Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
Proceedings IAU Symposium No. 193, ©1999 IAU
K.A. van der Hucht, G. Koenigsberger & P.R.J. Eenens, eds.

Properties of Wolf-Rayet stars from X–ray to radio data

Allan J. Willis

Department of Physics & Astronomy, University College London, UK

Abstract. This review outlines the impact of observations across the spectrum (X-rays to radio) on our understanding of the basic physical, chemical, wind and mass loss properties of Wolf-Rayet stars. Optical spectropolarimetry indicates that $\sim 15\%$ of the WR stars have anisotropic winds, whilst the majority have globally spherically symmetric outflows. All WR stars probably have winds structured (clumped) on the smaller scale as evidenced from: thermal radio spectral indices, optical-UV continuum/line/polarisation variablity and time-series spectroscopy, and the ubiquity of wind X-ray emission. *ROSAT* results indicate $L_X(\mathrm{WR}) = 10^{31-33}\,\mathrm{erg\,s^{-1}}$ with $kT \simeq 0.3\,\mathrm{keV}$. WR mass loss rates may be lower than previously thought: mean, clumping-corrected rates from radio data yield $\dot{M}(\mathrm{WN}) \simeq 3\times10^{-5}\ \mathrm{M_\odot\,yr^{-1}}$ and $\dot{M}(\mathrm{WC}) \simeq 2\times10^{-5}\ \mathrm{M_\odot\,yr^{-1}}$. Analyses of UV-optical-IR spectra lead to good constraints on T_{eff} and $L/\mathrm{L_\odot}$ and confirm the chemical separation of the WN and WC classes: WN stars show H-He-C-N abundances reflecting CNO-burning products, and WC(WO) stars show He-burning products. *ISO* data are confirming the H-deficiency of WC winds, and reveal a substantially enhanced Neon abundance in WC stars.

1. Introduction

Over the past three decades there have been significant advances made in the determination of the fundamental physical, chemical and mass loss properties of WR stars, and their role in the evolution of massive stars in galaxies. It is generally accepted that WR stars are the evolved descendents of massive O-type stars. High levels of stellar wind mass loss, either continuous or via short-lived 'outbursts' associated with an LBV phase, can peel off the outer atmospheric layers and reveal successive phases of nuclear processed material. In some cases the effect of Roche lobe overflow in binary systems may play a role in providing the material stripping. WN stars appear to exhibit atmospheric chemistries reflecting the exposition of CNO-burning material; WC and WO stars the subsequent proceeds of He-burning and α-capture products. The derived abundances of H-He-C-N-O determined from quantitative analyses of WR spectra (usually from optical, UV and near-IR data) have generally shown good agreement with the predictions of evolutionary models at the different WN-WC-WO phases. Mass loss rates for WR stars, based on analyses of their free-free emission at radio-mm-farIR wavelengths, have generally yielded very high values (typically $10^{-5,-4}\,\mathrm{M_\odot\,yr^{-1}}$), with wind terminal velocities lying in the range ~ 1000–$4000\,\mathrm{km\,s^{-1}}$ depending on WR subtype. The extremely high levels of WR mass loss is consistent with ongoing atmospheric stripping in the post-MS evolutionary phases, clearly has a determining effect on evolutionary lifetimes in the WR phases, and the level and importance of chemical enrichment and mechanical energy input into the interstellar medium.

Whilst there has undoubtedly been great advances in this field, it should be recognised that the interpretation of most datasets and the development of sophisticated non-LTE, moving atmosphere modelling codes has assumed a perhaps somewhat idealised picture of a WR star, in which the emergent radiation is formed in a spherically symmetric, time-independent, smooth stellar wind. As observational techniques expand and improve, and new wavebands open up, at least some of these assumptions have become open to question, with possible ramifications for our quantitative knowledge of WR stars. The purpose of this paper is to review some of the more recent observations secured at a variety of wavebands, and their impact on our understanding of the basic physical and chemical properties of WR stars. Emphasis will be placed on observationally-deduced aspects concerning the WR stellar wind properties and mass loss rates; temperatures and radiative luminosities, and their chemical composition. I will not be dealing with interaction effects in WR+O binaries, nor with aspects associated with WR populations in galaxies – both topics which will be covered by others at this meeting.

2. Stellar wind properties

2.1. Terminal velocities

Measurement of the terminal velocity, v_∞, probably provides the most secure WR wind parameter. Ultraviolet (largely *IUE*) spectroscopy of the maximum violet extent of the saturated intensity of resonance line P-Cygni profiles provides an excellent measure of v_∞ (Prinja *et al.* 1990) in good agreement with determinations at longer wavelengths using the P-Cygni profiles of He I 2.058 μm (Williams & Eenens 1989) or He I λ 10830Å (Howarth & Schmutz 1992) both of which are anticipated to be formed at large stellar radii. Results also show good agreement with determinations from optical line profile modelling (Hamann *et al.* 1995; Koesterke *et al.* 1991; Crowther & Smith 1996). Clear correlations are apparent between v_∞ and subtype in both the WN and WC sequences: $\sim$500–3000 km s^{-1} for WN9–WN2 and $\sim$800–3500 km s^{-1} for WC9–WC5. Values for WO stars are given by Kingsburgh *et al.* (1995) and reach 4500 km s^{-1} at WO2. There appears to be no significant difference in v_∞ between WN and WC stars in the Galaxy and the LMC, whereas OB stars show substantially smaller values in the LMC and SMC.

