SESSION 2

THE CHEMISTRY OF THE WOLF-RAYET STARS

Chairman: A.B.UNDERHILL

Introductory Speaker: A.J.WILLIS

1. C.D.GARMANY and P.S.CONTI: Chemical composition of WR stars: Abundant evidence for anomalies
2. D.N.PERRY and P.S.CONTI: H/He ratios for WN stars in the LMC and the Galaxy
3. L.J.SMITH and A.J.WILLIS: The C/N ratio in WN and WC stars.
4. D.VANBEVEREN: On the chemical abundance, evolutionary stage and bolometric magnitudes of WR stars.
5. P.MASSEY: Absolute spectrophotometry of WR stars : Are the colours the same ?
6. T.NUGIS: An explanation of the radio flux mystery of HD 192163 and empirical models for WN stars.
7. T.NUGIS: The carbon abundance in WC stars.
8. R.WEHRSE: Synthetic spectra for WN stars.
9. L.HOUZIAUX and A.HECK: Carbon abundance in the WC11 star CPD $-56^{\circ}8032$.

THE CHEMICAL COMPOSITION OF THE WOLF-RAYET STARS

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1. INTRODUCTION

This review summarises current knowledge of the chemical composition of PopI WR stars, concentrating on work carried out in this area since the last IAU, No. 49, symposium devoted to this stellar class (Bappu & Sahade 1973). Earlier reviews of this topic are found in Gebbie & Thomas (1968). The dichotomy of the WR stars into the WN and WC sequences (Beals 1934) has generally been qualitatively interpreted as arising because of gross differences in the C and N abundances: WN stars which exhibit emission lines of predominantly He and N ions with little evidence for C, being inferred as C-poor objects, whilst WC stars, showing predominantly He and C lines and virtually no evidence for N being inferred as N-poor. In both sequences the visible spectra show little or no evidence for hydrogen. However, although the WR stars have been acknowledged as a class for over a century now, progress has been very slow in putting quantitative determinations of their physical and chemical properties on a firm basis, with the bulk of work in this area being conducted during the past decade. The chemical nature of the WR stars has always been a matter of considerable uncertainty, controversy and, quite often, passionate disagreement, arising from uncertainties in the interpretation of the, often ambiguous,observational material available, as well as from disagreements as to the reliability of the use of comparatively simple analytical models employed to date. Recent results strongly suggest that the WR stars are chemically evolved objects, with low H/He ratios and quite different C/N ratios in the WN and WC sequences, with some measure of agreement in these results with the chemistries predicted to arise at various stages of evolutionary theory for hot massive stars which, by one means or another, have shed much of their atmospheric material during their evolution. My purpose in this review is to summarise the investigations and results that lead to the above conclusions. §2 deals with an assessment of the atmospheric H/He ratio in both WN and WC stars: a parameter of fundamental importance in addressing their evolutionary status, as well as providing a base species with which to compare other derived chemical abundances. §3 briefly deals with the models generally employed and gives recent results for

C. W. H. de Loore and A. J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, 87–104.

He, C and N abundances derived from both visible and UV line analyses. §4 summarises recent results from stellar evolutionary theory and in §5 compares these with those derived from observation, assessing the significance of these new results and their implications for the evolutionary status of the WR stars. Some areas for further advancement are identified.

2. THE H/He RATIO IN WR STARS

a. Results from visible spectra

The bulk of attempts to determine H/He ratios in WR stars have used measurements from visible spectra of the HeII (n-4), Pickering series decrement - a plot of the observed line intensities vs. n, the principal quantum number of the transition upper level. Since even-n HeII lines occur at almost the same wavelength as H-balmer lines, any appreciable atmospheric H present should cause an apparent enhancement in the even-n HeII line strengths resulting in a non-smooth Pickering decrement. To obtain a quantitative estimate of the H^+/He^{++} ratio, the analysis is restricted to optically thin lines with b_n values near unity. Castor van Blerkom (1970) have shown that, for any reasonable WR envelope conditions, these latter conditions are satisfied for HeII levels with $n > 10$. The observations thus yield emission line intensities of the HeII (n-4) series, I(HeII,n), and, if any contribution is present, the corresponding H-balmer line intensities, I(H,½n). From these data the H^+/He^{++} ratio can be deduced using the relation:

$$N(H^+)/N(He^{++}) = (I(H,\tfrac{1}{2}n)/I(HeII,n).(g_n/g_{\frac{1}{2}n}).An(HeII)/A_{\frac{1}{2}n}(H) \qquad (2.1)$$

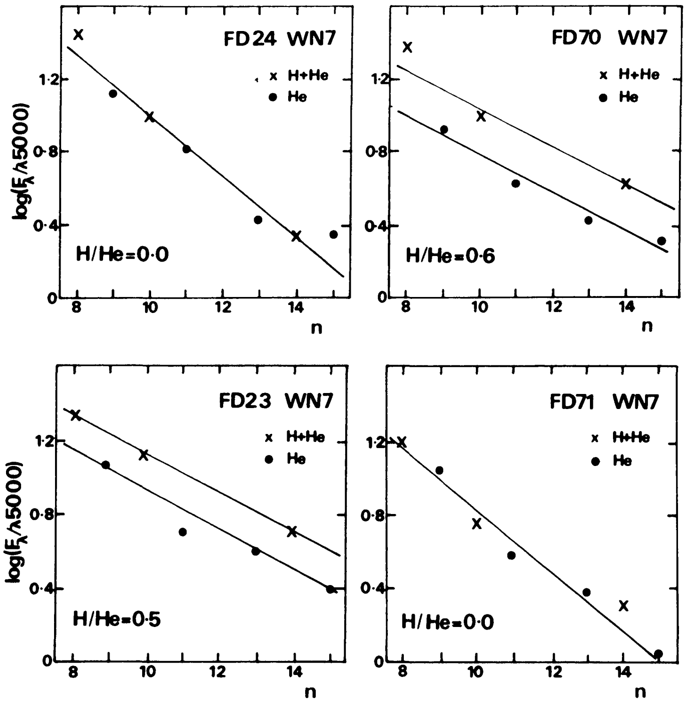
where the g and A values are the usual level statistical weights and transition probabilities respectively. HeI lines are usually only prominent in WN7, WN8 an, WC8 and WC9 spectra (Smith & Kuhi 1981), and the HeI contribution to the abundance ratio is usually assessed by using the relative intensities of HeI λ4471 and HeII λ4541 and an expression analogous to (2.1).

