The Neon Abundance in Wolf-Rayet Stars: A Test of Massive-Star Evolution Theory

Allan Willis, Luc Dessart, and Paul Crowther

Department of Physics & Astronomy, University College London, Gower St., London WC1E 6BT, UK

Pat Morris

Villafranca del Castillo Satellite Tracking Station, Madrid, Spain

Karel van der Hucht

SRON, Sorbonnelaan 2, Utrecht, The Netherlands

Abstract. We are using the Short-Wavelength Spectrometer (SWS) on ESA's Infrared Space Observatory (ISO) satellite to obtain mid-IR spectra of a sample of Wolf-Rayet stars. These data cover important fine-structure lines of [Ne II] 12.81μm, [Ne III] 15.55μm, and [Ne V] 14.32μm, which can be used to determine accurate neon abundances in the WR winds. We present first results from a detailed analysis of WR 146 (WC6 + O) from which we derive limits on the neon abundance of $3.4 \times 10^{-3} \leq$ Ne/He $\leq 6.8 \times 10^{-3}$ by number. This result is in good agreement with predictions from massive-star evolution models (e.g., Maeder 1991), in which neon is enhanced through nuclear reactions associated with the onset of the helium-burning phase. Preliminary analyses of the ISO–SWS spectra of γ^2 Velorum (WC8 + O9I) and HD 192103 (WC8) also indicate enhanced neon abundances. The ISO–SWS spectrum of the WN8 star WR 147 also indicates a neon enhancement of about a factor of 3 over solar, indicating the additional importance of rotational mixing in the exposition of nuclear-processed material for this star.

1. Introduction

Stellar-evolution models of massive stars, which include the effects of mass-loss atmospheric stripping (e.g., Maeder 1983, 1991) predict the exposition of different nuclear-processed material of the light elements at successive phases of advanced evolution. For most WR subtypes the model predictions appear well matched to differing chemical abundances of H/He/C/N/O derived from spectral analyses of WN stars which show CNO-cycle products (e.g., Crowther, Hillier & Smith 1995), for the (later phase) WC stars (e.g., Smith & Hummer 1988; Koesterke & Hamann 1995) which show He-burning products, and for WO stars (e.g., Kingsburgh, Barlow & Storey 1995) which show α-capture products. At the onset of interior He-burning the evolution models (Maeder 1991) predict a substantial increase in the neon abundance which should be seen in WC stars. This occurs through the nuclear reactions:

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

$$^{4}\mathrm{He}(2^{4}\mathrm{He},\gamma)\rightarrow^{12}\mathrm{C}(^{4}\mathrm{He},\gamma)\rightarrow^{16}\mathrm{O}(^{4}\mathrm{He},\gamma)\rightarrow^{20}\mathrm{Ne}$$

The first reaction involves the destruction of ^{14}N produced in the CNO-cycle burning in the (earlier) WN phase, and is expected to be the main source of enhanced neon, as ^{22}Ne, in WC stars in high-metallicity environments like the Galaxy. The second reaction, producing enhanced ^{20}Ne, is expected to be seen in WC stars in low-Z environments like the SMC, where the anticipated lower mass-loss rates in the precursor evolution leads to a WC phase only at a more advanced stage of He burning. For WC stars in the Galaxy, the model predictions lead to an increase of ^{22}Ne by about a factor of 100, and a Ne/He ratio of $\sim 5\times 10^{-3}$ – a factor of about 10× solar.