Combined ultraviolet-optical-infrared spectroscopy of individual WR stars provides measurements of P-Cygni profile absorption velocities and emission line widths spanning a very wide range of ionization potential (*IP*) and excitation potential (*EP*) transitions. It is very clear from such data that the winds of both WN and WC stars show substantial ionization stratification (as well as in *EP*) with higher *IP.* transitions being formed at lower wind velocity. This circumstance thus provides a larger range of radiative line opacity for wind driving than would be the case for an ionization frozen wind.

2.2. Non-spherical vs. spherical winds

There is now very strong evidence that the stellar winds of some WR stars are grossly asymmetric reflecting large scale anisotropies. This stems from optical spectropolarimetric observations attempted by Schulte-Ladbeck *et al.* (1991, 1992), followed by more extensive surveys by Schulte-Ladbeck (1994) and Harries, Hillier & Howarth (1998, hereafter HHH98). HHH98 provide very high quality spectropolarimetry for 16 northern WR stars, and combine their results with earlier work to yield a total sample of some 29 stars, covering both WN and WC subtypes and single stars and binary systems. The observation of reduced linear polarisation at emission line wavelengths compared to the neighbouring continuum polarisation — the 'line effect' — is a sure signature of an asymmetric wind (see Fig. 1). Of the 29 stars discussed by HHH98, five single stars show the line effect: WR 6 (WN4b), WR 16 (WN8h), WR 40 (WN8h), WR 134 (WN6b), WR 136 (WN6) (the latter only in the data of Whitney *et al.* 1989); whilst it is also seen in some binary systems: WR 137 (WC7+OB), WR 139 (WN5+O6), WR 141 (WN6+O5) and WR 155 (WN6+O9II).

What fraction of WR stars have anisotropic winds? From a detailed statistical analysis of the observed cumulative distribution of observed continuum polarisation HHH98 conclude that $\sim$15% of WR stars have intrinsic polarisations greater than $\sim$0.3%, whilst the remainder have zero polarisation. It appears therefore that the assumption of spherical winds for the bulk of WR stars ($\sim$85%) is reasonable. For those stars that do show the polarisation line-effect,

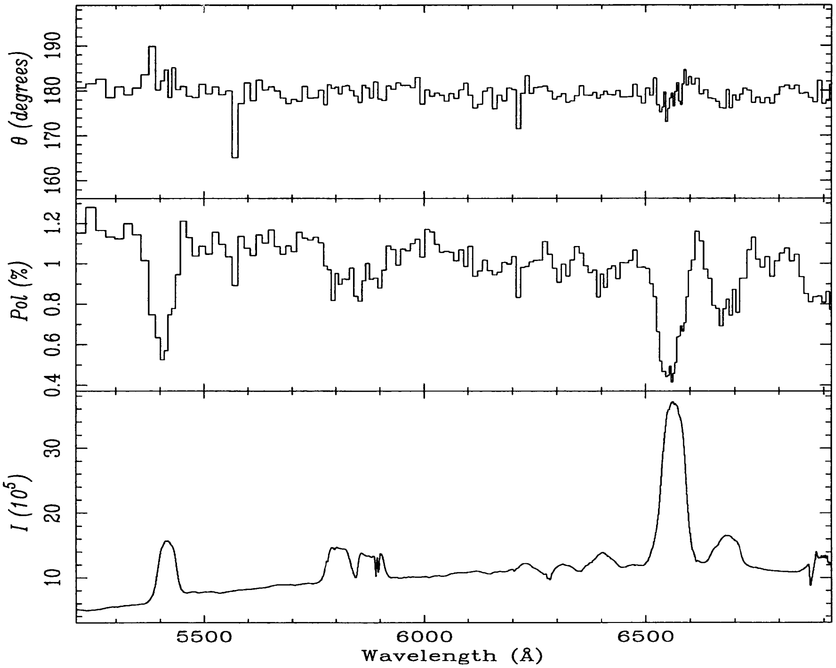

Figure 1. Spectropolorimetry of HD 191765 (WR 134, WN6) showing the line-effect reflecting an anisotropic stellar wind (from HHH98)

HHH98 estimate, from radiative transfer computations, that equator/pole density ratios of $\leq$ 2–3 are implied. They note that the line-effect stars appear to show the highest mass loss rates — but this may be a reflection of an overestimate of $\dot{M}$ based of spherical model analysis (see below). Further, since the mass loss rates for these stars derived from optical emission line analyses are very similar to those derived from radio data, the density contrast appears to be roughly constant with wind radius. HHH98 suggest that the main cause of the wind anisotropy is equatorial density enhancements produced by high rotation rates. By assigning the observed periodicity in optical photometric/spectroscopic variability for the single line-effect stars to a rotation period, they estimate rotational velocities of $\sim$10–20% of the critical velocity; values consistent with the expectation that wind-compression effects will become significant from the models of Ignace *et al.* (1996).

