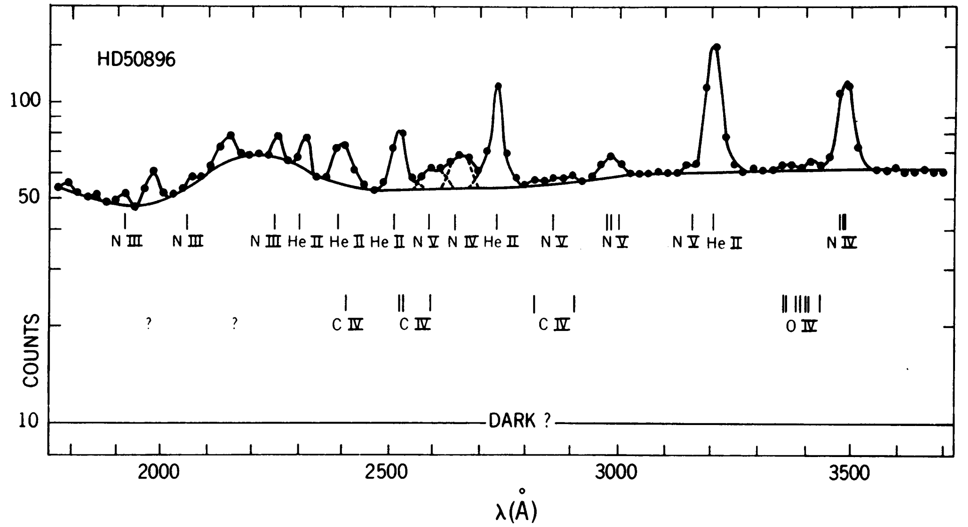


Fig. 3. The spectrum of HD 50896 in the wavelength range 2000–4000 Å obtained by Bless with OAO-II.

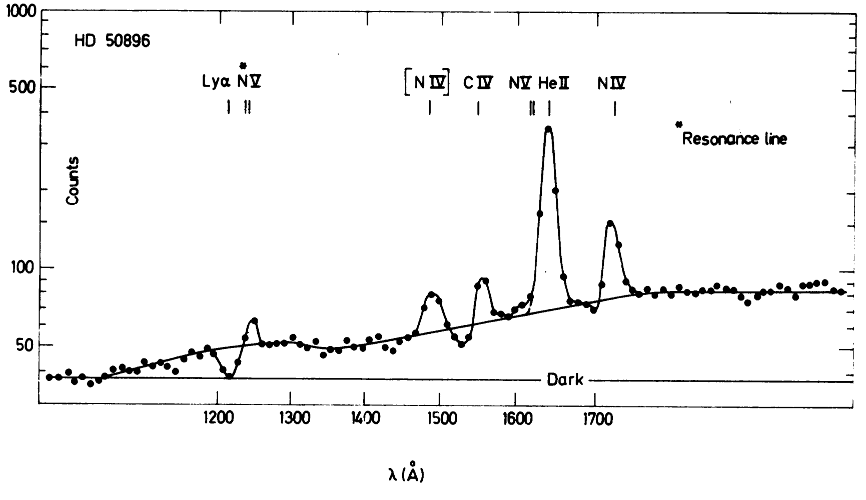


Fig. 4. The spectrum of HD 50896 in the wavelength range 1000–2000 Å obtained by Bless with OAO-II.

possible before adding them; however, data is taken every 10.5 Å and in some cases the spectra were clearly shifted by 5 Å. Thus, adding the scans produces some smearing; resolution on the integrated scan is probably about 15 Å. In this wavelength region the background may be estimated from the region shortward of 1000 Å where the system is insensitive to incoming radiation and only particle background and dark current are being measured.

TABLE II

Equivalent widths in the spectrum of HD 50896

Lab Int (N)	C II		N III		O IV		Transition
10	Resonance		1751.7		1338.6		$2p^2\,{}^2P{-}2p^3\,{}^2D^0$
9	lines		1747.8	< 2Å	1343.0	< 3Å	
6	λ 1335.7		1751.2		1343.5		
8	λ 1334.5		1184.5	?	923		$2p^2\,{}^2P{-}2p\,{}^2P^0$
7	not		1183.0				
10	observed		1885.2	< 2Å	1068		$3d\,{}^2D{-}4f\,{}^2F^0$
10			2064.0		1164.3		$3d\,{}^2F^0{-}4f\,{}^2G$
10			2063.5	1.5Å	1164.5		
6			2068.2				
10			4097.3	⩽ 30Å	3063.5	< 1Å	$3s\,{}^2S{-}3p\,{}^2P^0$
9			4103.4	(He II, Si IV)	3071.7		
10			4640.6		3411.8		$3p\,{}^2P^0{-}3\,{}^2D$
9			4634.2	7Å	3403.6		
7			4641.9		3413.7	4Å	
7			4510.9		3381.3		$3s'\,{}^4P^0{-}3p'\,{}^4D$
6			:	3Å	:		
4			4534.6		3409.8		
10			4379.1	5Å			$4f\,{}^2F^0{-}5g\,{}^2G$
	C III		N IV		O V		
2	1909	?(N III) < 2Å	1486.5	35Å	1218.4	?(Lα)	$2s^2\,{}^1S{-}2p\,{}^3P^0$
20	2296.9	?(He II) < 3Å	1718.6	40Å	1371.3	< 6Å	$2p\,{}^1P^0{-}2p^2\,{}^1D$
15	4647.4	?(N III)	3478.7		2781.0	?(He II)	$3s\,{}^3S{-}3p\,{}^3P^0$
14	4650.2	< 4Å	3483.0	91Å	2787.0	< 2Å	
13	4651.4		3484.9		2789.9		
10	4067.9	?(N IV)	2645.6		1643.7	?(He II)	$4f\,{}^3F^0{-}5g\,{}^3G$
11	4068.9	< 12Å	2646.2	18Å			
12	4070.3		2647.0				
8	5695.9	< 1Å	4057.8	23Å	3144.7	?(N V) < 3Å	$3p\,{}^1P^0{-}3d\,{}^1D$
	C IV		N V		O VI		
20	1548.2	20Å	1238.8	> 16Å	1031.9		$2s\,{}^2S{-}2p\,{}^2P^0$
19	1550.8		1242.8		1037.6		
12	5801.5	28Å	4603.3	34Å	3811.4	?(He II)	$3s\,{}^2S{-}3p\,{}^2P^0$
10	5812.1		4619.1		3834.2	⩽ 1Å	
9	2524.2	?(He II)	1616.3	?(He II)			$4d\,{}^2D{-}5f\,{}^2F^0$
12	2530.0		1619.7	~ 4Å			$4f\,{}^2F^0{-}5g\,{}^2G$
6	4646.0		2974.5				$5d\,{}^2D{-}6f\,{}^2F^0$
8	4658.3	?(He II)	2980.8	8Å			$5f\,{}^2F^0{-}6g\,{}^2G$
10			2981.3				$5g\,{}^2G{-}6h\,{}^2H^0$
9	7726.2	[a] yes	4944.6	6Å			$6h\,{}^2H^0{-}7i\,{}^2I$
6	2906.3	1.5Å	1860	1Å			$5g\,{}^2G{-}7h\,{}^2H^0$
6	2404.4	?(He II)	1548	?(C IV)			$4p\,{}^2P^0{-}5d\,{}^2D$
	2405.1		1549.3				

[a] Kuhi (private communication) confirms presence of this line from scanner observations.
?( ) Possibly blended with –

Equivalent widths have been derived by numerical integration. These are presented in Table II which are arranged to show comparison between the isoelectronic ions of C, N and O. Strengths of lines in the visible region of the spectrum are taken from Kuhi and Smith (1971). The results may be summarized as follows:

(1) N IV and N V lines are strong. N III lines are also present but are weaker so that only lines in the visible (where the spectra are of much higher resolution) have been observed.

(2) Carbon appears only as C IV, and the lines are of comparable strength to lines due to equivalent transitions of N V, with which C IV is iso-electronic. C III lines are not observed, however the presence of weak lines cannot be excluded since most would be blended with lines of other ions.

(3) Oxygen occurs very weakly as O IV only. (O III is not included in the Table; however, its strong lines at λ 3759, λ 3774 and λ 3791 are not observed and an upper limit of 3 Å is estimated for their equivalent widths.)

The data emphasizes that, when an ion is present in a WR spectrum, the spectrum of that ion is well developed; selective excitation processes that generate only a few lines of a given ion are relatively unimportant.