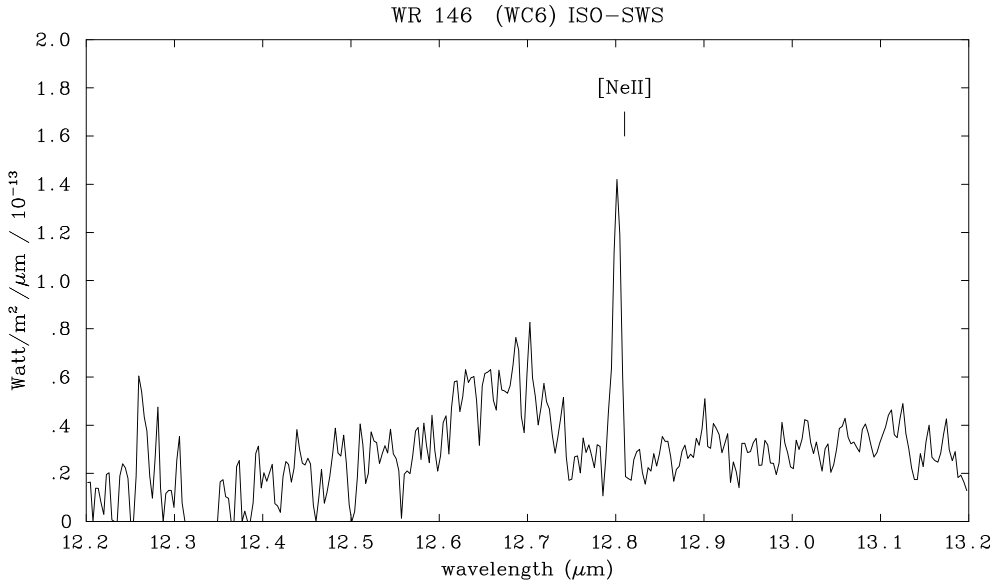
Clearly, the determination of the neon abundance in WC stars can provide a sensitive test of these nuclear reactions and of massive-star evolution models. However, there are no accessible spectral lines of neon available at optical or UV wavelengths, and it is only through the observation and analysis of ground-state fine-structure lines of [Ne II] 12.81μm, [Ne III] 15.55μm, and [Ne V] 14.32μm in WC spectra that their neon abundances can be determined. Moreover, prior to the ISO satellite, these mid-IR transitions were only feasible for the brightest WC star in the sky, γ^2 Velorum (WC8+O9I), for which Barlow, Roche & Aitken (1988) derived an neon abundance of Ne/He $\sim 1.0\times 10^{-3}$ – nearly solar! This result presented a major discrepancy with the evolution-model predictions. In order to progress this topic, we have used the ISO satellite to secure mid-IR spectra of a sample of WR stars in the Galaxy, to cover their neon fine-structure lines, determine neon abundances, and test the evolution models. Preliminary results are presented in this paper.

2. Observations

We have obtained mid-IR spectra, $\sim$2.5–25μm, of a sample of WR stars using the Short-Wavelength Spectrograph (SWS; de Graaw et al. 1996) on the ESA Infrared Space Observatory (ISO) satellite (Kessler et al. 1996). These were obtained in two ISO programmes: (i) a GTO programme with KvdH as PI, covering the stars γ^2 Velorum (WC8+O9I), HD 192103 (WC8), and WR 147 (WN8); and (ii) a GO programme with AJW as PI, covering WR 146 (WC6+O), HD 165763 (WC5), HD 156385 (WC7), HD 117297 (WC8), and HD 164270 (WC9). The former programme utilized the AOT1 (fast-scan) observing mode, whilst the latter used the AOT6 full-grating scan mode to achieve full SWS spectral resolution of $\lambda/\Delta\lambda \simeq 1300$–2500. Our results to date, concentrating on a detailed analysis of WR 146 together with a preliminary assessment for the three stars in programme (i), are discussed below.

2.1. ISO–SWS Spectroscopy of WR 146 (WC6+O)

For WR 146 we used the AOT6 mode to obtain SWS spectra in the wavelength range 2.58–19.5μm in an exposure of 4.75 hours. The raw data were processed