2.3. Small-scale wind structure: clumping

Whilst it appears that the majority of WR stars display basically spherical winds on the large-scale, there is compelling observational evidence that the winds are structured (clumped) on the small scale. Theoretical models of radiatively-induced instabilities (*e.g.*, Lucy 1982; Owocki *et al.* 1988; Gayley *et al.* 1995) predict that the winds of WR (and O-type) stars will be structured and permeated by shocked gas. Observational evidence for WR wind clumping comes from data across the electromagnetic spectrum, as follows:

(i) spectral indices of the free-free emission observed at radio-mm-IR wavelengths typically lie in the range 0.7–0.9, compared to the value of 0.6 expected for smooth wind flows (*e.g.*, Williams 1996). The observed wavelength dependence of the spectral index can be explained using clumped wind models (Nugis *et al.* 1998);

(ii) small-scale optical line, continuum and polarisation variability is a well-known phenomenon in many WR stars (*e.g.*, Moffat & Robert 1992);

(iii) intensive time-series optical spectroscopic studies of individual WR stars have revealed variable structures in the peaks of the emission lines, interpreted as due to 'blobs' in the winds (*e.g.*, Robert 1994);

(iv) time-series UV spectroscopy with *IUE* of several WN stars have shown highly variable P-Cygni profiles interpreted as arising in a structured wind modulated by rotation (*e.g.*, St-Louis *et al.* 1993, 1995);

(v) detection of Discrete Absorption Components (DACs) in the *IUE* spectrum of HD 93131 (WN6ha) by Prinja & Smith (1992) — similar to the DAC phenomenon which is ubiquitous in O-star winds attributed to radiatively-induced wind structures; and

(vi) observation of substantial levels of X-ray emission from WR stars first detected with the *Einstein* satellite and more reliably delineated from *ROSAT* data (Pollock *et al.* 1995) reviewed by Crowther & Willis (1996). *ROSAT* data show single WR stars to have X-ray luminosities in the range $L_X \simeq 10^{31,33}$ erg s^{-1} in the [0.1–2.5] keV energy range, with a range of $L_X/L_{\rm bol} \simeq 3 \times 10^{-8,-6}$. The relatively soft X-ray spectra deduced from the *ROSAT* data for HD 50896 (WN5) ($kT \simeq 0.28$ keV, Willis & Stevens 1996) and for the WC8 component in γ^2 Vel ($kT \simeq 0.19$ keV, Willis *et al.* 1995), implies large characteristic radii ($\geq 1000\,R_\odot$) for this emergent radiation. Recent observations of HD 50896 with the *ASCA*

satellite covering harder X-ray energies, have detected emission up to ~4 keV, but none above 5 keV, indicating that the wind is permeated by a range of temperature shocked gas (Skinner *et al.* 1997).

The recognition that WR winds are clumpy could potentially have serious implications for results from quantitative analysis of WR spectra using the *Standard Model*. However, it appears that the inclusion of clumping in the modelling may not seriously alter the determinations of stellar temperatures, luminosities and chemical composition, but does significantly modify derived mass loss rates (*e.g.*, Hillier & Miller 1998, see below).

2.4. Mass loss rates

Radio frequency observations of the free-free emission (formed at large radii in the terminal velocity regime) have provided a fundamental measure of WR mass loss rates. The most recent survey using this technique has been presented by Leitherer *et al.* (1997), who secured data with the *Australia Telescope* at 8.64 and 4.80 GHz for a sample of 30 southern hemisphere stars within 3 kpc, and combined these data with complementary data for northern stars principally from the *VLA* survey from Abbott *et al.* (1986). Using the standard Wright & Barlow (1975) formulation (which assumes a smooth wind flow at constant, terminal velocity), Leitherer *et al.* (1997) deduce an average rate of $\dot{M} = 4 \times 10^{-5}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ for all WN and WC subtypes observed, except for WC9 stars for which a factor of 2 lower rate is determined.

Standard Model analyses of optical emission lines are also used to deduce WR mass loss rates. Hamann *et al.* (1995) have applied this technique to WN stars and Koesterke & Hamann (1995) to WC stars — again yielding average mass loss rates $\sim 4 \times 10^{-5}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ for both WN and WC subclasses. The close agreement between rates derived from radio continuum and optical emission line techniques, commented on by Leitherer *et al.* (1997) and HHH98, implies that any underlying error (*e.g.*, through the neglect of clumping) would need to effect in essence the whole wind.

