THE CHEMICAL NATURE AND EVOLUTIONARY STATUS OF THE WOLF-RAYET STARS

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1 INTRODUCTION

Much interest has been shown in recent years concerning the possible link in stellar evolutionary terms between the O-type (particularly Of) and the WR stars, arising from both observational studies of O stars (Conti 1976, Bohannon and Conti 1977) and theoretical studies of the evolution of massive hot stars with high mass loss (Chiosi and Nasi 1974, de Loore et al. 1977, 1978). These investigations and ideas coincided with a renewed attack on the abundance problem in the WR stars based on the acquisition of new ultraviolet observations and the application of recently developed techniques for treating line transfer in rapidly expanding atmospheres (Willis and Wilson 1978a). The aim of this paper is to summarize some of the salient aspects of this latter reference and to examine the evolutionary status of the WR stars in the light of these new results.

2 THE S2/68 OBSERVATIONS AND EFFECTIVE TEMPERATURES OF THE WR STARS

The S2/68 experiment (described by Boksenberg et al. 1973) in the ESRO satellite TD-1 has provided an extensive set of ultraviolet data for nine WR stars - three WN, three WC and three WC+O binaries. These data are in the form of low resolution ($\Delta\lambda \sim 35$A) spectrophotometric measurements over the wavelength range 1350-2550A, together with a broad band (~ 310A) photometric measurement centred at 2740A. The data have been calibrated to give absolute energy fluxes with an absolute photometric accuracy believed to be better than twenty percent (Humphries et al. 1976). The ultraviolet spectra of the six single stars are shown in Fig 1, where we see that, as at visible wavelengths, the spectra are dominated by many strong emission lines, identified in the figure.

A combination of the S2/68 data with ground based measurements in the visible (Smith 1968, Cohen et al. 1975) provides energy distributions over the very extensive wavelength range of 1350A to 1 micron. Over this large wavelength range the variation in magnitude of the interstellar

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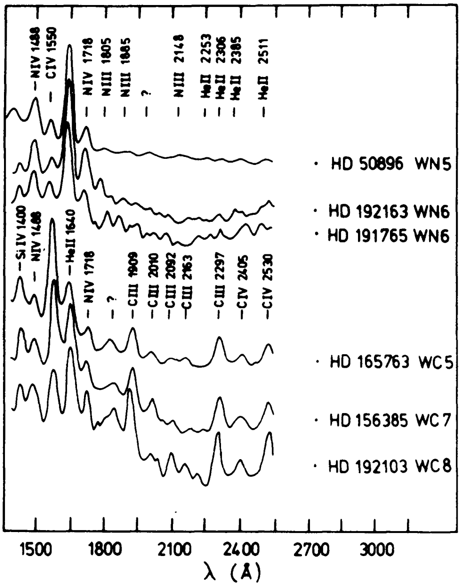

Fig 1 The S2/68 ultraviolet spectra of six single WR stars.

extinction is very large (Nandy et al. 1975) and thus accurate colour excesses and subsequent intrinsic energy distributions for the WR stars can be determined (Willis and Wilson 1978a). Colour temperatures based on this long-wavelength baseline were determined using both black body distributions and plane parallel model atmospheres (Kurucz et al. 1974) and these are given in Table 1 for the nine WR stars observed. The black body results are close to 33000 K whereas those derived from the model atmosphere calculations lie near the somewhat lower temperature of 27000 K. A detailed comparison of the observed and model distributions show severe discrepancies, particularly in the infrared, where the observed fluxes show an excess. These infrared excesses have been noted before (Kuhi 1966) and highlight the need for models which take into account the extended nature of the WR atmospheres. Only a few such models, employing spherical geometry, have been constructed to date, but the results of Kunasz et al. 1975 indicate that in this temperature range, the true effective temperature lies between the colour temperatures deduced by comparison with black body and plane parallel model distributions. We therefore take the average of the two colour temperatures listed in Table 1 as indicative of the effective temperatures, which results in a value close to 30000 K for the nine WR stars observed.