TABLE III

Summary – relative equivalent widths in WN spectra (ionisation potential)

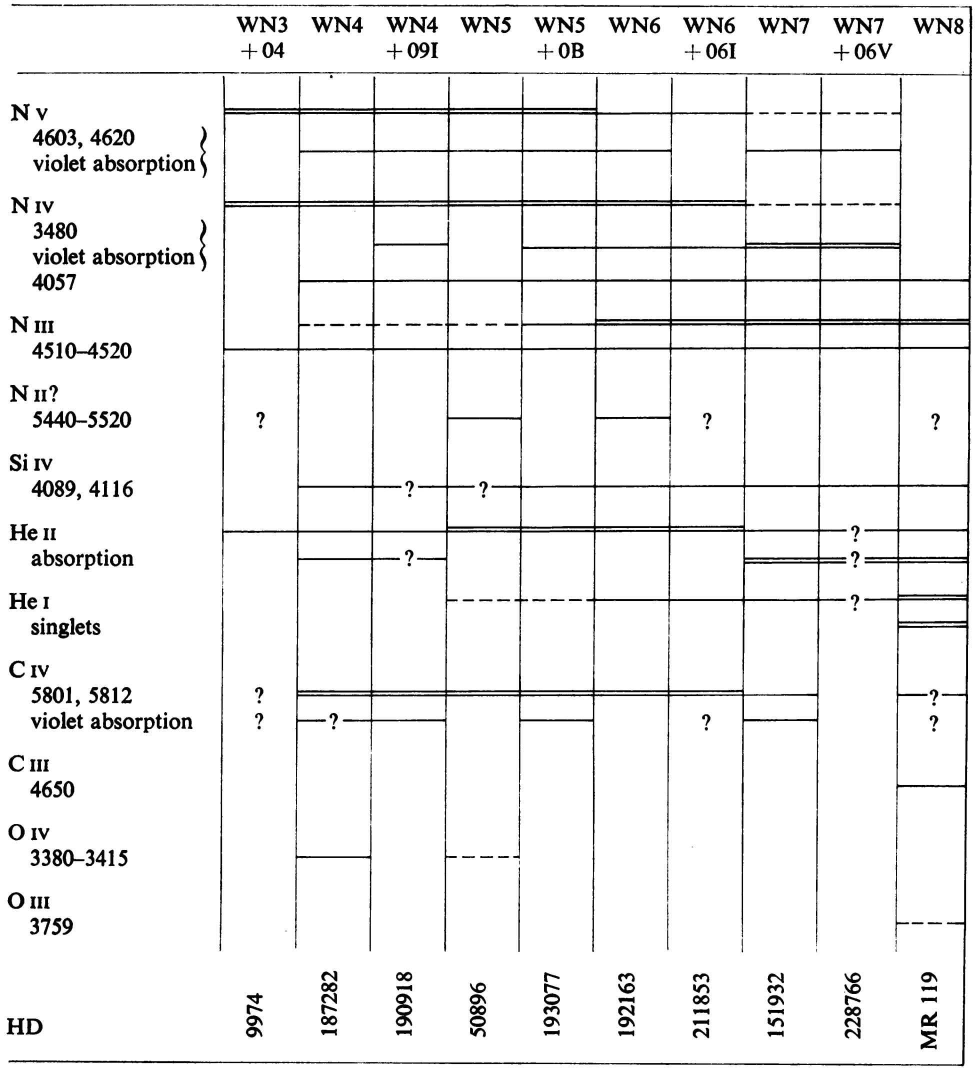
	C	N	O
II	24.3	29.6	35.1
III	?47.9?	//47.4//	54.9
IV	///64.5///	////77.4////	/77.4/
V	392	///97.9///	113.8
		552	138.1
Cosmic Abundance	45	12	100

The relative strengths of spectra of different ions are summarised in Table III which gives the excitation potentials of each of the ions and indicates, by the number of slashes, the relative strengths of the observed spectra. C IV and O IV, which are the strongest ions of C and O, respectively, have ionization potentials nearest to that of N IV, the nitrogen ion showing the strongest spectrum. This situation is not surprising and does not require any specialized ionization processes. There is no evidence here for a peculiar distribution among the ionization states of O and C.

The general applicability of this argument is indicated by Table IV which is taken from Kuhi and Smith (1973) (and is included here in its entirety because of its general usefulness as a quick reference). The Table shows, in a qualitative manner, the relative strengths of the spectra of the various ions in the visual spectral regions of WN stars of all subclasses. In the present context, note that the C IV lines λ5801, λ5812 are present in nearly all subclasses but become very weak in the lowest excitation classes

TABLE IV

Qualitative description of WN spectra



? No red plate.
–?– Data inadequate to be sure – due to noise, blending, etc.
Not visible.

Strong. ═════
Present. ─────
Weak. - - - - -

where N III becomes the dominant nitrogen ion; in the WN8 spectrum of MR 119, C III (whose ionization potential is approximately equal to that of N III) is observed also. Similarly, O IV appears in the highest excitation subclasses, and O III appears in the WN8 spectrum.

Thus, an explanation for the differences between the WN and WC stars in terms of different excitation or ionization mechanisms in the atmospheres is not supported by the observations. While it is possible that peculiarities in the WC atmospheres are alone responsible for the differences, I consider this unlikely. The data supports the hypothesis that there is an abundance difference between stars in the two sequences.

Which sequence, if either, has cosmic abundances ratios of He, C, N and O is an open question. In as much as the cosmic abundance ratio of H/He has been so drastically altered in the WN atmospheres, there seems no reason to expect that the other ratios should have retained their cosmic values. An overabundance of N with respect to C and O, and probably to He also, appears to be the obvious explanation for the line strengths summarised in Table III.

By analogy, low hydrogen abundance and high C and O abundances in WC atmospheres becomes a likely explanation for the very strong C and O lines in those spectra. It is unfortunate that H/He ratios and equivalent ultraviolet observations cannot be easily obtained for WC stars. Lines of the Pickering series are so badly blended with carbon lines that a meaningful H/He ratio cannot be derived. Gamma 2 Velorum is the only WC star that is bright enough to be observed in the ultraviolet with available equipment, and it is a binary in which the companion is the brighter; it is not clear to me which lines may be attributed to the WR star and which to the O star.

3. New Observations Relevant to the Classification System

Two new observations in the field of WR classifications should be noted at this time. First, Cowley and Hiltner (1969) have observed the star CPD-56°8032 and described its spectrum. While they do not give a print of the spectrogram it would appear, from the description, that we must classify this object WC10. The degree of excitation is lower than in WC9 stars and the lines are narrower, of the order of 2A! This is very narrow indeed for a WR star, but in as much as it appears to be a logical extension of the sequence, it should be provisionally accepted as such.

Of more basic importance to the subject of classification is the observation by R. Lynds of the spectra of two WR stars found by Wray and Corso (1972) in M33. These spectra show C III-IV λ4650 and C IV λ5810 as the strongest features, indicating that the classification should be WC5 or WC6. The weakness of other features would indicate that the objects are probably binary stars. However, the line widths are *very* much less than those observed in high excitation WC spectra of stars in the Galaxy and the Magellanic Clouds. This is a most startling observation! Line width is so uniformly and consistently correlated with excitation in WC stars that it is used as a classification criterion in the IAU system and in all modified systems proposed since (Hiltner and Schild, 1966; Smith ,1968a). Eventually it may be necessary to modify the classification system to incorporate this new dimension of possible spectral properties.

The absolute visual magnitudes of the two stars, $M_v = -4.9$ and -5.8, are to be compared with $M_v = -3.9$ to -5.1 for single WC5 stars in the Large Magellanic Cloud, and $M_v = -5.4$ to -8.1 for binaries (Smith, 1968b). The agreement is reasonable, although the fainter star is somewhat fainter than the LMC binaries.

4. Absolute Magnitudes of WR Stars

Absolute magnitudes of WR stars in the Galaxy have been reconsidered recently by Crampton (1971). He lists all WR stars which appear to be associated with nebulae. The distances of some of these nebulae may be estimated from spectroscopic parallaxes of O and B stars, or from kinematic methods. In general, the distances derived are less than those given by Smith (1968c) for the WR stars, although the derived reddening for the WR stars generally agrees well with those of the OB stars. The conclusion would appear to be that the luminosities of the WR stars are lower than estimated by Smith (1968b). Deriving luminosities for the galactic WR stars by subclass, Crampton arrives at the numbers in Table V; values derived by Smith are also given. Among the WN stars the largest discrepancy occurs between the two derived values for M_v for the WN6 stars. Smith's derivation depended mainly on three galactic stars; Crampton's depends on 7 stars and should definitely be taken in preference.