Are the radio/optical derived mass loss rates overestimated? Evidence that this is the case comes from a variety of analyses. Firstly, mass loss rates derived from phase-dependent optical polarisation variations in WR+O binaries (a method independent of clumping and distance) by St-Louis *et al.* (1988) yielded values of $\dot{M}$ systematically lower (by factors of 3–4) for the WR components than those from the radio data. Secondly, an analysis of the colliding wind X-ray emission observed in the *ASCA* data for γ^2 Vel (Stevens *et al.* 1996), yielded a value of $\dot{M}$ for the WC8 component a factor of ~3 lower than from the radio. Thirdly, the mass loss rate derived for the binary system V444 Cyg from orbital period increases yields a value of $[0.4\text{–}1.0] \times 10^{-5}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ — a factor of 2–5 times lower than deduced from the radio. These apparently systematic differences clearly point to a common cause, and, as stressed by Moffat & Robert (1992) the neglect of wind clumping in the radio-optical analyses is a likely bet, given the evidence for WR wind clumping (as outlined above).

A first attempt at re-deriving mass loss rates for WR stars from their radio data accounting for the clumped structure and (potential) variable ionization in their outer winds has been given by Nugis *et al.* (1998) based on a semi-empirical approach. They find that the clumping-corrected mass loss

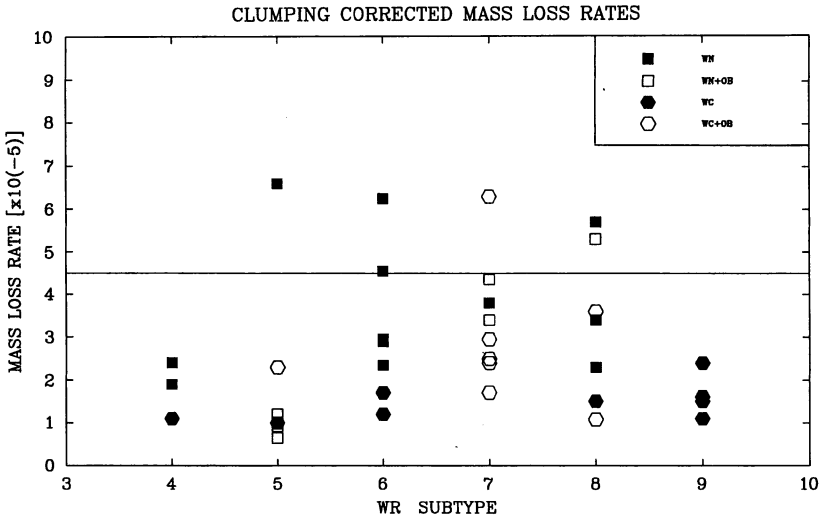

Figure 2. Clumping–corrected mass loss rates for WR stars from Nugis *et al.* (1998). The full line is the mean from smooth-wind analyses of radio data.

rates are generally lower than obtained by smooth wind models: for WN stars $\log\dot{M}_{\rm clumpy} - \log\dot{M}_{\rm smooth} = -0.19$ and for WC stars -0.62. Fig. 2 shows the resulting revised mass loss rate scale from Nugis *et al.* (1998). For binary stars the revised radio results show good agreement with those from the polarisation studies from St-Louis *et al.* (1988). Further support for these lower values of $\dot{M}$ is beginning to emerge as line blanketing and clumping effects are included in revised non-LTE quantitative analyses of WR spectra. Schmutz (1997) has used such models to derive $\dot{M} = 3.2 \times 10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}$ for HD 50896, whilst Hillier & Miller (1998) derive a value of $1.5 \times 10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}$ for the WC5 star HD 165763 — both values about a factor of 3 lower than from the 'normal' radio-optical analyses, and both comparable with the results for these stars given by Nugis *et al.* (1998).

If confirmed, these lower WR mass loss rates may have significant implications for stellar evolutionary models. For instance, as discussed by Leitherer *et al.* (1997), the evolutionary codes of Maeder & Meynet (1994) use a mass loss rate for WN7–WN9 stars of $8 \times 10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}$ — larger than derived from the normal radio analyses!

3. Temperatures and luminosities

Accurate values of $T_{\rm eff}$ and $L/{\rm L}_\odot$ and thus locations on the H-R diagram are an important prerequisite for comparing with evolutionary models. The most reliable determinations of these parameters comes from analyses of high quality UV, optical and/or infrared spectroscopy using state-of-the-art non-LTE, moving atmosphere modelling (see the reviews by Crowther, Hillier, Hamann, and Schmutz in these Proceedings).