Effective temperatures near this value are also indicated by a Zanstra analysis of the HeII 1640A line observed strongly in emission in the six single stars. These temperatures, denoted T_Z, are also given in Table 1. Additionally the effective temperature of the WC8 component in the WR spectroscopic binary γ^2 Velorum, for which angular diameter

HD	Sp	T_k (K)	T_b (K)	T_z (K)
50896	WN5	26400	33000	31600
191765	WN6	28200	36000	29200
192163	WN6	28100	35000	30200
165763	WC5	27000	35000	27500
156385	WC7	25400	32000	27200
192103	WC8	26000	32000	26000
68273	WC8+09I	27000	34000	
193793	WC6+0	25000	31000	
113904	WC6+0	27000	35000	

Table 1 WR colour temperatures T_k and T_b (see text) and Zanstra temperatures, T_z, determined from the HeII 1640A line.

information (Hanbury Brown et al. 1970) and a good distance estimate (Brandt et al. 1971) are available, is determined as 29000 K by Willis and Wilson (1978a). We can thus feel confident in ascribing effective temperatures of ~ 30000 K for the WR stars observed by S2/68. Morton (1973) has determined Zanstra temperatures for several WN stars exciting ring nebulae from observations of the radio emission. For the two WN stars in common with the S2/68 data he also determined temperatures close to 30000 K. However, for some of the other stars he estimates values in the range 40000-50000 K, which may indicate a real variation of effective temperature within each subclass. Further ultraviolet observations are probably needed to test this.

3 THE CHEMICAL NATURE OF THE WR STARS

Since the early separation of the WR stars into the WN and WC sequences (Beals 1934) the longstanding question has been whether the separation is the result of chemical or physical effects, i.e. is the apparent lack of nitrogen lines in WC spectra the result of an underabundance of N and likewise the lack of carbon lines in WN spectra the result of an underabundance of C, or can these differences be explained in terms of different excitation effects. Simple analyses of the HeII Pickering decrement in WN and WC stars have shown that hydrogen is very deficient in both sequences (Smith 1973, Nugis 1975), but little information has been obtained on the C and N abundances because of the longstanding lack of suitable models of line formation and of observations in the ultraviolet where the appropriate low excitation lines occur. With the S2/68 observations and the developement of techniques for the treatment of line transfer in rapidly expanding atmospheres (Castor 1970) a renewed attack on the abundance problem in the WR stars became possible.

The model used is based on the Escape Probability Method (EPM) developed by Castor (1970) and simplified by Castor and van Blerkom (1970) in their treatment of the HeII lines in the WN6 star HD 192163. The model assumes that the emission lines are formed in a spherical, homogenous region surrounding a continuum emitting core. The basic premise of the EPM is that since the expansion velocity in the emission region is very much larger than the thermal velocity, radiative interaction with distant parts of the atmosphere is negligible, and therefore the line transfer is locally constrained. The equations used in coupling the statistical equilibrium equations for the ionic level populations with the radiative transfer in the lines and continuum have been described by Castor and van Blerkom (1970) and reviewed by Willis and Wilson (1978a). It is possible through the EPM to set up these equations for the level populations (and hence line source functions and strengths) in terms of local values of electron temperature and density and ionic species density, and thus to produce grids of computed line strengths for each species in terms of these atmospheric parameters. The model grids are then compared with the observed line strengths to determine the physics and chemistry of the line emitting region. The EPM is best suited for line transfer involving transitions arising amongst levels whose populations are mainly determined by bound-bound processes; in general these are low-lying and usually occur in the UV. It is in this context that the S2/68 observations become important for abundance analysis of the WR atmospheres. Equivalent widths for the transitions of HeII 1640, CIII 2297, 1909, CIV 1550 and NIV 1718, 1488 observed in the six single WR stars have been given by Willis and Wilson (1978a). It turns out that the He modelling is best done using the visible Pickering lines, and our analyses to date have concentrated on four stars which have both UV and visible emission line measurements. These are HD 50896 (WN5), HD 192163 (WN6), HD 191765 (WN6) and HD 192103 (WC8). In order to determine the NIII density in each star (and hence with NIV the total N) we have used measurements for the excited lines of NIII 4640, 4100 in the three WN stars (Smith and Kuhi 1976) and for the WC8 star the measured strength of the NIII 991 resonance line arising in the WC8 component of the binary star γ^2 Velorum as observed in a rocket spectrum of the system (Burton et al. 1973, Willis 1976). The assumption of the similarity of HD 192103 with the WC8 component in γ^2 Velorum is also used to fix the radii of its continuum core and line emitting region, which are inferred from the angular diameter measurements of the system given by Hanbury Brown et al. (1970). The corresponding radii for the WN stars have been derived using the observed strengths of three optically thick HeII lines coupling levels n = 3, 4 and 5 using the method given by Castor and van Blerkom (1970). Other parameters which enter each model calculation are (i) the core continuum temperature, taken as 30000 K and with a black body distribution, (ii) the expansion velocity inferred from measurements of violet displaced absorption lines, (iii) the electron temperature, T_e, (iv) the electron density, N_e and finally (v) the ionic density of the species considered, $N(X^+)$. The last four values are local values at the representative radius adopted for the emission region. The model solutions, consisting of computed line strengths are determined for grids of T_e, N_e and $N(X^+)$, and these atmospheric parameters are determined for each star by fitting the observed line strengths for each ion. For a detailed description of this model fitting