TABLE V

Absolute magnitudes of Wolf-Rayet stars

Class	Smith			Crampton		Adopted
	M_v	σ[a]	n	M_v	n	
WN3	−4.5	0.1	2		1	−4.5
WN4	−3.9	0.3	5	−3.7	3	−3.9
WN5	−4.3	0.1	2		3	−4.3
WN6	−5.8		3	−4.8	7	−4.8
WN7	−6.8	1.0	4	−6.5	4	−6.8
WN8	−6.2	0.4	3			−6.2
WC5	−4.4	0.6	5 }	−3.6 (WC5–WC6)	1	−4.4
WC6	−4.4		0 }		2	−4.4
WC7	−4.4		2	−4.4	3	−4.4
WC8	−6.2		1	−5.4	1	−4.8
WC9	−6.2		0			−4.4

[a] σ = standard deviation.

For the other subclasses, I would retain the values given by Smith since these depended on observations in the Large Magellanic Cloud and are free from the uncertainties inherent in distance determinations based on OB star luminosities or on kinematic models. The differences between Smith and Crampton's values are not large compared to the intrinsic range in the luminosities derived for the LMC stars. While a real difference between LMC and galactic WR stars is a possibility, the data does not warrant that conclusion yet. However, when classifications of the faint LMC WR stars (presently based mostly on photometric colours) have been checked with good spectrograms and when classifications including reliable luminosity classes are available for the OB stars on which the galactic distances depend, this problem should be reconsidered.

Among the WC stars, similar comments apply. Smith's derivation for M_v of WC8 stars depends only on the galactic star, γ_2 Velorum, a binary with components WC8 and O. Taking Smith's (1955) classification of the companion as O7 and assuming it had the luminosity of a main sequence star of that class, Smith believed the WC8 star to be the more luminous. Baschek and Scholz (1971) and Conti and Smith (1972) have derived the luminosity ratio of the two stars from comparisons of line strengths in the spectrum of γ_2 Vel with other (presumed single) O and WR stars. The conclusion is definitely that the O star (which appears to be a supergiant) is the more luminous. Baschek and Scholz estimate the luminosity of the WC8 star as between -3.6 and -4.5, but they use a distance modulus of 7.5 mag., rather than the larger figure, 8.3 mag., derived by Graham (1965) and independently substantiated by Brandt *et al.* (1971). Conti and Smith derive $M_v = -4.8 \pm 0.3$ with the larger modulus. This value is within the range 4.4 ± 0.6 mag. observed by Smith for the WC5 stars in the LMC. Thus there is no longer evidence for a difference in luminosity between the WC8 and WC5 stars. I have, therefore, adopted -4.4 as the M_v of WC9 stars also. Crampton derives a significantly lower value, -3.6 for the luminosities of WC5 and WC6 stars. As for the WN stars, this may indicate a difference between LMC and galactic WR stars (and would againi ndicate a significant luminosity difference between WC8 and earlier subclasses). However, his value is based on only three stars and one should reserve judgement.

It is well to recall at this time that M_v refers to the narrow band system of Smith (1968b). This system effectively avoids emission lines in the spectra of WN stars, and magnitudes therefore refer to the continuum. This is not the case for WC stars, and while the effect of the emission lines is probably not greater than 0.1 or 0.2 mag., it has never been determined.

5. The Galactic Distribution

Revision of the absolute magnitudes revises the galactic distribution picture for the WR stars. The positions projected onto the galactic plane are shown in Figure 5. The diagram is a great deal tidier than the earlier version (Smith, 1968c); the big scatter of WN6 and WC9 stars over the galactic center region is removed. The H II regions whose distances are derived by Courtès *et al.* (1968) and by Georgelin and Georgelin (1970), the giant H II regions according to the diagram of Mezger (1970), and the outer edges of the OB star concentrations defined by Graham (1970) are also shown. The WR stars concentrate at approximately the same distances as do Courtès's H II regions, indicating that the distance scales of the two types of objects are in reasonable agreement. The WR stars also conveniently bridge the gap between the normal H II regions, which are, in general, only observed to distances of the order of 3 kpc, and the giant H II regions which are mostly at distances of 5 kpc or more.

The Carina arm is very clearly delineated and its connection to the Sagittarius arm in the north is re-inforced. The Sagittarius arm in the south appears to branch from the Carina-Sagittarius arm at a point between the Sun and the galactic centre. An inner arm at about 6 kpc from the galactic centre is weakly defined. The pitch angle

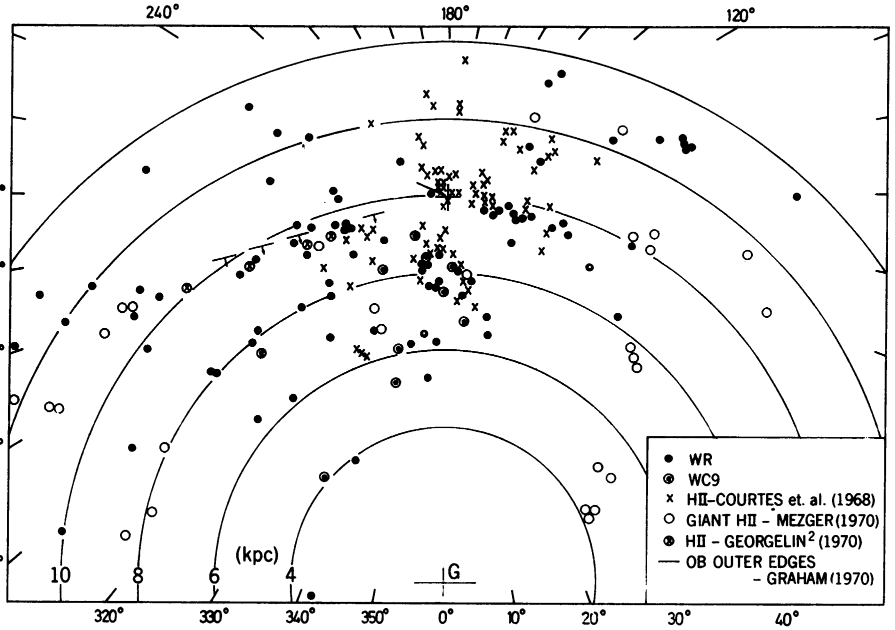


Fig. 5. The positions of WR stars projected onto the galactic plane, compared with position of H II regions and the outer edge of the OB stars concentrations in Carina.

of about 20° for the Cygnus arm, advocated by Courtès *et al.* (1969) and many previous optical observers, is reinforced; this arm appears to stop about 1 kpc beyond the Sun. The Cepheus arm appears to be rather irregular. The distances of the WR stars agree moderately well with those of the H II regions in the nearer parts of the arm, between $l^{II} = 115°$ and 140°; in these directions the arm lies about 11.5 kpc from the galactic center. Between $l^{II} = 100°$ and 115°, where the arm is defined by WR stars alone, its distance from the galactic center is about 13 kpc.

Comparison to the H I distribution given by Kerr (1970) is shown in Figure 6. The agreement is good for the distant parts of the Carina arm and the southern part of the Sagittarius arm. However, the optically defined Cygnus arm and the nearer parts of the Cepheus arm fall definitely closer to the galactic center than do the H I arms in Kerr's diagram, and the connection between the Sun and Carina, shown in the H I diagram, is definitely not substantiated by the optical objects. The lack of any optical equivalent to the northern Sagittarius arm is largely due to heavy absorption. Some WR stars are known in those directions but are not on the diagram due to lack of photometric data.