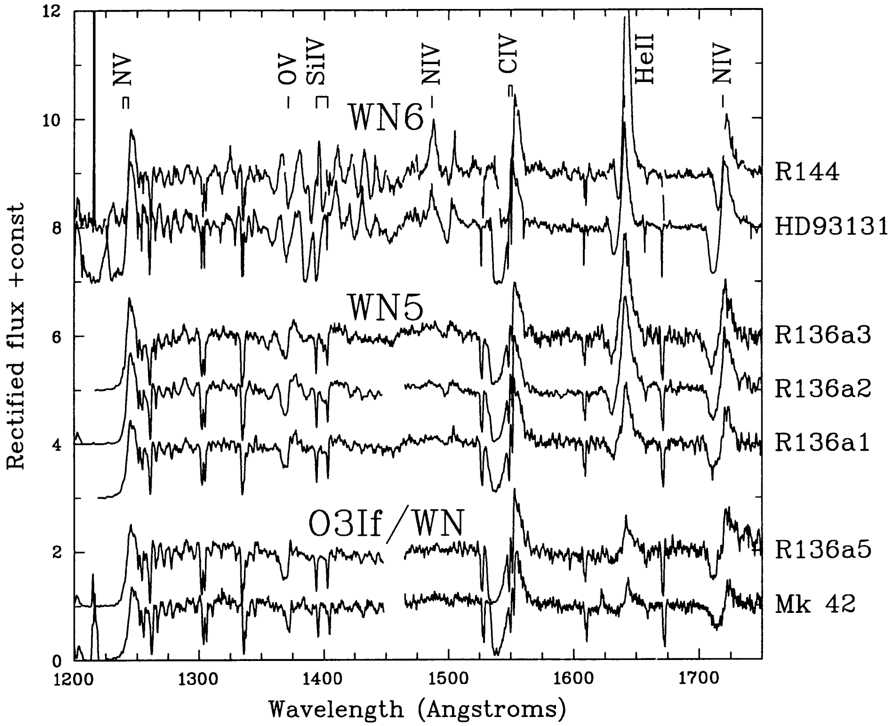

Figure 3. *HST* ultraviolet spectra of LMC WN stars in the R 136 region (from Crowther & Dessart 1998)

For WN stars Hamann & Koesterke (1998a) have performed detailed analyses of galactic stars (non-LTE He+N line modelling), broadly confirming previous results for WNL and WNE-s stars from Hamann *et al.* (1995a) but with higher temperatures and luminosities of WNE-w stars. Typical results give:

WNL	$T_{\rm eff} \simeq$ 30–35 kK;	$\log(L/{\rm L}_{\odot}) \simeq 5.9$
WNE-s	$T_{\rm eff} \simeq$ 40–90 kK;	$\log(L/{\rm L}_{\odot}) \simeq 5.5$
WNE-w	$T_{\rm eff} \simeq$ 40–90 kK;	$\log(L/{\rm L}_{\odot}) \simeq 5.6$

Crowther & Smith (1996) have shown that non-LTE modelling of ground-based infrared spectroscopy for WNE stars gives very similar results, demonstrating the utility of such data for highly obscured objects for which UV-optical spectroscopy is not feasible (*e.g.*, in the Galactic Centre).

The excellent spatial resolution of the *HST* is providing high quality optical-UV spectra for analyses of individual stars embedded in the concentrated, central regions of giant H II regions in the Galaxy and LMC (*e.g.*, Heap *et al.* 1994; Drissen *et al.* 1995). For instance, Crowther & Dessart (1998) find values of $T_{\rm eff} \simeq$ 35–46 kK and $\log(L/{\rm L}_{\odot}) \simeq$ 5.9–6.3 for a sample of WN5–WN6 stars in the cores of HD 97950 in NGC 3603 and in R 136a in 30 Dor (see Fig. 3). The luminosities are amongst the highest derived for WR stars.

For WC stars Koesterke & Hamann (1995b) give non-LTE modelling results of optical spectra for 25 Galactic WR stars (WC5–WC8). For weak lined stars (WC-w) they find: $T_{\rm eff} \simeq 50$ kK, $\log(L/{\rm L}_\odot) \simeq 4.7$–5.5, and for strong-lined (WC-s) stars: $T_{\rm eff} \simeq 60$–100 kK, $\log(L/{\rm L}_\odot) \simeq 4.7$–5.5. Gräfener *et al.* (1998) analyse the *HST* UV and ground-based optical spectra of six WC4 stars in the LMC deriving $T_{\rm eff} \simeq 100$ kK and $\log(L/{\rm L}_\odot) \simeq 5.1$–5.6.

Early indications are that the inclusion of wind-clumping effects in the modelling does not significantly affect values of $T_{\rm eff}$ and $L/{\rm L}_\odot$ (*e.g.*, Hamann & Koesterke 1998b) although the neglect of detailed line-blanketing may lead to an underestimate of a factor of 2 or so in luminosities (*e.g.*, Hillier & Miller 1998; Schmutz 1997).

4. Chemical composition

The observed spectral dichotomy at UV-optical-infrared wavelengths between WN, WC and WO stars is believed to result from gross differences in their atmospheric chemical composition reflecting the exposition of nuclear processed material at different epochs in their evolution.

4.1. WN and WN-C stars

Pickering decrement studies together with quantitative spectral analyses show low H/He ratios. Most WNL stars show some (depleted) hydrogen content, with H/He $\simeq 0.4$–8; whilst most WNE stars show effectively zero H-content, some have values of H/He $\simeq 1$ (see Crowther *et al.* 1995, 1996; Hamann & Koesterke 1998). The presence/absence of hydrogen is now used as a parameter in the revised spectral classification scheme for WN stars presented by Smith, Shara & Moffat (1990). Analyses of observed carbon, nitrogen and oxygen lines in UV-optical spectra yield determinations of abundances which clearly reflect the products of CNO-cycle burning: typically $\log({\rm C/N}) \simeq -1.5$, $\log({\rm C/He}) \simeq -4.0$ (*e.g.*, Crowther *et al.* 1995b).