HD	N(CIII)	N(CIV)	N(NIII)	N(NIV)	N(He)	C/N	C/He	N/He
50896	5.0(6)	1.0(6)	1.0(9)	8.0(7)	2.0(11)	5.4(-3)	9.0(-5)	1.7(-2)
192163	5.0(6)	1.2(6)	1.4(9)	7.0(7)	2.0(11)	2.6(-3)	9.0(-5)	3.5(-2)
191765	5.0(6)	1.2(6)	1.1(9)	6.0(7)	2.0(11)	4.7(-3)	9.0(-5)	1.9(-2)
192103	3.0(8)	2.0(6)	7.0(7)	2.0(7)	1.0(11)	2.9(00)	9.0(-3)	3.2(-3)

Table 2 The abundances of He, C and N in four single WR stars observed by S2/68. The densities for each ionic species are in cm^{-3} with the values in () being the exponent.

see Willis and Wilson (1978a). It is noteworthy that the separate model fitting for each ion results in similar values of T_e and N_e, providing a good consistency check on the model employed.

The results are shown in Table 2 which lists the derived mass abundance fractions of He, C and N in each star. The deduced electron temperatures for the WN and WC stars are 50000 K and 30000 K respectively. With He as the principle constituent and mainly doubly ionized, N_e is simply twice the He density to good accuracy. Within the framework of the EPM used it is concluded that the errors in these abundances resulting from uncertainties in the radii and effective temperatures employed are less than a factor of two, with the C/N ratios more accurate still. The attainment of more accurate values will require the construction of more sophisticated models of line transfer and also more observations in the ultraviolet.

4 THE EVOLUTIONARY STATUS OF THE WR STARS

With the effective temperatures determined as outlined above and the absolute magnitudes given by Smith (1968), the location of the WR stars on the H-R diagram can now be reliably defined and this is shown in Fig 2. The WR stars are seen to lie to the right of the MS and below the Of-supergiant branch. A similar location was inferred by Conti (1976) who also noted that the WN7,8 stars, which are more luminous lie close to the realm of the Of stars to which they also bear some strong spectral similarities. This prompted him to propose that the Of stars may be the progenitors of the WR class, with the WN7,8 stars as an intermediate stage. Bohannon and Conti (1977) have shown that in the binary BD +40 4220 both components are Of but the secondary has a mass of only 7 $M_{\odot}$ despite its normal high Of luminosity which they suggest points to the secondary as being " on its way to becoming a WR star ". The WR stars are known to be overluminous for their mass and Smith (1973) has pointed out that their masses and luminosities are consistent with those expected for helium burning stars. The predominance of helium in their atmospheres would support this assertion. Although very little information exists concerning the abundances of H, He, C and N during the course of hydrogen and helium