The WC9 stars have been plotted with a different symbol to the other WR stars. I argued at the 1968 meeting (Smith, 1968e) that the high visual luminosity ($M_v = -6.2$) was necessary for these stars to explain their strong concentration towards the galactic center direction. With the lower value now adopted for the visual absolute magnitude, most of them fall in the section of spiral arm immediately interior to the Sun. There

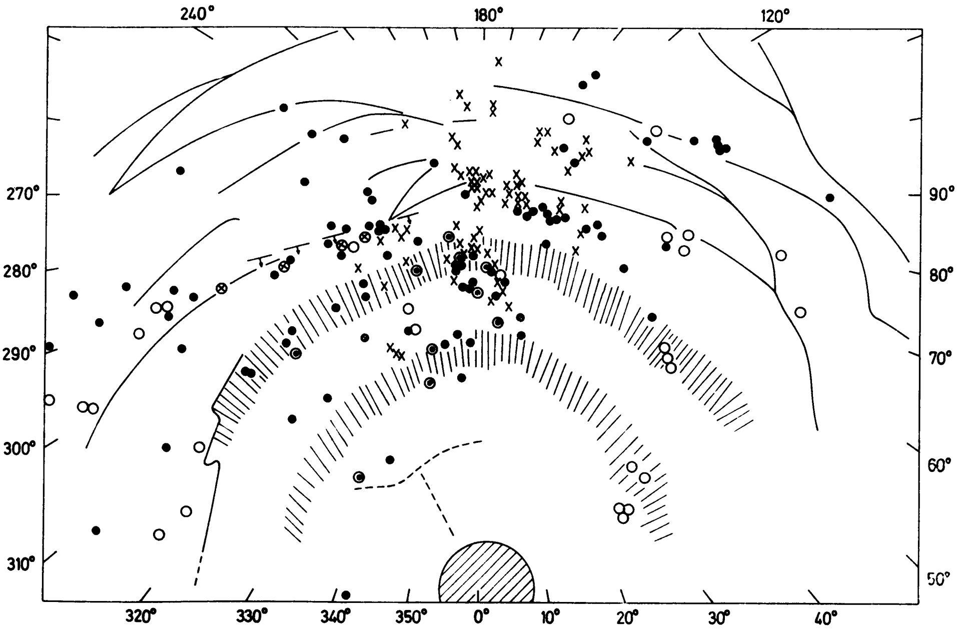


Fig. 6. The positions of WR and H II regions shown in Figure 5 compared to the H I distribution given by Kerr (1970).

is only one known in the rest of the southern Sagittarius arm and none in the Carina arm. The distribution is without explanation at this time.

Apart from the WC9 stars, the discussion of galactic distribution of WR stars, of the concentration of WC9, WN6 and WC7 stars to regions within 9kpc of the galactic center, and the complete absence of subclasses WC6–9 and probably WN6 from the Magellanic Clouds, remains as given in 1968.

6. The Distribution of WR Stars in M33

Wray and Corso (1972) have recently found, in M33, 25 objects which have strong emission at wavelengths near λ 4670 and do not have strong emission around λ 5007. They identify these as WR stars and have spectra of two of the objects (discussed in Section 3) to verify that identification. The positions of the objects found are shown in Figure 7 (Figure 1 of Wray and Corso). The circles in that figure represent the boundaries of the regions observed. Clearly the stars fall within the spiral arms, justifying again the assignment of WR stars to extreme population I and validating their use as spiral tracers in our own Galaxy. Obviously, determination of the subclassification of these stars is of great interest, in order to determine whether there is segregation of some subclasses, as there appears to be in the Galaxy, or complete lack of some subclasses, as occurs in the Magellanic Clouds.

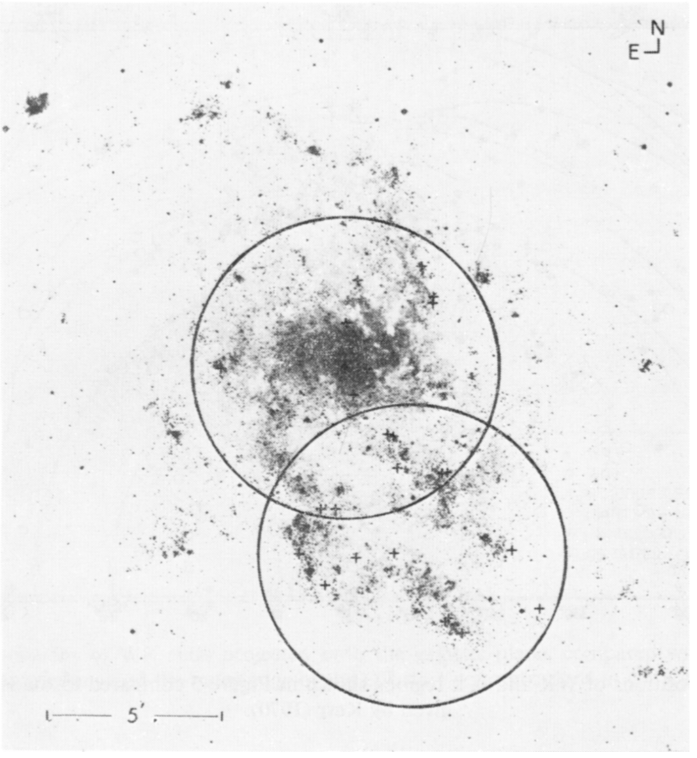


Fig. 7. The positions of Wolf-Rayet stars in M33 identified by Wray and Corso (1971).

7. The Bolometric Luminosities, Radii and Compositions

Morton (1970) has derived temperature for a few WN stars. These are Zanstra temperatures based on the visual luminosities (in the continuum) of the WR stars and on radio observations of associated nebulae (Johnson and Hogg, 1965; Gebel, 1968; Smith and Bachelor, 1970). The method requires the assumption that the WR stars radiate like line-blanketed model atmospheres, a dangerous assumption. However, since the deviation of the true flux distributions from those of the models may be similar for all these stars, the relative temperatures may be approximately correct, even if there is a systematic error. Morton's results are given in row 2 of Table VI. In row 1 are the visual magnitudes as adopted in Section 4. In row 3 are bolometric corrections, as tabulated by Morton (1969), applicable to models at the derived temperatures. Row 4 gives the bolometric magnitudes. We have the surprising result that, despite a range of approximately 3 mag. in visual luminosity, all the WN stars appear to have bolometric magnitudes between −8.1 and −9.1. Thus, the total rate of energy production is approximately the same for all the stars. The different visual magnitudes appear to be due to different surface temperatures (causing differing portions of the energy to be observed in the visual region of the spectrum). Obviously, R^2T^4 must remain constant; thus the hottest stars are the smallest.

TABLE VI

Luminosities of WN stars

	WN5	WN4	WN6	WN7	WN8	Error	Range
M_v	−4.3	−3.9	−4.8	−6.8	−6.2	±0.5	3 mag.
T_{eff}[a]	54000° 52000	46000°	40000° 29000		23000°	±5000°?	
B.C.[b]	4.6	4.2	2.8, 3.7	2.3?	2.3	±0.4	
M_{bol}	−8.9	−8.1	−7.6, −8.5	−9.1	−8.5	±1.0	1 mag.

[a] Morton (1970).
[b] Morton (1969).

The derived temperatures are included in Table I, where the H/He ratios were derived; it is clear that there is a correlation between the temperatures and the H/He ratios in the sense that the stars with the lowest H/He ratios are the hottest. We deduce that the stars with the lowest H/He ratio are the smallest!

Bolometric magnitudes between −8 and −9 correspond to pure helium, helium-burning stars with masses between 8.5 and 14 $M_\odot$ or to pure hydrogen, hydrogen-burning stars with masses between 28 and 45 $M_\odot$ (see Table VII). Since WR stars are

TABLE VII

Comparative luminosities: helium-burning helium stars to hydrogen-burning hydrogen stars

Log $L/L_\odot$	M_{bol}	M(He)[a] ($M_\odot$)	M(H)[b] ($M_\odot$)
4.9	−7.5	7	23
5.1	−8.0	8.5	28
5.3	−8.5	11.5	35
5.5	−9.0	14	45
5.7	−9.5	17	57

[a] Van der Borght and Meggitt (1963).
[b] Stothers (1963, 1965, 1966).

characteristically 11 $M_\odot$, not 30 $M_\odot$ (see Kuhi's discussion in this Symposium), the conclusion is that WN stars are not hydrogen burning. Pure helium, helium-burning stars are consistent with the observations; carbon cores and carbon burning are not excluded.

A small amount of hydrogen in the atmosphere causes a star to have a size much greater than that of a pure helium star. Thus, the deduction above, that stars with little or no hydrogen in their atmospheres are the smallest, is in complete accord with the theory.

It should be noted that this analysis has relied on data from binary and apparently-single stars, with the implicit assumption that these stars are intrinsically identical. In fact we do not know if the 'single' and binary stars have the same evolutionary history, so some caution may be in order. It can, however, by more careful use of the data, be shown that the masses and luminosities are almost certainly equal for the two types of object. The observations are as follows: the WR stars in binaries are observed to have masses of the order of 11 $M_\odot$. The H/He ratios are demonstrated to be the same for binary and 'single' stars of the same class. The luminosities derivations (Table VI) depend almost completely on 'single' stars.

Thus, the luminosities of the 'single' stars correspond to those of pure helium stars with masses equal to those derived for the binary stars. Since the very high helium abundance observed in the atmospheres are inconsistent with other than a nearly pure helium star, it follows that both 'single' and binary stars are pure helium stars approximately of the same mass and luminosity.

8. How 'Rare' are the WR Stars?

The statement has often been made that WR stars are exceedingly rare objects. It is clear that a WR spectrum is probably characteristic of only a part of any given star's evolution. The 'rarity' of WR stars has been taken to imply that only a small fraction of stars have a WR phase. Let us re-examine the evidence.