Analyses of the optical-UV spectra of three WN-C stars (of the seven known in the Galaxy and LMC) by Crowther *et al.* (1995d) yield H/He $\simeq 0$, C/He $\simeq 0.02$, C/N $\simeq 3$, and C/O $\simeq 4$: a composition intermediate between normal WN and WC stars, and indicative of mixing at the boundary of the convective He core.

4.2. WC and WO stars

The optical-UV-IR spectra of WC (and WO) stars do not show evidence for any (unambiguous) H or N lines, and zero atmospheric abundances are usually taken for these elements. Recent *ISO*-SWS spectroscopy of WC dust shells by Williams *et al.* (1998) are confirming their hydrogen deficiency, since the emission peak expected at 5.8–6 μm for amorphous carbon grains produced in a H-rich atmosphere (*e.g.*, by a C_2H_2 pathway) is *not* seen. A recent analysis of *IUE* line-eclipse data for γ^2 Vel (WC8+O8III) by Lloyd (1998) has placed an upper limit of N/He $\leq 10^{-4}$ for the WC component.

Quantitative analyses of observed He-C-O lines in WC spectra reveal abundances consistent with the exposition of He-burning products. Koesterke &

Hamann (1995) find carbon mass fractions in the range 0.2–0.6 in their analysis of 25 Galactic WC stars, but no correlation with subtype (in contrast to the earlier conclusions of a trend by Smith & Hummer 1988). For WC4 stars in the LMC Gräfener *et al.* (1998) find carbon mass fractions close to 0.4, with oxygen mass fractions in the range 0.1–0.3

Kingsburgh *et al.* (1995) have analysed the optical and *IUE* spectra of WO stars. For galactic and LMC stars they derive $C/He \simeq 0.5$, and $C/O \simeq 4.6$–5.2; the SMC WO star gave $C/He = 0.81$, $C/O = 2.7$. Whilst these ratios are at the high end of those derived for WC stars, Crowther, de Marco & Barlow (1998) argue that the spectral sequence from WC to WO is the result primarily of excitation effects rather than significant abundance differences.

4.3. Neon abundances from ISO-SWS data

Evolutionary models for Galactic WC stars (*e.g.*, Maeder 1991) have predicted Neon enhancements of $\sim 10 \times$ solar resulting from the destruction of nitrogen accompanying He-burning according to the nuclear reaction:

$$^{14}\mathrm{N}(\alpha,\gamma) \rightarrow ^{18}\mathrm{F}(\beta,\nu) \rightarrow ^{18}\mathrm{O}(\alpha,\gamma) \rightarrow ^{22}\mathrm{Ne}(\alpha,\mathrm{n}) \rightarrow ^{25}\mathrm{Mg}$$

However the early results for γ^2 Vel (WC8+O8III) from Barlow *et al.* (1988) showed only a marginal enhancement from an analysis of *AAT/IRAS* measurements of [Ne III] 12.81μm and [Ne III] 15.55μm emission lines. The *ISO*-SWS instrument provided new IR data on these Neon fine-structure lines for a larger

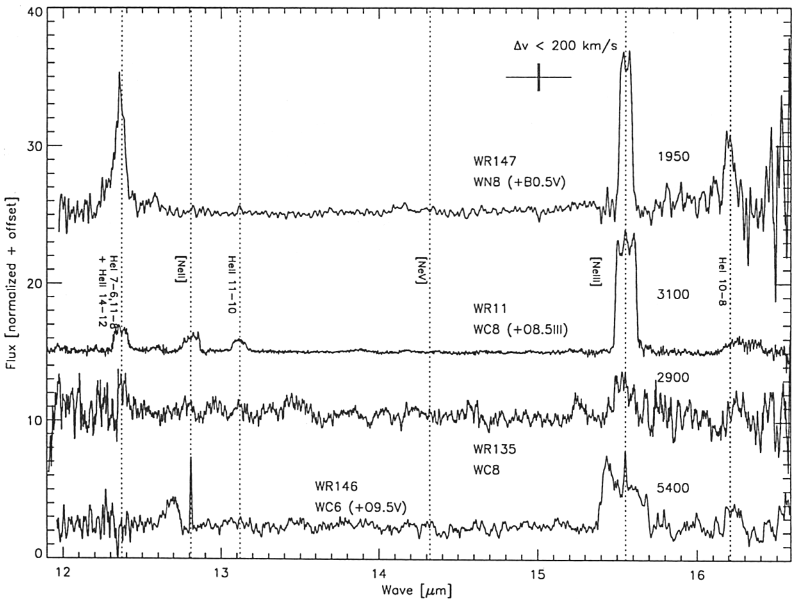

Figure 4. *ISO*-SWS spectra of four WR stars covering [NeII] 12.81μm and [Ne III] 15.55μm (from Morris *et al.* 1998)

sample of WC stars (see Fig. 3). For WR 146 (WC6+O) Willis *et al.* (1997) find $3.4\times10^{-3} \leq \mathrm{Ne/He} \leq 6.8\times10^{-3}$ by number, consistent with the model predictions. Morris *et al.* (1998) find Ne/He enhancements of ≥ 10 for γ^2 Vel, and ≥ 4.3 for WR 135 (WC8). The latest *ISO*-SWS results thus favour the efficacy of the evolutionary models. Moreover they support the contention that the reaction $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ in massive stars is the source of neutrons captured onto Fe-peak elements producing *s*-process elements (for $A \leq 100$, *e.g.*, Meynet & Arnould 1992), and the possibility that WC stars are a significant source of enhanced Ne-abundance found in galactic cosmic rays (*cf.* Maeder & Meynet 1993).