Using this approach Smith (1973) deduced values of $N(H)/N(He) \sim 1\text{-}2$ for several WN7, WN8 stars and lower values of ~ 0.0 for a few WNE stars, compared to the solar value of ~ 10, implying chemically evolved objects with WNE stars more advanced than WNL stars. Nugis (1975) in summarising earlier work by Rublev (1972), has presented results for several WC stars based on an assessment of blending of HeII λ4861 and Hβ, with values of $N(H)/N(He) < 0.08$ being deduced. For HD 192103 (WC8), Underhill (1980) has re-examined available visible spectra to conclude that some even-n HeII enhancement is present implying some atmospheric H, contrary to the results from Nugis (1975). In her analysis, an additional underlying, 15% deep H-balmer photospheric absorption spectrum is assumed and corrected for, which by definition produced some even-n enhancements, but these alone are not sufficient to explain the observed odd-even n modulation. However, inspection of the coude visible spectrum of HD 192103 (Smith & Kuhi 1981), and indeed for WC stars in general, shows that blending effects of the HeII series with many C and O transitions is very severe, and it is dubious whether inferences for WC stars from the Pickering decrement are meaningful. Recent UV evidence for HD 192103 (Willis 1981b, see below) strongly suggests a near zero atmospheric H abundance.

Underhill (1973) has argued that the apparent weakness or absence of visible H-lines may be due to ionisation balance effects in these hot stars, and moreover that simple analyses based on line ratios alone, without detailed considerations of line transfer effects, cannot yield reliable abundance fractions. This latter contention is not supported by the models of Castor & van Blerkom (1970), who show that in HeII for $n > 10$ the lines are optically thin and $b_n \sim 1$. The question of ionisation effects has been more difficult to disentangle, but recent work strongly suggests that these are not responsible for the apparent low H/He ratios. An analysis of extensive high quality visible spectra obtained over a long time interval, has shown that some WNE stars, previously classified as WNE+OB binary systems, in fact show no radial velocity variations and are more probably single WNE stars with intrinsic absorption lines. Examples are HD 9974 WN3 abs, (Massey & Conti 1981) and HD 193077 WN5 abs (Massey 1980) for which a low, but non-zero, ratio of N(H)/N(He) = 0.8 is deduced. Thus we have examples of some WNE stars which do show H and others of similar classification, and hence ionisation line ratios, which do not. A similar situation has recently been recognised for some WNL stars. Massey & Conti (1980) present a detailed discussion of the visible spectrum of HD 177230 WN8 - used as a standard for this subtype - in which neither H emission or absorption is seen, although many other WN8 stars do show such features. The spectrum of HD 177230 exhibits lines from a wide range on ions, NII-NV and HeI, with relative line strengths similar to those found in other WN8 stars, convincingly arguing that ionisation effects are not responsible and the lack of H signatures in the star being due to a real abundance deficiency. Fig 1 illustrates similar results found for a sample of 4 WN7 stars in the LMC for which Linda Smith and I have recently acquired spectra. All four stars show very similar N line spectra but clearly have radically different HeII Pickering decrements. The estimated, different, H/He ratios are marked on the figure.

To further test the contention of ionisation effects on expected H-emission line strengths, I have used the Escape Probability Model of line transfer in WR winds (Castor & van Blerkom 1970) for some test cases with an assumed pure H atmosphere. A typical model result is shown in Fig 2 which plots the predicted emission equivalent widths of H_α, $H\beta$ and P_α as a function of N(H). Labelling each H_α point is the computed ionisation fraction H/H^+, which is, as expected very low in all cases. Nevertheless despite this, strong emissions in the leading members of the Balmer and Paschen series are produced, which could hardly be missed on available spectra. Changing T* (the core temperature) or T_e within acceptable levels does not alter these conclusions. The model is crude, and the results in Fig 2 just one example, but clearly one cannot simply infer ionisation effects as the cause of the lack of H in WR spectra.

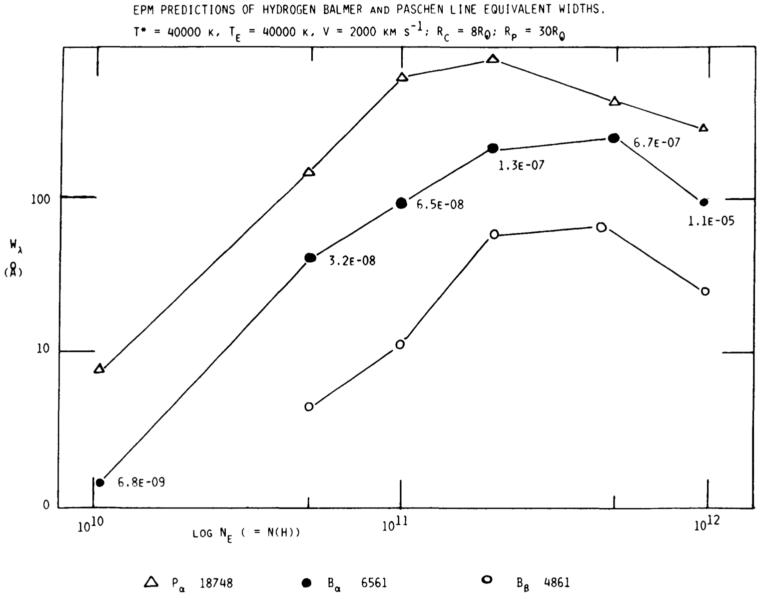
Fig 1: The observed HeII Pickering decrements in 4 LMC WN7 stars taken from spectra at UCL. All 4 stars have similar N-ion spectra but clearly have different H/He ratios.