The Hamburg, Warner and Swasey Catalogue lists 5800 stars of spectral type earlier than B 1 V (see Sim, 1969). Their limits were: $l^{11}=10°$ to $220°$ and $m_{pg}<13$ mag. If we guess that this represents completeness to a distance of 3 kpc, we may count the number of WR stars known to this distance; in the same longitude limits, the answer is 15. (This number allows for the change in the distance scale of the WR stars resulting from changes of some of the M_v's adopted in Section 4.) Now a B 1 V star has a mass of about 10 $M_\odot$ and a main sequence lifetime of about 2×10^7 yrs (Iben, 1967). Thus:

$$\left[\frac{\text{The number of WR Stars}}{\text{The number of OB stars with } M>10M_\odot}\right]\sim\left[\frac{1}{400}\right].$$

And, if a fraction, 1/W, of all stars with $M>10M_\odot$ become WR stars, the lifetime of the WR stars must be of the order of $5\times W\times10^4$ yrs. Kippenhahn (1969) [See also Smith, 1968d)] estimates the total lifetime for helium *and* carbon burning of an 8.5 $M_\odot$ nearly-pure-helium star as less than, but of the order of, 10^6 yrs. Thus, we might imagine that $W\approx20$, and indeed the WR phenomenon would be moderately rare.

However, there is a fallacy in the above logic. To generate an 8 $M_\odot$ pure helium core during its main sequence lifetime, a star must be initially about 25 $M_\odot$ (Kippenhahn, *loc. cit.*) and it is therefore probably only stars of 25 $M_\odot$ or greater that have any possibility to become WR stars. From Sandage's (1957) mass function, only about 1/100 of stars with masses greater than 10 $M_\odot$ are also greater than 25 $M_\odot$; thus the ratio of WR stars to 'progenitor OB stars' is only $\frac{1}{4}$. The lifetime on the main sequence of a 25 $M_\odot$ star is 5.5×10^6 yrs. (Stothers, 1963; Stothers, 1965). Thus, if 1/W of all main sequence stars greater than 25 $M_\odot$ becomes a WR star, the lifetime of the WR phase must be approximately $W\times10^6$ yrs. In as much as a lifetime greater than about

https://doi.org/10.1017/S0074180900098648 Published online by Cambridge University Press

10^6 yrs appears theoretically impossible for 8-14 $M_\odot$ pure helium stars, it would appear that W must be of order 1, and all stars with initial masses greater than 25 $M_\odot$ must have a WR phase. Thus, far from being rare, the WR phenomenon would appear, among massive stars, to be the rule.

Obviously this calculation can, and should, be checked with the stars in the Magellanic Clouds.

9. Interpretation of the WN Sequence

It may be concluded from the data presented in Sections 2 and 7 that WN stars of all subclasses are pure helium stars with masses between 8 and 14 $M_\odot$ and that the stars in various subclasses differ from one another in their atmospheric composition and, thereby, in their sizes and surface temperatures. To demonstrate more clearly the consequences and uncertainties inherent in this statement, the subclasses are arranged in a two dimensional grid in Table VIII. The mass and bolometric magnitudes, which

TABLE VIII

The WN sequence

$M/M_\odot$	M_{bol}					
17	−9.5					
14	−9.0		WN7			WN5
11.5	−8.5	WN8			WN6	
8.5	−8.0			WN3	WN4	
7	−7.5					
(H/He)		2.3	1.0	0.8:	0.4	0.0
T_{eff} (K)		23000°			46000° / 40000° / 29000°	53000°

are assumed to be related as for pure helium, helium-burning models, are displayed vertically. The H/He ratio is displayed horizontally; temperatures, when known, are also indicated. It is implicitly assumed that each subclass may be associated with a comparatively small range of each of these parameters.

Several things are immediately noticeable:

(1) The constancy of M_{bol}, within the uncertainties, is demonstrated. The bars correspond to the observed range of M_v in the LMC or to ±0.4 mag., the rang observed for the WN4 stars; the latter are the most numerous subclass in the LMC, the intrinsic range of their luminosities is better determined than for any of the other subclasses and is probably typical. For the WN6 stars the bars include the uncertainty due to two divergent temperature determinations. The observed range of M_v presumably corresponds to a spread in both M_{bol}-mass and radius-temperature.

https://doi.org/10.1017/S0074180900098648 Published online by Cambridge University Press

(2) The H/He ratio alone is not sufficient to determine the subclass of the star; e.g., WN4 and WN6 stars are found to have comparable H/He ratios. While the H/He ratio may be an important parameter in determining the subclass, a second parameter is obviously necessary. The data give no clear indication what that may be. However, one should recall that the WN6 stars differ from other subclasses of the WN stars in their galactic distribution, being found more often than other types in directions close to the galactic center (Smith, 1968c). Moreover, among the WC stars, there are gross differences from galaxy to galaxy; in the Magellanic Clouds many of the subclasses are completely missing; in M33, the spectra of the two WC stars observed by Lynds (Wray and Corso, 1971) are quite unlike those in either the Galaxy or the Magellanic Clouds. Whatever the parameters are that control the WR subclasses, at least one of them is variable from place to place.

I have previously (Smith, 1968c; Smith, 1968d) suggested that the parameter responsible for the observed distribution of subclasses in the Galaxy and the Magellanic Clouds is initial chemical composition. Data has accumulated supporting the hypothesis that there are indeed variations of the interstellar chemical composition from galaxy to galaxy and from the center to the edge of large galaxies (see Peimbert and Spinrad, 1970). However, no causal relation between initial chemical composition and spectral subclass has yet been established.

(3) The sequence of decreasing H/He ratio is not monotonically related to the excitation subclass. In fact, the subclasses WN3, WN4 and WN5 are inverted. The observed correlation between H/He ratio and temperature strongly implies that the WN3 stars have the lowest surface temperature and the WN5 stars the highest. There is no serious objection to the suggestion, although it is, at first glance, surprising. The excitation temperatures of the atmospheres appear, in general, to be higher than the effective temperatures of the stars. Thus, the atmospheric temperature must be supported by a source other than the radiation field and there is no *a priori* reason why the two temperatures should be monotonically related. It is of interest in this regard to notice that the progression of spectral appearance from WN5 to WN3 consists mainly of progressive reduction of first the N III and then the N IV contributions to the spectrum; N V lines are strong in all of these subclasses. If ionisation decreases outwards (see Kuhi, in this Symposium) the observed spectral sequence could be produced by stars whose atmospheres have basically the same ionization structure, but different density structures, such that densities in the outer layers, where the N III and N IV ions are found are successively reduced as one proceeds from WN5 to WN3.

(4) The relative position of WN7 and WN3 is somewhat arbitrary since the H/He ratios for both are uncertain. However, there is obviously a sudden break in properties of the spectra as we pass from WN3 to WN7 and WN8; the excitation drops radically, He I lines become prominent and violet absorption edges become more frequent (most notably on the Pickering lines). The energy supply to the atmosphere of WN7 and WN8 stars is apparently insufficient to keep the helium doubly ionized. Since helium is presumably the dominant element in the atmosphere, a profound change of atmospheric excitation and structure is not surprising.

10. WC Stars

An attempt to interpret the WC stars in the same framework is possible. Unfortunately, H/He abundances may not be derived with the same facility as for WN stars because of severe blending of carbon lines with the Pickering series. Since the stars are not commonly associated with nebulae, temperatures are not available either. The interpretation depends heavily on the properties of binary systems and is better held until after Kuhi's review of binaries later in this Symposium.

Acknowledgements

I thank James Wray and George Corso for making their data and diagrams available prior to publication. The final manuscript and diagrams were prepared while the author was at the Institut d'Astrophysique, Liège, supported by an ESRO Fellowship; assistance given with typing, diagrams and photography is appreciated.