Morris *et al.* (1998, and these Proceedings) surprisingly find a Neon enhancement of a factor 3 from the *ISO*-SWS data for the WN8 star WR 147, suggesting that this may result from the exposition of some ^{14}N-processed material through rotational mixing.

5. Future prospects

There are a number of upcoming ground- and space-based facilities which should provide important new diagnostic information on the properties of WR stars. Clearly the *HST* will further extend studies of the UV-optical-IR spectra, at high spatial resolution, of individual WR stars and WR-ensembles in many extragalactic environments. The *FUSE* mission will provide high spectral resolution FUV data (912–1190 Å) for a large sample of WR stars in the Galaxy and Magellanic Clouds following the limited data obtained with *HUT* (Schulte-Ladbeck *et al.* 1995) and the ORFEUS spectrum of HD 50896 (Mandel *et al.* 1996). The *ISO*-SWS data has yet to be fully exploited, and should encourage mid/far-IR spectroscopy at higher sensitivity with instruments like *SIRTF* and *SOFIA*. The *XMM* and *AXAF* missions will provide real X-ray line spectroscopy and detailed emission measures for a large number of WR stars. Such data will provide a new window for abundance studies (*e.g.*, for species like Fe, Ne, Mg) to further test and refine models of the chemical evolution of WR stars, and yield diagnostics of the high temperature plasmas permeating their stellar winds. The next few years should be a very interesting time for our field!

Acknowledgments. I am grateful to Paul Crowther for a critical reading of this paper and for his useful input.

References

Abbott, D.C., Bieging, J.H., Churchwell, E., Torres, A.V. 1986, ApJ 303, 239
Barlow, M.J., Roche, P.F., Aitken, D.K. 1988, MNRAS 232, 821
Crowther, P.A., Hillier, D.J., Smith, L.J. 1995a, A&A 293, 172
Crowther, P.A., Smith, L.J., Hillier, D.J., Schmutz, W. 1995b, A&A 293, 427
Crowther, P.A., Smith, L.J., Hillier, D.J. 1995c, A&A 302, 457
Crowther, P.A., Smith, L.J., Willis, A.J. 1995d, A&A 304, 269
Crowther, P.A., Smith, L.J. 1996, A&A 305, 541

Crowther, P., Willis, A.J. 1996, in: J.-M. Vreux, A. Detal, D. Fraipont-Caro, E. Gosset & G. Rauw (eds.), Wolf-Rayet Stars in the Framework of Stellar Evolution, Proc. 33^{rd} Liège Int. Astroph. Coll. (Liège: Univ. de Liège), p. 109

Crowther, P.A., Dessart, L. 1998, MNRAS 296, 622

Crowther, P.A., de Marco, O., Barlow, M.J. 1998, MNRAS 296, 367

Drissen, L., Moffat, A.F.J., Walborn, N.R., Shara, M.M. 1995, AJ 110, 2235

Gayley, K.R., Owocki, S.P., Cranmer, S.R. 1995, ApJ 442, 262

Grafener, G., Hamann, W-R., Hillier, D.J., Koesterke, L. 1998, A&A 329, 190

Hamann, W.-R., Koesterke, L., Wessolowski, U. 1995a, A&A 299, 151

Hamann, W.-R., Koesterke, L., Wessolowski, U. 1995b, A&AS 113, 459

Hamann, W.-R., Koesterke, L. 1998a, A&A 333, 251

Hamann, W.-R., Koesterke, L. 1998b, A&A 335, 1003

Harries, T.J., Hillier, D.J., Howarth, I.D. 1998, MNRAS 296, 1072

Heap, S.R., Ebbets, D., Malmuth, E.M., Maran, S.P., de Koter, A., Hubeny, I, 1994, ApJ 435, L39