b. Inferences from IR data

It is pertinent to consider what deductions on the H/He ratio arise from the recent availability of IR spectroscopy. Kuhi (1966, 1968) has given a summary of early near IR data, noting weak emissions at λ10938 and λ10040 which could, at first sight be attributed to P_γ and P_δ respectively. This has been taken up by Sahade (1980) to suggest unambiguous evidence for abundant H in most WN and WC stars. However, Kuhi (1968) makes no reference to likely blending effects from HeII recombination lines in WN and WC spectra, nor in CIV lines in WC stars. Such considerations have to be taken into account before any H-identification is made - as is so well illustrated at visible wavelengths. Similar comments pertain to the 'identification' of P_β, P_γ and P_δ emissions in the 0.9-1.7μm spectrum of γ^2 Velorum reported by Barnes et al. (1974). IR spectra of several WR stars in the wavelength range 1.4-2.5μm, encompassing the P_α and $P\beta$ transitions, are reported by Williams et al. (1980) and Williams and Allen (1980). Emissions near these wavelengths are ascribed by these authors to HeII (n-6) transitions and not H-lines. Without a detailed assessment of line blending, published IR data seems open to ambiguous interpretation. Consequently the assertion of Sahade (1981) that the IR spectra presented by Kuhi (1968) demonstrate unequivocally a substantial H content in most WR stars, seems at best premature. Further data, covering more series members in HeII and CIV as well as more detailed

Fig 2: Results of an EPM computation for a pure H-atmosphere predicting the emission equivalent widths of H- Ba_α, B_β and P_α . The H/H$^+$ ratio labels the H_α points.



analyses are required.

c. Recent UV results

The IUE satellite has provided the bulk of high resolution UV data of WR stars to date. Its wavelength range λλ1150-3250 encompasses the H Lα λ1215.7 line, which occurs at the same wavelength as HeII (4-2). A detailed description of the IUE spectra of ten WR stars in the Ly-α region is given by Willis (1981 a,b) in an investigation of P-Cygni UV and visible line profiles. Although the bulk of any Lyα or HeII (4-2) emission is destroyed by interstellar Lyα absorption, the stellar wind velocities are sufficiently large to allow the observation of violet shifted absorptions attributable to either Lyα or HeII (4-2) outside the interstellar damping wings. The former is, of course, a resonance line whilst the latter arises from a 40.1 eV lower level and Willis (1981b) uses this to isolate the possible origin of the observed P-Cygni absorption by fitting the inferred velocity in the well defined correlations of displaced velocity vs. E.P. found for each star. Ly_α wind absorption is identified in those stars (WN7, WN8) which already show evidence for H from the visible HeII Pickering decrement. The WNE and WC stars in the sample show HeII but not Ly_α wind absorption. For HD 192103, WC8, wind absorption is also seen in the resonance lines of SiII (I.P. = 16.3 eV) providing clear evidence that the lack of H absorption is this star is not caused by ionisation effects but reflects a gross underabundance of H. The result implies a similar, near zero, H abundance for other WC stars which show P-Cygni profiles in highly ionised species alone.

Table 1 lists the various estimates of the H/He ratio derived in the investigations alluded to above. These data will be extended by Perry & Conti (1982) who have used the HeII Pickering lines to derive H/He ratios for 60 WN stars in the Galaxy and LMC. The broad conclusion of Smith (1973) that the WR stars are generally H-deficient, is substantiated by the bulk of more recent work. The lack of H lines in most WR stars cannot be solely explained by ionisation effects and WC stars seem devoid of hydrogen. For the WN sequence, an important realisation from recent studies is that stars of similar WN types (both WNL and WNE) can have different (but invariably very low) H/He ratios. Some WNE stars like HD 193077 seems to have winds which are sufficiently transparent to allow the observation of photospheric absorption lines (Massey 1980). As Conti & Massey (1981) point out these variations within a given subtype may well be a reflection of subtle differences in the mass loss rates, causing different degrees of atmospheric stripping from star to star, which may be consistent with that expected in the mass loss-controlled WR evolutionary scenario presented by Conti (1976).

3. THE C AND N ABUNDANCES IN WR STARS

a. Observational evidence for anomalies

The direct observational evidence in the visible for C in WN spectra and N in WC spectra has been well covered in the extensive reviews of line identifications given by Kuhi (1968) and Bappu (1973) and will not be elaborated on herein. The most certain identification of C in WN spectra

Table 1: A compilation of recent estimates of the H/He ratios (by number) for several WN and WC stars.

STAR	Sp	H/He	REF	STAR	Sp	H/He	REF
MR 119	WN8	<< 2.3	1	HD 177230	WN8	~ 0.0	4
HD 151932	WN7	< 1.0	1	HD 193077	WN5 abs	0.8	5
HD 192163	WN6	$\lesssim$ 0.4	1	HD 9974	WN3 abs	> 0.0	6
HD 50896	WN5	0.0	1	HD 192103	WC8	>> 0.0	2
HD 187282	WN4	0.4	1	HD 192103	WC8	0.0	3
HD 9974	WN3 abs	0.8	1	FD 24	WN7	~ 0.0	8
HD 190918	WN4+09I	0.0	1	FD 71	WN7	~ 0.0	8
HD 211853	WN6+0B	$\lesssim$ 0.3	1	FD 70	WN7	~ 0.6	8
HD 192163	WN6	$\lesssim$ 0.5	9	FD 23	WN7	~ 0.5	8
HD 192163	WN6	< 0.2	7	FD 12	WN8	~ 1.0	8
HD 191765	WN6	< 0.1	7	FD 13	WN3	~ 0.0	8
HD 193077	WN5 abs	< 0.1	7				
HD 192103	WC8	< 0.02	7				
HD 192641	WC7	< 0.08	7				