References

Aller, L. H. and Heap, S. R.: 1971, *Bull. Am. Astron. Soc.*, **3**, 400.
Bashek, B. and Scholz, M.: 1971, *Astron. Astrophys.* **11**, 83; **12**, 322.
Beals, C. S.: 1938, *Trans. IAU* **6**, 248.
Brandt, J. C., Stecher, T. P., Crawford, D. L., and Maran, S. P.: 1971, *Astrophys. J. Letters* **163**, L99.
Castor, J. I. and Van Blerkom, D.: 1970, *Astrophys. J.* **161**, 485.
Conti, P. S. and Smith, L. F.: 1972, *Astrophys. J.*, **172**, 623.
Courtès, G., Georgelin, Y., Monnet, G., and Pourcelot, A.: 1968 in Y. Terzian (ed.), *Interstellar Ionized Hydrogen*, Benjamin, New York, p. 571.
Courtès, G., Georgelin, Y. M., and Monnet, G.: 1969 *Astrophys. J. Letters* **4**, 129.
Cowley, A. P. and Hiltner, W. A.: 1969, *Astron. Astrophys.* **3**, 372.
Crampton, D.: 1971, *Monthly Notices Roy. Astron. Soc.* **153**, 303.
Gebel, W. L.: 1968, *Astrophys. J.* **153**, 743.
Georgelin, Y. P. and Georgelin, Y. M.: 1970, *Astron. Astrophys.* **7**, 133.
Graham, J. A.: 1965, *Observatory* **85**, 196.
Graham, J. A.: 1970, in W. Becker and G. Contopoulos (eds.), 'The Spiral Structure of Our Galaxy', *IAU Symp.* **38**, p. 262.
Hiltner, W. A. and Schild, R. E.: 1966, *Astrophys. J.* **143**, 770.
Iben, I.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 586.
Johnson, H. M. and Hogg, D. E.: 1965, *Astrophys. J.* **142**, 1033.
Kerr, F. J.: 1970, in W. Becker and G. Contopoulos (eds.), 'The Spiral Structure of Our Galaxy', *IAU Symp.* **38**, p. 95.
Kippenhahn, R.: 1969, *Astron. Astrophys.* **3**, 83.
Kuhi, L. V.: 1966, *Astrophys. J.* **143**, 753.
Kuhi, L. V.: 1968, in K. B. Gebbie and R. N. Thomas (eds.), *Wolf-Rayet Stars*, U.S. Government Printing Office, Washington, D.C., p. 110.
Kuhi, L. V. and Smith, L. F.: 1973, *Atlas of Wolf Rayet Line Profiles*, U.S. Government Printing Office, Washington, D.C.
Mezger, P. G.: 1970, in W. Becker and G. Contopoulos (eds.), 'The Spiral Structure of Our Galaxy', *IAU Symp.* **38**, p. 107.
Morton, D. C.: 1969, *Astrophys. J.* **158**, 629.
Morton, D. C.: 1970, *Astrophys. J.* **160**, 215.
Oke, J. B.: 1954, *Astrophys. J.* **120**, 22.
Peimbert, M. and Spinrad, H.: 1970, *Astron. Astrophys.* **7**, 311.

Popper, D. M., Jørgensen, H. E., Morton, D. C., and Leckrone, D. S.: 1970, *Astrophys. J. Letters* **161**, L. 57.
Sandage, A.: 1957, *Astrophys. J.* **125**, 422.
Sim, M. E.: 1968, *Publ. Roy. Obs. Edinburgh* **6**, No. 5, 123.
Smith, H. J.: 1955, Dissertation, Harvard.
Smith, L. F.: 1968a, *Monthly Notices Roy. Astron. Soc.* **138**, 109.
Smith, L. F.: 1968b, *Monthly Notices Roy. Astron. Soc.* **140**, 409.
Smith, L. F.: 1968c, *Monthly Notices Roy. Astron. Soc.* **141**, 317.
Smith, L. F.: 1968d, in K. B. Gebbie and R. N. Thomas (eds.), *Wolf-Rayet Stars*, U.S. Government Printing Office, Washington, D.C., p. 54.
Smith, L. F.: 1968e, in K. B. Gebbie and R. N. Thomas (eds.), *Wolf-Rayet Stars*, U.S. Government Printing Office, Washington, D.C., p. 72.
Smith, L. F.: 1972, in A. D. Code (ed.), *The Scientific Results from the Orbiting Astronomical Observatory (OAO-2)*, National Aeronautics and Space Administration, Washington, D.C., p. 429.
Smith, L. F. and Bachelor, R.: 1970, *Australian J. Phys.* **23**, 203.
Smith, L. F. and Kuhi, L. V.: 1970, *Astrophys. J.* **162**, 535.
Stothers, R.: 1963, *Astrophys. J.* **138**, 1074.
Stothers, R.: 1965, *Astrophys. J.* **141**, 671.
Stothers, R.: 1966, *Astrophys. J.* **144**, 959.
Van der Borght, R. and Meggitt, S.: 1963, *Australian J. Phys.* **16**, 68.
Wray, J. D. and Corso, G. J.: 1972, *Astrophys. J.*, **172**, 577.

DISCUSSION

Thomas: Regarding the question of the masses, suppose I accept that some central stars of planetary nebulae have a Wolf-Rayet phase, what do you do then? The mass drops to one or two or three solar masses.

Smith: Kuhi has the data relating to masses assembled; the Population I Wolf-Rayets range from 5 to 15 solar masses. So they must evolve from stars which are ten solar masses or greater. The nuclei of planetaries are probably about one solar mass and must be considered separately. Here I am considering only Population I WR stars.

Thomas: But you cannot close your eyes to the other things.

Smith: I am just saying that every star greater than a certain mass or a large fraction of stars greater than some mass go through the Wolf-Rayet phase. The phenomenon is not as rare as we thought. We are not talking about one in a thousand stars becoming a Wolf-Rayet star. We are talking about one in ten.

Thomas: If the central star of a planetary is a Wolf-Rayet phenomenon and if the central star is one or two solar masses, then just taking the kind of numbers you gave (the smaller the mass the less life time of the phase) one would get down to 10^3 yrs or something like this for the life time of a Wolf-Rayet star in a planetary nebula.

Smith: Obviously the planetary nebulae nuclei have a completely different evolutionary situation. To derive their lifetime you would have to know what mass range on the main sequence they evolve from and compare the number of WR nuclei with the number of main sequence stars. It could be done but I have not done it.

Thomas: All I say is that if I have two different kinds of things exhibiting a Wolf-Rayet spectrum then I would just worry if you restricted your attention to one of them as representing all Wolf-Rayet phenomena.

Smith: One should also do the same calculation, comparing numbers of OB and WR stars in the Magellanic Clouds.

Thomas: In regard to the question of the observed visual magnitude and the bolometric corrections, I wish Lindsey Smith to clear one thing up. It seemed to me that what you were going to say was that those stars which have a low visual magnitude, but a high bolometric correction, would do so because of the difference in size. But I expected something different. Here you say that WN5 has a greater extended atmosphere than WN8 and I would expect it the other way because it has a lower visual magnitude.

Smith: What you say is correct. The bolometric magnitude depends on the effective temperature and on the size of the photosphere. It appears to be approximately constant. Thus the radius you would observe in the continuum must decrease dramatically with increasing temperature.

Thomas: So that when you say bigger you imply that the momentum transfer is still larger.

Smith: To explain the properties of the emission spectrum, I suggest that the radius of the line emitting region increases as you go upwards and to the right in the diagram.

Thomas: Now, physically, how does this happen?

Smith: I do not know. Three years ago I would have suggested that pulsational instability increases in that direction. The failure of all efforts to detect light variations due to pulsational instability and the increase in the theoretical mass limits for instability to occur make that suggestion very weak now. So I merely emphasize that the intensities and widths of the lines in the subclasses WN5 and WN6 (both binary and 'single') are much greater than in subclasses WN3 and WN4. It implies that the amount of material in the atmospheres is much greater, i.e., that the atmospheres are probably both bigger and denser. Thus, one requires a greater energy input into the atmospheres of WN5 and WN6 than in WN3 and WN4. In terms of our 1968 discussions, I suggest a greater *mechanical* energy input. The anticorrelation I suggest between T_{eff} and excitation class speaks against radiative control.

Underhill: There are two points which I think it important to clarify concerning your deduction of zero or low hydrogen abundances in WN stars. (1) The unit of flux in your diagram giving line strength vs. upper quantum number of He II is F (5000 Å). The emission line strengths were measured at the wavelengths of the lines. I assume that you used spectral scans such as those of Kuhi to relate the continuous spectrum at the line to that of the unit at 5000 Å; if so, we can infer that the measurements are all on the same scale and any error on this point is proportional to the uncertainty of defining the continuous spectrum; (2) My greatest dismay with your implied knowledge of the H/He ratio is that you have implied that the answer is known to some very serious theoretical problems which are intrinsically very significant for understanding Wolf-Rayet spectra.