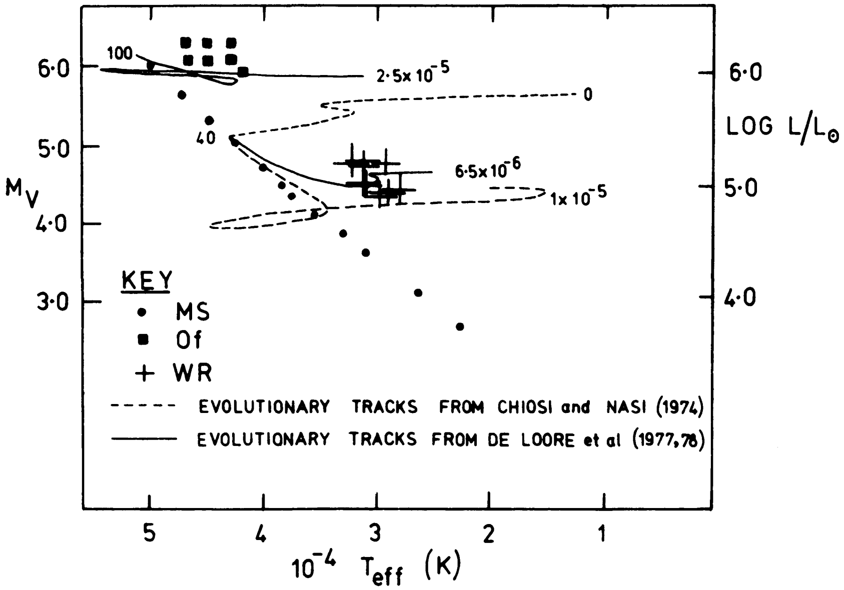

Fig 2 The upper region of the H-R diagram showing the location of the M-S, Of and WR stars and several evolutionary tracks for massive stars with high mass loss rates.

burning, we do find that the values deduced in the present study are consistent with those expected to occur during these stages in massive hot stars. Paczynski (1973) has tabulated in a semi-qualitative way the abundance profiles to be expected during the course of hydrogen and helium burning in massive stars where the former process operates through the CNO-cycle and CNO-bicycle. These profiles are shown schematically in Fig 3, starting with normal cosmic abundances. In the CNO-cycle and bi-cycle, nearly all the hydrogen and much of the carbon is burned and in the subsequent helium burning the carbon is quickly replenished and some nitrogen is burned. The He, C and N abundances determined for the WR stars are shown on the right of Fig 3, and it is clear that they match the nuclear burning products at two specific stages which are marked at the foot of the diagram. The WN point occurs at a very early stage of helium burning, while the WC point occurs well into that process where both C and N are quite abundant. Thus it appears that the WN stars are at an earlier stage of evolution than the WC stars.

This comparison between the observed abundances and the nuclear burning products is only valid if the products of the nuclear burning can be exposed to observation in the WR atmospheres. This can only occur if there is extensive mixing and/or extensive mass loss, the latter removing the outer unprocessed material. The WR stars are clearly losing mass at a high rate and it is reasonable to suppose that the mass loss process is the operative one. The atmospheric helium densities together

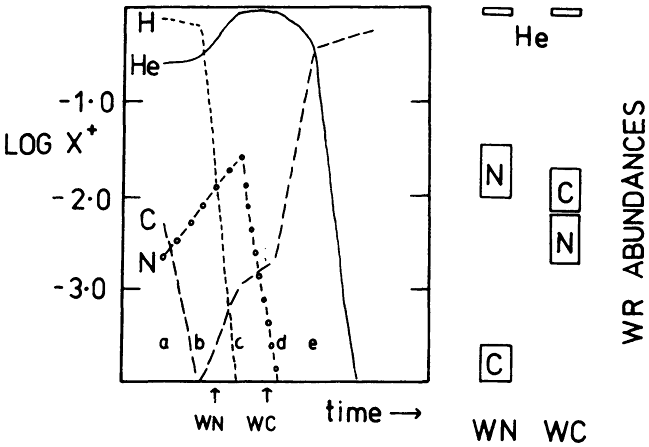

Fig 3 The abundance profiles of He, H, C and N during the course of hydrogen burning, points a to c, and helium burning, c to e, in massive hot stars, compared to deduced abundances for WR stars.