Hillier, D.J., Miller, D.L. 1998, ApJ 496, 407

Howarth, I.D., Schmutz, W. 1992, A&A 261, 503

Ignace, R., Cassinelli, J.P., Bjorkman, J.E. 1996, ApJ 459, 671

Kingsburgh, R.L., Barlow, M.J., Storey, P.J. 1995, MNRAS 295, 75

Koesterke, L., Hamann, W.-R., Schmutz, W., Wessolowski, U. 1991 A&A 248, 166

Koesterke, L., Hamann, W.-R. 1995, A&A 299, 503

Koyama, K., Kawada, Y., Tsuru, T., Nagase, F., Skinner, S.L. 1994, PASJ 46, L87

Leitherer, C., Chapman, J.M, Koribalski, B. 1997, ApJ 481, 898

Lloyd, C. 1998, PhD Thesis, University of Leicester, UK

Lucy, L.B. 1982, ApJ 255, 286

Maeder, A. 1991, A&A 242, 93

Maeder, A., Meynet, G. 1993, A&A 278, 406

Maeder, A., Meynet G. 1994, A&A 287, 803

Mandel, H., Appenzeller, I., Barnstedt, J. *et al.* 1995, A&A 310, 239

Meynet, G., Arnould, M. 1992, in: Nuclei in the Cosmos (Bristol: IOP Publ.), p 487

Moffat, A.F.J., Robert, C. 1992. in: L. Drissen, C. Leitherer & A. Nota (eds.), Non-isotropic and Variable Outflows from Stars, ASP-CS 22, 203

Morris, P.W., van der Hucht, K.A., Willis, A.J., Williams, P.M., 1998, in: L.B.F.M. Waters, C. Waelkens, K.A. van der Hucht & P.A. Zaal (eds.), *ISO*'s View on Stellar Evolution, ApSS 255, 157

Nugis, T., Crowther, P.A., Willis, A.J. 1998, A&A 333, 956

Owocki, S.P., Castor, J.I., Rybicki, G.B. 1988, ApJ 335, 914

Pollock, A.M.T., Haberl, F., Corcoran, M.F. 1995, in: K.A. van der Hucht & P.M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, Proc. IAU Symp. No. 163, (Dordrecht: Kluwer), p. 512

Prinja, R.K., Smith, L.J. 1992, A&A 266, 377

Prinja, R.K., Barlow, M.J., Howarth, I.D. 1990, ApJ 361, 607

Robert, C. 1994, in: A.F.J. Moffat, S.P. Owocki, A.W. Fullerton, N. St-Louis (eds.), Instability and Variability of Hot-Star Winds, Proc. Isle-aux-Coudres Workshop 1993, ApSS 221, 137

Schulte-Ladbeck, R.E., Nordsieck, J.H., Taylor, M., Nook, M.A., Bjorkman, K.S., Magalhães, A.M., Anderson, C. 1991, ApJ 382, 301

Schulte-Ladbeck, R.E., Nordsieck, K.H., Taylor, M., Bjorkman, K.S., Magalhães, A.M., Wolff, M.J. 1992, ApJ 387, 347

Schulte-Ladbeck, R.E. 1994, in: A.F.J. Moffat, S.P. Owocki, A.W. Fullerton, N. St-Louis (eds.), Instability and Variability of Hot-Star Winds, Proc. Isle-aux-Coudres Workshop 1993, ApSS 221, 347

Schulte-Ladbeck, R.E., Hillier, D.J., Herald, J.E. 1995, ApJ 454, L51

Schmutz, W. 1997, A&A 321, 268

Skinner, S.L., Itoh, M., Nagase, F. 1997, New Astronomy 3, 37

Smith, L.F., Hummer, D.G. 1988, MNRAS 230, 511

Smith, L.F., Shara M.M., Moffat A.F.J. 1996, MNRAS 281, 163

St-Louis, N., Moffat A.F.J., Drissen L., Bastien, P., Robert, C. 1988, ApJ 330, 286

St-Louis, N., Howarth, I.D., Willis, A.J., Stickland, D.J., Smith, L.J., Conti, P.S., Garmany, C.D. 1993, A&A 267, 447

St-Louis, N., Dalton, M.J., Marchenko, S.V., Moffat, A.F.J., Willis, A.J. 1995, ApJ 452, L57

Stevens, I.R., Corcoran, M.F., Willis, A.J., Pollock, A.M.T., Skinner, S.L., Nagase, F., Koyama, K. 1996, MNRAS 283, 589

Whitney, B.A., *et al.* 1989, BAAS 20, 1013

Williams, P.M. 1996, in: J.-M. Vreux, A. Detal, D. Fraipont-Caro, E. Gosset & G. Rauw (eds.), Wolf-Rayet Stars in the Framework of Stellar Evolution, Proc. 33^{rd} Liège Int. Astroph. Coll. (Liège: Univ. de Liège), p. 135

Williams, P.M., Eenens, P.R.J. 1989, MNRAS 240, 445

Williams, P.M., van der Hucht, K.A., Morris, P.W. 1998, in: L.B.F.M. Waters, C. Waelkens, K.A. van der Hucht & P.A. Zaal (eds.), *ISO*'s View on Stellar Evolution, ApSS 255, 169

Willis, A.J., Schild, H., Stevens, I.R. 1995, A&A 298, 549

Willis, A.J., Stevens, I.R. 1996, A&A 310, 577

Willis, A.J., Dessart, L., Crowther, P.A., Morris, P.W., Maeder, A., Conti, P.S., van der Hucht, K.A. 1997, MNRAS 290, 371

Wright, A.E., Barlow, M.J. 1975, MNRAS 170, 41