Consider a line in a hydrogen like spectrum with upper level n and lower level m. Then the measured flux in arbitrary units is given by

$$F(n \rightarrow m) \sim N(m)\, A_{nm} \times hc\lambda^{-1}{}_{nm} \times (\text{transfer effects in line } n \rightarrow m).$$

For two lines $n_1 \rightarrow m_1$ and $n_2 \rightarrow m_2$ measured in the same units,

$$\frac{F_{n_1}}{F_{n_2}} = \frac{N(n_1)}{N(n_2)} \times \frac{A_{n_1}}{A_{n_2}} \times \frac{\lambda_{n_1}}{\lambda_{n_2}} \times \frac{(\text{transfer effects})_1}{(\text{transfer effects})_2}$$

Here n_1 represents the upper quantum number of line 1, n_2 represents the upper quantum number of line 2. My criticism lies in that you are assuming that the ratio of the line transfer effects (which is the solution of the equation of transfer) for both lines is unity. This is only in a truly thin nebula. If you take the estimated electron temperature and density in a typical Wolf-Rayet atmosphere of the type WN6 to be 10^5 and 10^{11} respectively, you find that an optical depth 10 is reached in a distance of the order of 1000 cm. Allowing for optical transparency introduced by motion, the effective path length may possibly be extended to 10^8 cm for Hε or 10^9 for the He II line (4–14). The geometric length of a Wolf-Rayet atmosphere is considered to be something like thirty solar radii which means that complete optical thickness will be reached in both lines. If this is so, then it is essential that the transfer effects in the H and He II lines be evaluated before anything can be said about the relative abundance of H and He.

Smith: We measured the equivalent width relative to the continuum in each case. And then we have used Kuhi's published continuum flux determinations corrected for reddening to convert to flux in units of the continuum of the star at 5000 Å.

Observationally the case is based, first of all, on Castor and Van Blerkom's calculations that, for HD 192163, the Pickering lines are thin for $n > 10$. The change in slope of the decrement observed for HD 192163 and HD 50896 dramatically confirms the suggestion that there is a change at about $n = 10$ from thin lines to thick lines. Second, when the Pickering line is blended with N III or He I the optical thickness is not so great that the line strength is not greatly increased. Third, there is marked consistency of the slope of the graph between the high-n sections of HD 192163 and HD 50896 and those other subclasses in which the lines are weaker and a contribution from hydrogen is clearly observed.

Fourth, if you did have an abduance ratio of 10 to 1 between H and He in these stars your H lines might still be thick to high value sof n,but the helium lines certainly would not be. Thus, from observational evidence alone, I think it is clear that the higher Pickering lines are optically thin in al.

https://doi.org/10.1017/S0074180900098648 Published online by Cambridge University Press

the stars observed. I emphasize that we are talking about lines that only exceed the continuum by about ten per cent and their equivalent widths are down to an angstrom by the highest members of the series.

Underhill: How do you account for that formula that I just sketched on the blackboard?

Smith: If you had such high opacity in such weak lines, I wonder what is the opacity in the continuum. Perhaps you had better choose different numbers.

Underhill: I am talking about the opacity just in a line. If I add the continuous absorption in an atmosphere with typical parameters, as deduced by Castor and Van Blerkom, I have a really opaque atmosphere.

Smith: Then you are not talking about the atmosphere, you are talking about the interior of the star.

Conti: May be a few more people would like to contribute to this discussion.

Niemela: In γ_2 Velorum, He I lines and the hydrogen lines display the so-called V/R variations; these variations are not present in the He II and C lines. This suggests that hydrogen may be present.

Bappu: At what phases were the plates taken?

Niemela: At 47 and at 4 days.

Conti: You now say that the V/R variations are purely due to the presence or absence or dominance of H or He. On certain occasions, could it not be due to the fact that the O companion's velocity mutilates the emission. What strikes me is that the effect is not shown by all the He II lines.

Bappu: You find it only in Hα?

Niemela: I find it in Hα, Hβ, Hγ, etc. and also in He I lines, but not in 5411 Å, 4200 Å and 4570 Å.

Conti: Are there any comments on this particular theme?

Van Blerkom: The optical depth in He II Pickering lines from two WN6 stars were computed by John Castor and myself on the basis of a simple expanding envelope model. In that analysis, the lines became optically thin for transitions out of levels with $n > 9$, which agrees with Lindsey Smith's interpretation.

Underhill: I know your calculations of He II, and I think the result is true. I am not at all certain that you can make the same argument for the Hε line of hydrogen. You went on to argue that if Hε was optically thin, your answers would come out as indicated. However, it is an interesting mental experiment to ask yourself what would be the answer with a normal hydrogen abundance and the same N_e and T_e.

Conti: Even despite the fact that you really do not see the hydrogen?

Underhill: Yes, I can see of ways of hiding the hydrogen lines. Possibly you cannot find them because of the free-free emissions.

Morton: Since the expanding atmosphere enhances the optical thinness, can Lindsey Smith tell us whether anyone of the stars you analyzed do show shifted absorption lines in the visual spectra, suggesting the existence of an expanding atmosphere?

Smith: Yes, WN5, WN6, WN8 and WN9 have the strongest violet displaced absorption; however, some violet edges are observed in all spectra, I think. I do not have the velocities now.

Underhill: It depends which lines you look at. Absorption edges are there in all of the Wolf-Rayet stars. You may look at He I, for example; sometimes you can see absorption edges in C III, sometimes in N IV. Sometimes you see strong displaced absorption lines from levels that are not expected to be strongly overpopulated by non-LTE effects. In C IV and N V such lines are extremely strong. That is interesting because you cannot hold the atoms up there unless you get tremendous optical depths.

Conti: Then, I suppose we might say that most WC and WN stars have at least some violet displaced components in some lines, and it is different for different stars.

Smith: And in certain stars you see them in He II; in some stars they are not conspicuous in He II.

Alcaino: Coming back to your absolute luminosity slide Lindsey Smith, you said that most of them are calibrated from the distance moduli of the Magellanic Clouds. Are there any of these stars in globular clusters? Because it could bring up a very important point! If they are globular cluster members they must belong to Population II.

Smith: I know none in globular clusters.

Alcaino: Are there any anomalies in the color excesses? What about the U−B colors?

Smith: Crampton found that the color excesses from the Wolf-Rayet stars are very consistent with the color excesses from the OB stars, so there seems to be no problem with the colors. There are some WR stars in the Galaxy, in the galactic clusters, in Carina and in Sco-Cen OBI; in these cases, his numbers and mine do not differ very greatly. So most of the strong disagreements come from derivations that depend on distances of H II regions derived from one or two O and B stars, and you have all the uncertainty of luminosity assignment for O and B stars as well as assignment of the stars to the same H II regions.

Conti: I have just one question recalling our experience with γ_2 Velorum. You only have four or five stars in the Clouds which have −6.8. Could they not be binaries and could any of the possible companions really dominate the spectrum?

Smith: It is possible, particularly in the more luminous subclasses.

Conti: It really struck me when we made the absolute magnitude of the WC8 component of γ_2 Velorum fainter by one and a half magnitudes.

Underhill: Crampton in sending me the copy of his paper noted that the only stars he had significantly brighter than −5 were the WN7s which came up to −6.5 or so. He notes that these are in exotic places like η Car and Sco OBI. For two of the WN7 stars in Carina, as published in the Annual Reviews, you can see an O type spectrum superposed. Sally Heap told me of an O subdwarf star that has almost an identical looking spectrum. I do not know what is going on with type WN7. Crampton wrote to me and asked whether I thought there are two different kinds of WN7 stars. All I can say is yes, but I do not know the full answer.

Conti: We may end up with the same experience we had in γ_2 Velorum, that the O star, in fact, dominates. Perhaps Lindsey Smith would like to add something.

Smith: I indicated an enormous range for the mass and luminosity of the WN7 stars. This is based on two things. First of all, the observed range in absolute magnitude for the WN7 stars in the Magellanic Clouds is nearly two magnitudes; so, either they do have companions, as has been suggested, or they do have an enormous range in their intrinsic luminosity. Second, they also appear to have an enormous range in their mass. The binary HD 228766 (WN7 + O) has a large mass function and may be edge on; that would put the mass of the WN7 star at about 5 $M_\odot$, one of the lowest mass Wolf-Rayet stars we know. On the other hand, if there really are WN7 stars with absolute magnitude as high as −7.5, their masses must be about 15 $M_\odot$.

Bappu: I was just wondering whether the calibrations of the WN7 stars you have picked up from the Magellanic Clouds, are affected by inadequate sky background corrections or field stars below the limit of visibility. Do the WN stars have any preference for the bar of the Clouds?

Smith: The WN7 stars are in 30 Doradus, η Carinae, etc. The problem is not so much about faint stars, but the nebulosity. I did the obvious things like taking the nebulosity on two sides and so on. I do not think it is a serious problem.

Bappu: Regarding HD 151932, if you look at the spectrum of this star in the near infrared, there seems to be positively something odd in the energy distribution. The energy increases towards longer wavelengths. I wonder if Kuhi has any scans of this star, for it certainly is an object which one should look with a scanner as early possible. It is in NGC 6231. I shall show later today a slide which will give a rough idea of the energy distribution.