REFERENCES: 1) Smith (1973), 2) Underhill (1980), 3) Willis (1981), 4) Massey & Conti (1981), 5) Massey (1981) 6) Massey & Conti (1981), 7) Nugis (1975), 8) Smith & Willis (1981), 9) Castor & van Blerkom (1970) is for CIV λ5801, λ5812 seen prominently in WNE stars and as generally weaker (often P-Cygni) emission in WNL stars. Examples taken from Smith & Kuhi (1981) are shown in Fig 3. Other features, particularly in CIII have been tentatively identified from time to time in WN spectra (e.g. Underhill 1959) but as Kuhi (1968) points out their presence is often inferred because of peculiar shapes or apparent strengths in some He or N lines. In WC spectra the visible data shows no conclusive evidence for any N lines, although Underhill (1959) has suggested weak NIII emissions as possible contributors to distorted or anomalously strong C or O features. The near IR range apparently exhibits a complete dichotomy between the WN and WC sequences, since no C lines are reported in WN spectra or N lines in WC spectra (Kuhi 1968). Further IR data confirms this assertion (e.g. Williams et al. 1980). Ultraviolet observations of WR stars, recently reviewed by Willis (1980) provide further clear evidence for C in WN atmospheres - the CIV λ1550 line is seen, usually as a P-Cygni profile, in most subtypes. In addition Willis (1981b) has found marginal evidence for P-Cygni absorption in CIII λ1175 in some WNL stars. For WC stars, the early Rocket UV spectra of γ^2 Velorum (Stecher 1970) and the low resolution S2/68 observations of 3 WC stars (Willis & Wilson 1978) showed quite prominent emissions at λ1480 and λ1720 identified as NIV λ1486, λ1718, implying at least some N in WC atmospheres. However, these identifications are not supported by the improved IUE data available, which shows these emissions displaced from their NIV wavelengths, with CIII and SiIV lines now being preferred (Willis 1980). Thus the earlier, apparently strong, evidence for N lines in WC spectra has largely disappeared. Johnson (1978) provisionally identified NV λ1240 P-Cygni absorption in the Copernicus UV spectrum of γ^2 Velorum (WC8+09I), however it is likely that this is due to the 09I star and not the WC8 component. However, Willis (1981b) has found some evidence, illustrated in Fig 4, for NV λ1240 P-Cygni absorption in the WC8 star HD 192103 from IUE spectra. Thus similar conclusions can be drawn from the visible, IR and UV spectra available: C lines are definitely present in WN spectra; the evidence for N in WC spectra is rather marginal. The demanding question, of course, is what are the C and N abundances in the two sequences, and recently several attempts have been made to derive these important parameters.

b. Sobolev-Escape Probability Modelling (EPM) and results

The most convincing attempts to quantitatively determine the WR C and N abundances have been carried out in the last decade, in which modelling of the observed line strength data (both in the visible and UV) uses the simple picture of a WR star in which the emission line spectrum is assumed to originate in a spherical, rapidly expanding extended atmosphere, around a central, hot continuum emitting stellar core.

For most lines it is clear that non-LTE conisderations are needed in the models which require the coupled solution of the ionic level population statistical equilibrium equations and the radiative transfer in the emission line region. The latter involves the transfer in J_{un}, the mean intensity in the u-n line radiation field, involved in the bound-bound

Fig 3: Examples of the CIVλ5801,λ5812 identifications in two WN stars taken from Smith & Kuhi (1981).

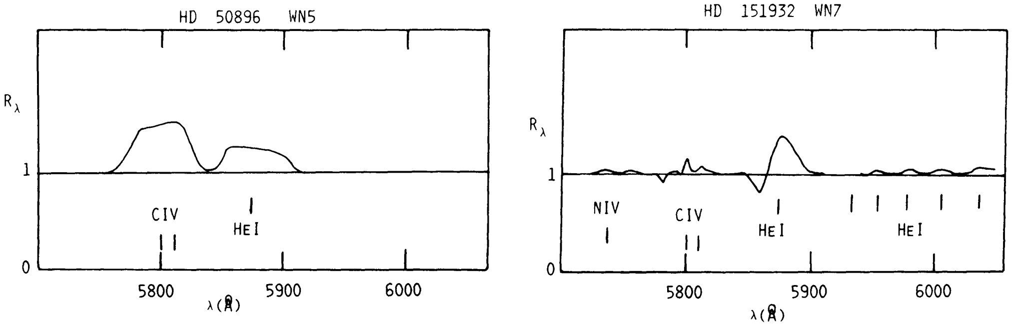
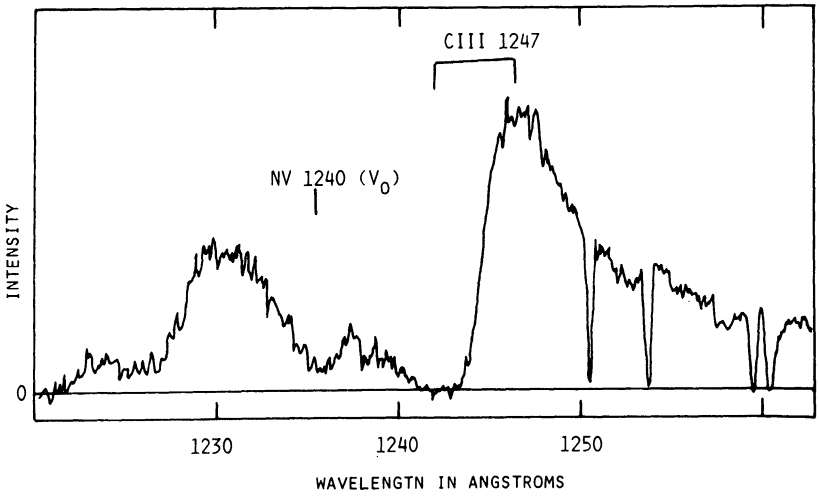


Fig 4: A tentative identification of P-Cygni absorption in NVλ1240 in the IUE spectrum of HD 192103, WC8. The inferred velocity of the absorption centre is close to that found for other (WC) resonance line P-cygni absorptions in this star.



level population processes, and J_ν, the specific intensity of the continuum radiation involved in the radiative bound-free processes. A tractable method of solving these radiative transfer effects was formulated by Sobolev (1960) and developed by Castor (1970) who both recognize that in a rapidly moving extended atmosphere, with the expansion velocity far in excess of the thermal velocity, radiative interaction in the lines with distant parts of the atmosphere is negligible and thus the line transfer is locally constrained. The history of a line photon can thus be described by an escape probability, β, which is determined solely by the physical and chemical conditions at its point of creation. Most analyses to date have used a further simplification, introduced by Castor & van Blerkom (1970), where it is assumed that the emission lines arise in a spherical, homogeneous region, characterised by a representative radius R_p and expansion velocity, v_p. Then J_{un} can be simply written as:

$$J_{ur} = (1-\beta).\ S(R_p) + w\beta I^c_\nu \qquad 3.1$$

where I^c_ν is the core continuous radiation field at frequency ν and w is the dilution factor at R_p. The former is usually approximated by a black body distribution for the best T_{eff} values for WR stars available, now believed to lie in the range 25000-40000K depending on the WR subtype (Underhill 1980, 1981, Nussbaumer et al. 1981). β can be written in terms of the line optical depth, τ as:

$$\beta_{lu} = (1-\exp(-\tau_{lu}))/\tau_{lu} \qquad 3.2$$

$$\tau_{lu} = (\pi e^2/mc).(gf\lambda).(R_p/v_p)\ \{N_l/g_l-N_u/g_u)\} \qquad 3.3$$