with the observed expansion velocities and line emitting radii deduced in the present study imply mass loss rates of ~ 10^{-4} $M_\odot$ y^{-1}. Willis and Wilson (1978b) deduce a mass loss rate of 9×10^{-5} $M_\odot$ y^{-1} for the WC8 star in γ^2 Velorum from observations with Copernicus of violet displaced absorption in the intercombination CIII 1909 line. Mass loss rates of this scale sustained over an extended period imply that the progenitors of the WR class would have to be very massive stars, and Conti (1976) has suggested that the Of stars with such large masses may have mass loss rates sufficiently high enough to remove a large fraction of their outer material during hydrogen burning and leave a star with WR characteristics. In the past few years several papers have dealt with the evolution of massive stars with high mass loss rates. Chiosi and Nasi (1974) studied the evolution of 20 and 40 $M_\odot$ models with a variety of mass loss rates, and their track for a 40 $M_\odot$ star with an initial mass loss rate of 1×10^{-5} $M_\odot$ y^{-1} is shown in Fig 2, together with the track for the conserved case. When the mass loss rate is sufficiently high they find that the star sheds most of its outer material and moves down the M-S during the hydrogen burning phase and that during the subsequent helium burning the star moves into the WR region. Although the masses studied by Chiosi and Nasi (1974) are too small to give a starting point among the Of stars, their results in many ways support the idea of a Of-WR link through heavy mass loss in the hydrogen burning phase. Similar results are reported by de Loore et al. (1977) who suggest that the high mass loss rates needed to give the required evolution of a single Of star to a WR star may not in fact occur. Subsequently de Loore et al. (1978) extended their results to a star of 100 $M_\odot$ and an initial mass loss rate of 2.5×10^{-5} $M_\odot$ y^{-1} and this track is also shown in Fig 2 in which about 60 percent of the mass has been expelled by the end of the hydrogen burning but the track has not proceeded down to the WR stars.

Additionally they find that the atmosphere is still comparatively rich in hydrogen, in contrast to the observed situation in most classes of WR star. Thus it would appear that the mass loss rates considered are still not large enough to produce the required drop in luminosity from Of to WR: perhaps rates of 3 to 4 $\times 10^{-5}$ $M_\odot$ y^{-1} are needed and one has to ask whether such large mass loss rates can occur. This seems to be the case for the WR stars themselves, and Hutchings (1976) has noted a few O-type cases, and he has given evidence that mass loss is enhanced in binary systems. De Loore et al. (1978) have argued that in massive binaries it is very easy to remove 70 percent of the mass and leave a pure helium star. It may therefore be that membership of a binary system is a necessary condition for a WR star to develop, and that all WR stars are thus in binary systems, a suggestion invoked by Kuhi (1973).

The evolution is clearly critically dependent on the mass loss rate and it is not clear that the required very high mass loss rates for single stars can be ruled out. It is possible that the mass loss rates determined for O-type supergiants of 10^{-6} to 10^{-5} $M_\odot$ y^{-1} (Hutchings 1976) may refer to stars which are well into their hydrogen burning, much higher rates having occured earlier in the evolution. In that case it would not be inappropriate to consider higher mass loss rates than those studied by de Loore et al. (1978) for the Of stars. Clearly there is a need for more accurate and more extensive measurements of mass loss rates for massive hot stars, together with more exhaustive models of stellar evolution incorporating mass loss, in order to clarify the links between the O-type and the WR stars.

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DISCUSSION FOLLOWING WILLIS and WILSON

Hutchings: The very close grouping of WN7 stars in the HR diagram and the similar close grouping of the 5 Of extreme stars in the same place reinforces the connection between them. It also suggests that something special happens to enhance mass loss, at this combination of temperature, luminosity and gravity.

Willis: The grouping of the WN7 stars in the extreme Of region is the result of absolute magnitude determinations of WN7 stars from LMC measurements and temperature determinations from Zanstra analyses. We have not observed WN7 stars with S2/68. However their apparent close grouping does suggest an evolutionary link, as does the comparative similarity of their spectra in the visible.

Castor: I am a little confused about the composition determination for the WC stars. If the He/C ratio is normal, then the mass fraction of carbon is enhanced by a factor 4 or so, since the hydrogen is missing.

Willis: The carbon abundance determination is consistent with the C being replenished in the helium burning phase and so the He/C ratio should not really be compared with abundances relative to hydrogen in the hydrogen burning phase.