Kuhi: I do not have any scans of the star but I hope that I shall soon come to Chile when the scanner at Tololo gets into operation.

Bappu: I am very happy to see that all WC stars have come down within the same domain of absolute magnitudes. However, I still find WC8 brighter by about 0.4 of a magnitude. Rajamohan at Kodaikanal has looked into this problem by using Mount Stromlo spectra of γ_2 Velorum at 6A mm^{-1} dispersion. He has utilized the hydrogen absorption lines, with the old-fashioned way of making corrections. He has also determined the distance of γ_1 Velorum, using Petrie's technique, but with the improved calibration, and the absolute magnitude of γ_2 comes out to −3.1. With a difference of 2.4 mag., the entire γ_2 system becomes −5.5. The absorption line intensities give you the fact that the O star is brighter than the Wolf-Rayet star by 0.6 magnitudes while the emission line intensities in infrared give a difference of 1.4 mag. Assuming then that the O star is brighter by 1.0 mag., the final values of the absolute magnitudes are −4.2 for the WC8 star and −5.2 for the O star.

Smith: That is awfully faint for stars that are 15 and 60 solar masses. Conti and I have summarized the argument in our current paper which Kuhi will review later. My inclination is to stick to Graham's distance of 460 pc which has been recently confirmed by Brandt *et al.*

Conti: Lindsey Smith and I have had a re-analysis of γ Velorum and have come out with somewhat different numbers all around. We derived an absolute magnitude of −4.6; we have the O star brighter by 1.4 mag., and the distance is taken from Hβ photometry.

Kuhi: I would like to remark that Lindsey Smith's comments as far as the H/He ratio, apply only to the WN stars. It is almost impossible to do the same sort of analysis for the WC stars because their spectra are so badly blended that it is almost completely hopeless to trace out the Pickering series or any series throughout the normal photographic spectral region. I have also obtained scans out to 1μ or so, of a number of the brighter WC stars in the hope of finding relatively free spectral regions and have not succeeded. The WC spectrum is full of emission lines, all the way out to about 1.2μ; the WN's, on the other hand, out to about 1.3μ, are dominated by helium lines and virtually nothing else.

Sahade: I would just like to make two comments. In regard to γ Velorum; I wish to remark that γ_1 Velorum is a spectroscopic binary and that its velocity curve is somewhat peculiar, atleast we have not been able to settle on a definite velocity curve so far. The second comment is that the so-called V/R variations of the intensities of the emission lines which Virpi Niemela showed this morning to be phase dependent in stars like γ_2 Velorum, are also present in WN objects. They are seen very nicely on the illustrations of Giudo Munch's paper on V444 Cygni, and they also appear to be phase dependent.

Kuhi: I think that those changes in V444 Cygni or any of the other stars that are binaries really just confuse the problem of determination of the H/He ratio and of everything else. I am sure that they arise from material between the two stars. In fact, changes occur in geometrical properties as one looks at the system from different aspects, as well as changes in the physical properties of the material associated with the stars, especially the material located in the regions between them. So, I think one should stick to the single stars, in all cases, if one is going to determine anything about hydrogen and helium.

Sahade: I agree with Kuhi that these effects are connected with the matter which is between the two stars. But I think we should make a point in trying to see whether there are any changes in the spectra of those stars which we think are single.

Underhill: There is a point that Kuhi covered rather quickly. If it is a binary you can see the material at certain phases and you can see changes. Now, you should ask yourself the question why do these changes happen? Is it something originating in the Wolf-Rayet star? If so, then, the same thing may originate in a single Wolf-Rayet star and you should ask yourself, how could I observe it? It may be that a particular geometric arrangement in specially lined up binaries enables us to see it, but if these changes are going on anyway, it may have a lot to do with the ratio of transfer effects 1 to 2. Just glibly putting that ratio equal to 1, still remains a problem to me.

Kuhi: It is very likely in the binaries that we do see and detect this kind of effect if the material that we are looking at has large motion in the line of sight, which obviously, can happen very easily with systems seen edge on. However, if you are looking at a system face on, you are likely to miss everything.

Thomas: I cannot help sitting back and trying to just see overall what Lindsey Smith has done. And I must say, you make an awfully convincing case for the self-consistency of your argument, which seems to be based on three separate things; and you will forgive me if I do not worry about details. (A) you worry about your line ratios; (B) you worry about some absolute magnitudes (and that involves an observed visual magnitude and a computed bolometric correction), and (C) you come up with some stellar interior calcualtions resting on mass. In (A), I can have all kinds of uncertainty in the direction that Anne Underhill is worried about, but for the moment let us forget about it since it is simply an observational question. In (B) and (C) it is a question of the model, with all kinds of uncertainties. What you come up with is self-consistent for a mass in the range 10 to 15 solar masses. Now, if I go back and ask the same kind of question I asked before, namely, if I look at the Wolf-Rayet spectrum and ask, as at the last Symposium, is it a phenomenon or is it a kind of object, in my answer, I also observe that central stars of planetary nebulae are objects that show a Wolf-Rayet spectrum and have masses like one solar mass. How, then, can I reconcile this with the conclusion from (A) to (C)? Lindsey Smith's argument is beautifully self-consistent until I introduce something with a mass like 1, unless we say there exists several kinds of objects capable, for different reasons, of producing a Wolf-Rayet spectrum.

Smith: My intuitive answer to that would be, at the moment, give me a pure helium star and I will give you a Wolf-Rayet star.

Thomas: But I may also get a Wolf-Rayet star from something which is not a pure helium star. That is the basic thing.

Smith: No, I would suspect that the situation regarding the planetary nuclei is probably also one where we have a pure helium star of mass 1. I do not see why there should be any trouble with the same sort of arguments for this case. (I use the term 'helium star' rather loosely. Lack of hydrogen is required. Carbon cores or other more complicated models are not excluded).

Thomas: Yes, but you put a lot of emphasis on this being in the 10 to 15 mass range.

Smith: The observations suggest that the stars I have discussed are 10 to 15 solar masses, they do have the bolometric magnitudes and hydrogen to helium content I have shown.

Thomas: I thought your argument was that the interior models for a helium star, with mass 10 to 15 solar masses, would give me the kind of absolute magnitude to which all the WN sequence reduce.

Smith: I am saying that the observed stars must be pure helium stars because they are observed to have a certain bolometric magnitude and a certain mass, which eliminates them from being pure hydrogen stars. Population I stars are observed to be 5 to 15 solar masses.

Thomas: Can you get the same consistency with one solar mass?

Conti: I do not think we know the masses of the nuclei of planetary nebulae.

Thomas: Would you accept that they have a mass not much greater than one?

Conti: No, but your point is whether we can get Wolf-Rayet stars from two different kinds of masses, and I think both Lindsey Smith and I would agree with it.

Thomas: No, all I am saying is that you have a beautifully self-consistent argument, each link of which has a number of weak points. Either it is unique to mass 1 or 15 or it is not. If it is not, you had better examine each weak point.

Conti: I think the bolometric correction is a little shaky.

Thomas: I am not disputing a single thing. All I am saying is that there is a lot of uncertainty and the coherence of this very nice argument depends on the absolute magnitude being of the value (forget about fluctuations here) that a 10 to 14 solar mass pure helium star would produce. So, I say now, go to whatever the central star of the planetary nebuale are (helium, hydrogen), whatever their mass is; can I, then, make the same kind of a nice, self-consistent argument from them, and come up with some kind of a conclusion?

Bappu: I would like to ask Lindsey Smith how she explains the absence of λ 5696 in some of the WN stars, particularly, when you have an abundant supply of C IV ions. Selective excitation I could understand normally, but, how do you have a sort of selective supression?

Smith: We see C IV in the λ 5810 line in nearly all of the WN stars. You see the whole of the C IV spectrum, as I showed you in HD 50896, and we do not know if this situation applies also to the others. The only place I have seen C III, is in the WN8's, where it appears quite well developed. I have never seen λ 5696 in a WN spectrum. Henry Smith does claim to see it in HD 50896 but it certainly was not on our spectrogram. I guess the implication is that most of N stars have C IV and it is only when you get down to the WN8s that the excitation is low enough that you see C III. After all, the ionization is comparable. C IV is the ion you expect to be the strongest in HD 50896.

Bappu: Yes, but C III could not be that weak.

Smith: I agree. By strict analogy between the C and N spectra we should have been able to see the stronger C III lines.

Underhill: That is still in question. You have to work it out. I can show some graphs, giving some rough calculations that are not applicable to Wolf-Rayet stars, but if you are brave you can interpolate and get an idea of the ionization fractions in non-LTE situations.