The line source function, $S(R_p)$ is given by:

$$S(R_p) = 2h\nu^3.\ \{(N_{lgu}/N_{ugl} - 1\}^{-1} \qquad 3.4$$

A similar, but less reliable escape probability formulation can be used for the continuum radiation field, J_ν (Castor & van Blerkom 1970). J_ν and J_ν depend on the level populations which makes the statistical equilibrium equations non-linear and these are solved iteratively to give converged populations, line source functions and thus line intensities which are compared to observed values to derive abundances. This formulation has been used by Castor & van Blerkom to study the HeII visible lines in HD 192163, WN6, and by van Blerkom & Patton (1972) for the HeII lines in HD 50896, WN5. Good agreement could be achieved with the models and observations implying $N_e \sim 4\times10^{11}$ cm^{-3}, Te $\sim 5\times10^4$K as typical conditions in the WNE envelopes. Oegerle & van Blerkom (1976) used the EPM to study the HeI spectrum in MR118, WN8 and deduced lower values of Ne $\sim 6\times10^{10}$ cm^{-3} and $T_e \sim 2\times10^4$K. Castor & Nussbaumer (1972) were the first to use the EPM for a WC star, analysing the CIII spectrum in γ^2Velorum. A high C abundance of at least 8 times solar was inferred.

Nugis (1975) has analysed the visible spectra of several WN and WC stars to derive estimates of the H/He, C/He and N/He ratios. The modelling extends the simple EPM approach outlined above, in that attempts are made to take into account ionisation statification in the WR envelopes. The abundance ratios by number taken from Nugis (1975) are listed in Table 2 and these results showed a gross overabundance of N in the WN stars, and conversely of C in the WC stars, with a clear reversal between the C/N ratio in the two sequences. Nugis (1981, & private communication) has extended this analysis to more stars, and incorporated recent T_{eff} estimates for WN stars (lower than those used in the 1975 paper) to find the following revised abundance ratios by number: WNE stars:N/He $\sim$.01-0.02; WNL stars: N/He $\sim$ .002-.005; WC stars C/He $\sim$ 0.1-0.2. These latter values are probably to be preferred than those in Table 2.

For lines where non-LTE effects are important, EPM techniques are best suited to transitions arising between levels whose populations are mainly controlled by bound-bound processes involving the radiations transfer in J_{un} alone as outlined above. Such levels are generally low lying and the

Table 2: Estimates from optical spectra Sobolev modelling of abundance ratios (by number) from Nugis (1975).

STAR	Sp	N/He	C/He	H/He
HD 193077	WN5abs	0.1	0.0083	0.06
HD 192163	WN6	0.076	0.0019	0.1
HD 191765	WN6	0.046	0.0030	0.08
HD 192103	WC8	-	0.75	0.02
HD 192641	WC7	-	0.84	0.08

relevant C and N lines occur in the vacuum UV. Observations in this range can thus be considered important for abundance studies. Willis & Wilson (1978), in recognising this aspect, have analysed low resolution (∿35Å) UV S2/68 spectrophotometry coupled with visible HeII measurements to derive the C/He, N/He and C/N ratios in 3WNE and 1WC8 stars using the EPM in its 'representative radius' simplified form (Castor & van Blerkom 1970). For the WNE stars the following mass abundance ratios were found: N/He ∿ 2×10^{-2}; C/He ∿ 9×10^{-5} and C/N ∿ 4×10^{-3} and in the WC8 star: N/He ∿ 3×10^{-3}; C/He ∿ 9×10^{-3} and C/N ∿ 3. The analysis was limited by the enforced use of high excitation NIII λ4100, λ4640 lines to estimate the atmospheric NIII densities; upper limits of $W_\lambda < 10$Å in the UV CIII λ1909 λ2297 lines in WN spectra and uncertainties in blending effects in NIV λ1486, λ1718. Nevertheless the results highlighted the gross chemical differences between the WN and WC stars, and moreover the derived ratios appeared qualitatively consistent with those expected from varying nuclear burning products at stages of H-burning and He-burning in massive hot stars (Paczynski 1973) provided that these could be exposed in the outer atmospheres (Willis & Wilson 1979). The results provided support for the WR evolutionary scenario presented by Conti (1976) that the WR stars may be descendants of the Of stars with mass loss stripping occuring

Many of the limitations in the above S2/68 results have now been alleviated by the acquisition of the IUE UV spectra of a large sample of WR stars. Continuum measurements in these new data, coupled with complemextary visible observations, have yielded new estimates of WR core temperatures (Nussbaumer et al. 1981) for use in EPM analyses and observations in the high resolution IUE spectra of P-Cygni profiles in C and N resonance and low excitation transitions have provided further information on the appropriate stellar wind velocities (Willis 1981 a,b). Smith and Willis (1981) have carried out an extensive analysis of the IUE data to derive the C/He, N/He and C/N ratios in 6WN and 4WC stars using the EPM analysis employed by Casor & van Blerkom (1970) and Willis & Wilson (1978). From the observational point of view the major advances of this IUE study over its S2/68 forbear are as follows: (i) the higher resolution spectra available (Δλ∿0.1-0.2Å) give more accurate equivalent width measurements and line blending assessments (ii) the availability of the low excitation NIII λ1750 line improves the reliability of the derived NIII density rather than the use of NIII λ4110, λ4640; (iii) the recognition that in WC stars features previously ascribed to NIV λ1486, λ1718 are actually CIII and SiIV lines respectively, resulting in a reassessment of the NIV density in this sequence; (iv) improved limits of $W_\lambda < 1Å$ for the CIII λ1909 λ2297 lines in WN spectra; (v) in WC spectra the observation and analysis of comparatively unblexded HeII (n-3) lines resulting in improved values of the atmospheric He density in this sequence; and (vi) the availability and use of more accurate recent values of atomic rate coefficients. Table 3 presents a summary of these new results from Smith & Willis (1981). This gives for each star the core temperature used (taken from Nussbaumer et al. 1980), the H/He ratio used in the modelling - generally taken from the visible Pickering decrement for WN stars and for WC stars from the assertion of Willis (1981b) of a near zero H-abundance-and the best fit values of electron temperature, T_e and electron dexsity N_e deduced from the combined analysis of the UV C and N lines and the available HeII measurements. The derived abundance ratios, C/N, C/He and N/He are also given for each star. For the WN stars the C/N and C/He ratios lie between bounds derived from the lower value determined from modelling of the observed CIV λ1550 resonance line and an upper value derived from upper limits to the CIII λ1909, λ2297 line strengths. In WC stars, since the NIII λ1750 and NIV λ1846, λ1718 transitions used for the N modelling are unobserved, only lower limits to the C/N and He/N ratios are available. These new results confirm the previous conclusions of Nugis (1975) and Willis & Wilson (1978) of a reversal in the C/N ratio between the WN and WC stars and highlight the chemical separation of the two sequences. Although it is estimated that the C/He and N/He ratios may have errors of a factor of 2-4, with the framework of the EPM used, Smith & Willis (1981) find little latitude is possible in the deduced C/N ratios with varying model input parameters, because of the use of similar transitions in similar C and N ions in the analysis.

Table 3: Mass abundance ratios and deduced atmospheric parameters (T_e, N_e) for 6WN & 4WC stars deduced from IUE & visible spectra from Smith & Willis (1981).

STAR	Sp	T^*	T_e	N_e	N(He)	H/He	C/N	C/He	N/He
HD 187282	WN4	4×10^4	6×10^4	3×10^{11}	1.5×10^{11}	0.0	1.1(-2) - 7.5(-2)	2.0(-5) - 1.4(-4)	1.9(-3)
HD 50896	WN5	4×10^4	5×10^4	4×10^{11}	2.0×10^{11}	0.0	1.8(-2) - 4.6(-2)	4.5(-5) - 1.2(-4)	2.6(-3)
HD 191765	WN6	3.6×10^4	5×10^4	4×10^{11}	2×10^{11}	0.0	3.5(-2) - 7.1(-2)	6.8(-5) - 1.4(-4)	2.0(-3)
HD 192163	WN6	3.6×10^4	5×10^4	4×10^{11}	2×10^{11}	0.0	2.3(-2) - 6.0(-2)	4.5(-5) - 1.2(-4)	2.0(-3)
HD 151932	WN7	2.4×10^4	2.5×10^4	1×10^{11}	2.5×10^{10}	1.0	4.3(-3) - 9.0(-2)	8.6(-5) - 1.8(-3)	2.0(-2)
HD 96548	WN8	3.2×10^4	3×10^4	2.3×10^{11}	6×10^{10}	1.9	8.6(-3) - 3.9(-2)	3.5(-4) - 1.6(-3)	4.1(-2)
HD 165763	WC5	4×10^4	3×10^4	2×10^{11}	1×10^{11}	0.0	$\gtrsim$ 94	6.6(-2)	$\lesssim$ 7.0(-4)
HD 16523	WC6	4×10^4	3×10^4	1.2×10^{11}	6×10^{10}	0.0	$\gtrsim$ 20	1.1(-1)	$\lesssim$ 5.5(-3)
HD 156385	WC7	3×10^4	3×10^4	1.6×10^{11}	8×10^{10}	0.0	$\gtrsim$ 63	3.0(-2)	$\lesssim$ 4.8(-4)
HD 192103	WC8	2.6×10^4	2.8×10^4	1.2×10^{11}	6×10^{10}	0.0	$\gtrsim$ 65	2.5(-2)	$\lesssim$ 3.8(-4)

ALL IONIC DENSITIES ARE IN cm^{-3}. IN THE ABUNDANCE RATIOS NUMBERS IN () ARE THE EXPONENTS. TEMPERATURES ARE IN K.

4. THE CHEMISTRY OF WR STARS PREDICTED FROM STELLAR EVOLUTION MODELS

The expectation that the WR stars are evolved objects, in which a H-rich outer atmosphere has somehow been removed, has prompted many theoretical stellar evolution investigations for both binary systems involving mass exchange (de Loore 1980) and single stars, with heavy stellar wind mass loss, located either in the hot region of the HR diagram (Conti 1976, Noels et al. 1981) or in the red giant phase (Chiosi 1978, Maeder 1981). Whichever atmospheric 'stripping' process is invoked, one would expect to observe the exposition of changing interior nuclear burning products as the evolution advances, and for such a situation Paczynski (1973) qualitatevely showed a reversal in the C/N ratio from low to high values from H-burning to helium burning stages. More recent studies have put these expected chemical changes on a quantitative basis.

Vanbeveren & Doom (1980) have calculated the changing H, He, and CNO abundances during H-burning in close binary stellar evolution models for initial primary masses in the range 40-100 $M_\odot$, including the effects of stellar wind mass loss from the primary. As a result of Roche lobe overflow considerable mass is removed from the primary star resulting in a low atmospheric H/He ratio of < 0.2 by mass, which they equate with a 'WNL' stage. Subsequent stellar wind mass loss removes the remaining atmospheric hydrogen by the end of core-H-burning, and altering the CNO abundances which are exposed in the outer atmospheres. The atmospheric N/He, C/He and O/He ratios (by mass) calculated by Vanbeveren & Doom (1980) at both the 'WNL' and 'WNE' stages show little variation with the initial primary mass considered, and are given here in Table 4a. Vanbeveren & Doom (1980) argue that these results should also apply to single star evolution cases where extensive mass loss removes much of the initial mass. This assertion has recently been confirmed by Noels et al. (1980) who have computed a series of H-burning evolutionary models for single stars in the range 40-100$M_\odot$ including stellar wind mass loss effects. Using mass loss rates of $4\text{-}7 \times 10^{-6}$ $M_\odot$ y^{-1} - typical for an Of star - during the bulk of the H-burning lifetime it is found that CNO burning products appear at the stellar surface while the star is still in the core H-burning phase, viz the atmosphere still has appreciable H, but increased N and reduced C. Increasing the mass loss rate by a factor of ten at this time, in an attempt to accommodate the values appropriate for WR stars of $\sim 4 \times 10^{-5}$ $M_\odot$ y^{-1} (Barlow et al. 1981), results in a rapid reduction in the H/He ratio accompanied by an increase in N/C, with relative abundances very similar to the 'WNL' results found by Vanbeveren and Doom (1980) for the binary evolution models. Gabriel & Noels (1981) have extended these single star-mass loss evolution models to the core He-burning phases and Table 4b lists the deduced abundance ratios for stages when (a) in H-burning the atmospheric hydrogen content has been reduced to $X_{atm} < 10^{-2}$ and (b) a stage in He-burning when the convective core has reached its maximum extent. The latter may be equated with a WC stage. During He-burning, Gabriel & Noels (1981) find that the C, initially low from CNO reactions, is rapidly replenished, whilst N is quickly removed through the process $N^{14}(\alpha,\gamma)\ F^{18}(\beta^+,\nu)\ O^{16}$. Indeed they argue that to the numerical accuracy of their models the N abundance could be zero!

Table 4a: Mass Abundance ratios prediced by Vanbeveren & Doom (1980) for binary evolution models (see text).

H-content	N/He	C/He	O/He
$0.0 < X_{atm} < 0.2$	1.3 ± 0.2(-2)	1.8 ± 0.6(-4)	5.5 ± 0.3(-4)
$X_{atm} = 0.0$	1.0 ± 0.1(-2)	2.7 ± 0.7(-4)	2.3 ± 0.5(-4)

Table 4b: Mass abundance ratios predicted for single star evolution models by Gabriel & Noels (1981) when $X_{atm} < 10^{-2}$ in core H-burning and during He-burning at the max convective core

	N/He	C/He	C/N
$X_{atm}\quad 10^{-2}$	1.1(-2)	2.2(-4)	2.0(-2)
Max He-conv. core	4.0(-7)	0.12-0.35	10^6

5. DISCUSSION

The evolutionary scenario most usually adopted now for the WR stars is one in which they are believed to be evolved objects at advanced stages of H-burning (WN stars) or He-burning (WC stars) in which material loss has significantly altered their evolution. Recent models for the evolution of massive hot stars in which the mass removal occurs through Roche lobe overflow in binary systems or through extensive mass loss by stellar winds in single stars has indeed shown the possibility of generating low H/He ratios near the end of core H-burning or early He-burning in agreement with that expected from the observations. With the recent chemical studies reviewed in §3 and §4 it is now possible to further test these evolutionary schemes by comparing the 'observed' and 'predicted', He, C and N abundances.

WN STARS: The evolutionary models predict for both WNL and WNE stars a mass abundance ratio N/He ~0.01 (Table 4). The recent optical results given by Nugis (1981) give somewhat higher values of ~0.03-0.07 for WNE stars, but better agreement for the WNL stars studied for which N/He ~ 0.007-0.02 is deduced. The UV IUE results of Smith & Willis (1981) give values of N/He ~ 0.002 for WNE stars, lower than expected, but rather higher values of ~ 0.02-0.04 for WNL stars (cf. Table 3). A similar level of discrepancy is found in the IUE results for the C/He ratio deduced for WN stars compared to the model expectations of ~ 0.0002. Within the assessment of accuracy in the Sobolev modelling, quoted by both Nugis (1975) and Smith & Willis (1981) as factors of 2-4 in the N/He and C/He results, I consider the level of agreement above rather encouraging. Smith & Willis argue that the C/N ratios derived from the IUE data are quite insensitive to uncertainties in the model input parameters such as core temperature and atmospheric T_e, and thus the most appropriate check with the model evolution predictions lies with the C/N ratios. For WNL stars the models predict C/N $\sim$0.01-0.02. This agrees very well with the IUE results in Table 3, if, as expected for these subtypes, ionisation conditions are such that CIII $\sim$CIV. Similarly for the WNE stars the model and IUE results agree well if CIV > CIII, as implied spectroscopically. Thus for the WN stars the abundances of H, He, C and N agree quite tolerably with those predicted, and this provides compelling evidence for the basic correctness of the evolutionary schemes invoked for these objects.

WC STARS: The He-burning models of Gabriel & Noels (1981) predict a C/He ratio of $\sim$ 0.1-0.3. The optical spectra analysis of Nugis (1981) gives values C/He $\sim$ 0.3-0.6, whilst the results from the IUE analysis of Smith & Willis (1981) gives $\sim$ 0.03-0.1. The agreement is again reasonable. A somewhat unexpected result from the Gabriel & Noels (1981) study is the prediction of a near zero N abundance in WC stars. Although the lower limit of C/N > 60 from the IUE analysis, is consistent with this, there is some evidence for N lines in WC spectra (cf. §3) which implies a higher N abundance than predicted in the evolutionary codes. Calrification of this potential discrepancy must await confirmation of the Gabriel & Noels result by further theoretical modelling with, say mixing fully incorporated, as well as more reliable identifications of N lines in WC spectra than are currently available.

Underhill (1981) has argued that the WR stars must have a normal chemical composition based on a consideration of their location in the HR diagram. Recent temperature and luminosity assignments (Underhill 1980, 1981, Nussbaumer et al. 1981) place the WNL stars near the HR region occupied by BOI stars, whilst WNE and WC stars lie near the BOIII stars - both in the normal H-burning band. Underhill (1981) notes that the stellar evolution models of Sothers (1976 a,b) for conservative evolution and of Stothers & Chin (1979) which incorporate stellar wind mass loss effects, locate He-rich stars of similar masses and luminosities to the WR stars, at much higher values of T_{eff} ($>10^5$K) than are observed. From this discrepancy, she concludes that the WR stars cannot be He-rich and most likely have a normal chemistry. Although this T_{eff} discrepancy is clearly serious, it is surely premature to cast aside the wealth of evidence of low H/He ratios and abnormal C/N chemistries in WN and WC stars discussed above, based on this disagreement alone. There is already some suggestion that better agreement in T_{eff} values can be obtained when the interior and (extended) atmosphere radiative transfer calculations are more properly coupled in the evolutionary codes (de Loore, private communication). Clearly other modifications to our knowledge of the stellar structure models for hot stars are likely to be required in order to accommodate the very high mass loss rates found in the WR stars ($\sim$ 10-50xL/v_∞c, Barlow et al. 1981) as well as deviations in the mass loss properties of O-type stars from radiation pressure wind models (Conti & Garmany 1980). Further, independent evidence for abnormal WR chemistries has been given by Kwitter (1981) from a detailed spectrophotometric study of the ring nebula NGC 6888 surrounding the WN6 star HD 192163. The results show that the nebula is enriched in N and He by factors of 9 and 3 respectively, and moreover, that this enrichment is consistent with that expected from contamination of the ambient material by a N-rich and He-rich wind emanating from the central star.

Clearly major quantitative improvements have recently been made to our knowledge of the chemical composition of the WR stars. However, one can easily consider areas for further advancement. The emission line modelling employed to date has been crude, and there is much scope here for more sophistication. Gross line strength analyses will be replaced by profile fitting and extensive sets of both visible and IUE UV high resolution spectra are available for this purpose. A start in this area has already been made by Rumpl (1980) in a preliminary analysis of the UV Copernicus P-Cygni profiles observed in HD 50896, WN5, and by Dreschel & Rahe (1981) for the IUE-UV and visible lines in HD 192163, WN6. Further tests on the evolutionary models can be made by deriving the oxygen abundance in WN and WC stars. Important OIII, IV, V, VI lines for this purpose lie in the UV region at λ<1150 and will need future satellite experiments for their observation. Modelling of IR lines observed in both WN and WC spectra may yield important abundance results which can be compared with those derived from material acquired in the UV and visible. A first such study of available IR spectra will be reported by Hummer, Barlow and Storey in these proceedings.

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DISCUSSION

Perry: On your determinations of number densities for CIII and CIV lines and NIII and NIV lines, I was a bit puzzled by the apparent decrease of NIII/NIV from WN to WC types but the apparent increase of CIII/CIV. Can you explain this.

Willis: Yes. You are referring to the old results from the S2/68 study, which I showed for historical reasons. As I explained, these low resolution (~35Å) data were wrongly interpreted in WC stars as showing NIV λ1486 and NIV λ1718. We now know from the much higher resolution IUE spectra that emission features in WC stars near these two wavelengths are not due to NIV. The improved number density results from the IUE analysis (Smith and Willis, these proceedings) do not show the puzzling variations in the ionization fractions you mention.

Abbott: 1) Have you calculated line profile fits for typical density distributions to evaluate the accuracy of the one-point fits ? 2) Is the discrpeancy between the empirical $C/N > 60$ ratio in WC stars and the predicted evolution ratio $C/N \sim 10^6$ fatal, or can it be reconciled ?

Willis: 1) We have not yet calculated line profile fits, by solving the Sobolev analysis throughout the emission region. My feeling is that, within the Sobolev one-point framework employed to date, the use of similar C and N transitions in the UV in similar ions, results in only a comparatively small uncertainty in the derived C/N ratios.

2) The lower limit of C/N 60 we find from the IUE analysis for WC stars is not in itself discrepant with the predictions of Gabriel and Noels (1981). However they predict an effectively zero N abundance in the helium burning (eg. WC) model stages, whereas both visible and UV spectra of WC stars indicate the presence of at least some nitrogen. I rather feel that we would expect to find in the models a more shallow gradient in the C/N ratio between WN and WC stars, viz the occurence of WN-C stars, than is given in the Gabriel and Noels evolutionary models. I wonder if the current theoretical treatments cover interior mixing properly.

Maeder: I would like to emphasise that the number of transition stars having intermediate abundances between normal O-stars and WN stars represents a strong constraint on the evolutionary models and their physics. The same is valid for stars with features intermediate between the WN and WC stars. For example, models with only mass loss as the basic mechanism of WR stars formation predict that the transitions occur in quite a short time, thus giving rise to few or even no intermediate stars. However, some degree of internal mixing may account for a larger scatter in the observed features, as well as for smooth composition transitions. For now, I just do not know which is favoured by observations and this is a point to examine in the future.

Nugis: I have recently newly determined the carbon abundance in the WC star envelopes. My results for the C/He ratio are nearly two orders of magnitude higher than your estimates. I think that my estimates are the more realistic ones because I have tried to use methods which are not sensitive to model predictions. I think that if one takes for the C/He ratio the value smaller than 0.1, then it is not possible to explain the specific features of WC stars, namely the presence in their spectra of strong subordinate lines of carbon ions, arising in transitions between comparatively high-lying energy states.

Willis: You have made your comparison between the newly derived optical results and the old, and ,as I said before, somewhat erroneous S2/68 UV results. A comparison of your new results with your old ones (Nugis 1975) also shows large discrepancies , in that the deduced C/He ratio is much reduced ! A comparison, however, of your recent results from optical spectra with the UV estimates from the IUE spectra shows much better agreement. We will have to look at the remaining differences, by considering the details of the optical and UV line modelling and try to tie down the origin of the discrepancies that are still apparent. A factor of say 5 difference in the C/He ratio is probably not significant, bearing in mind the crudeness of the modelling of both sets of data. Have you also checked possible blending effects in the optical lines you use ?

Henize: In the IUE spectra of WR stars in the LMC I find strong SiIV emission in WC stars and no SiIV emission in WN stars. Is this reflected also in galactic WR stars and, if so, what do we know about the Si abundances in WN and WC stars.

Willis: We certainly see much stronger emission in SiIV in galactic WC stars than in WN stars in high resolution IUE spectra. However, in WC stars strong OIV lines are also apparent in the λ1400 region and at low resolution you should be careful in identifying emission at λ1400 as soley due to the SiIV resonance lines. As to abundances, we would not expect to see a Si abundance difference between WN and WC stars. The apparent weakness of SiIV in WN spectra may be the result of a higher temperature in the WN winds than the WC winds.