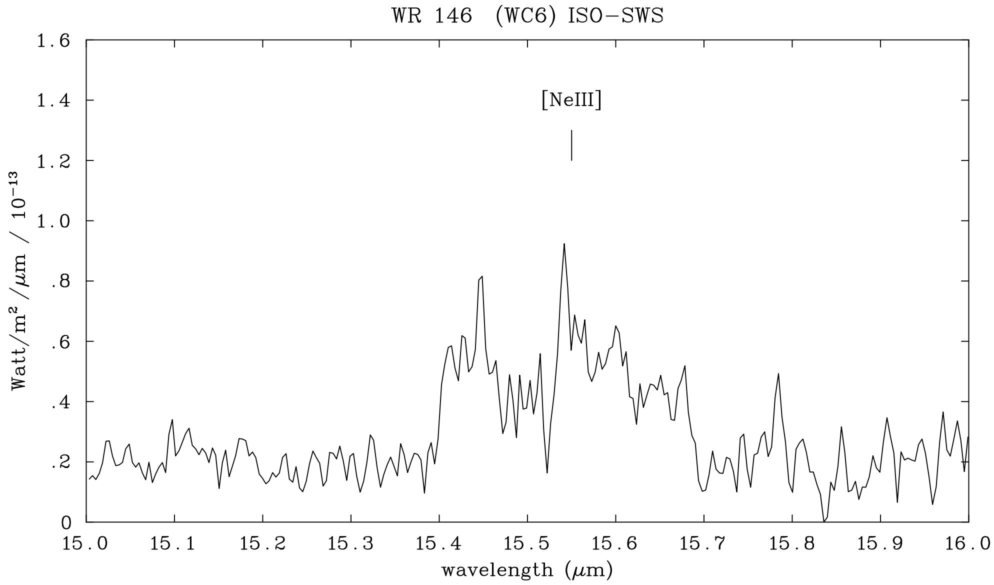


Figure 1. A section of the ISO–SWS spectrum of WR 146 in the region of the [Ne II] 12.81-μm and [Ne III] 15.55-μm lines

at VILSPA (by PM) to yield a final wavelength- and photometric-calibrated spectrum with an estimated photometric accuracy of $\leq$15%; full details are given in Willis et al. (1997). A section of the SWS spectrum of WR 146 covering the region of the neon fine-structure lines is shown in Fig. 1. The [Ne III] 15.55-μm line is seen as a prominent, broad stellar-wind emision feature, which has a square, flat-topped profile with a FWHM of 2700 km s^{-1}. This type of profile is expected for such a fine-structure line, formed at critical densities of $\sim 10^5$ cm^{-3}, far out in the wind where the flow has reached a terminal velocity. We thus assign $v_\infty = 2700$ km s^{-1} for the WC6 wind. Whilst strong, sharp nebular emission is evident in [Ne II] 12.81μm, there is *no* evidence for any broad [Ne II] stellar-wind emission, nor is wind emission seen in the [Ne V] 14.32-μm line. Note that Ne^{3+} does not have any ground-state fine-structure transitions, and the abundance of this ion has to be inferred from indirect methods (see below). Inspection of our overall SWS spectrum of WR 146 does not reveal significant emission in the fine-structure lines of [Mg IV–V] 4.49, 5.61μm, nor in [Ca IV] 3.21μm or [S IV] 10.51μm – see Fig. 2. The SWS spectrum of WR 146 is dominated by numerous, broad emission lines due to transitions in He^+ and C^{3+}, all with round-topped or gaussian-type profiles, and some of these lines are used to infer the C/He abundance ratio in the WC6 component.

2.2. Stellar-Wind Properties of WR 146

In Fig. 3 we show the flux-calibrated SWS spectrum of WR 146 combined with our ground-based near-IR (UKIRT) and optical (INT) spectrophotometry, together with the *JHKLM* photometry of the star given by Dougherty et al. (1996). The agreement between the different datasets is excellent, and confirms the fidelity of the SWS calibrations. The combined spectral datasets have been used to refine the stellar wind properties of WR 146 by Willis et al. (1997). The results are summarized as follows:

The He II and C IV emission-line intensities in WR 146 compared to those observed in single WC6 stars indicate a significant dilution due to an O-star companion, from which we estimate a continuum-light ratio of WR:O = 1:2$\pm$1. The overall continuum-energy distribution, on dereddening and comparing with combined model flux distributions for a WC6 and O8.5V star, yields a colour excess of $E(B-V) = 2.8 \pm 0.1$. Adopting $M_v(\mathrm{WC6}) = -3.7$ implies $M_v(\mathrm{OB}) = -4.5$; with an overall absolute magnitude for the binary system of $M_v = -4.8$ and $v = 13.91$ observed, this yields a distance to WR 146 of 750^{+100}_{-150} pc.

A recombination-line analysis of the observed line intensities in several He II and C IV infrared lines yields an estimate of C/He = 0.15 for the WC6 star. Using this value, and the evolutionary models from Meynet et al. (1994), we estimate O/He $\simeq$ 0.02. From our non-LTE models we estimate a mean molecular weight of $\mu = 5.29$; mean ionic charge per ion of $Z = 1.2$; mean number of electrons per ion of $\gamma_e = 1.15$; and a gaunt factor of 4.5. Using the radio (thermal-component) 5-GHz flux of WR 146 of 1.0 mJy from Dougherty et al. (1996), our SWS-derived terminal velocity of 2700 km s^{-1}, and the Wright & Barlow (1975) formulation, we derive a mass-loss rate for the WC6 star of $\dot{M} = 2.6 \times 10^{-5}\ M_\odot$ yr^{-1}.

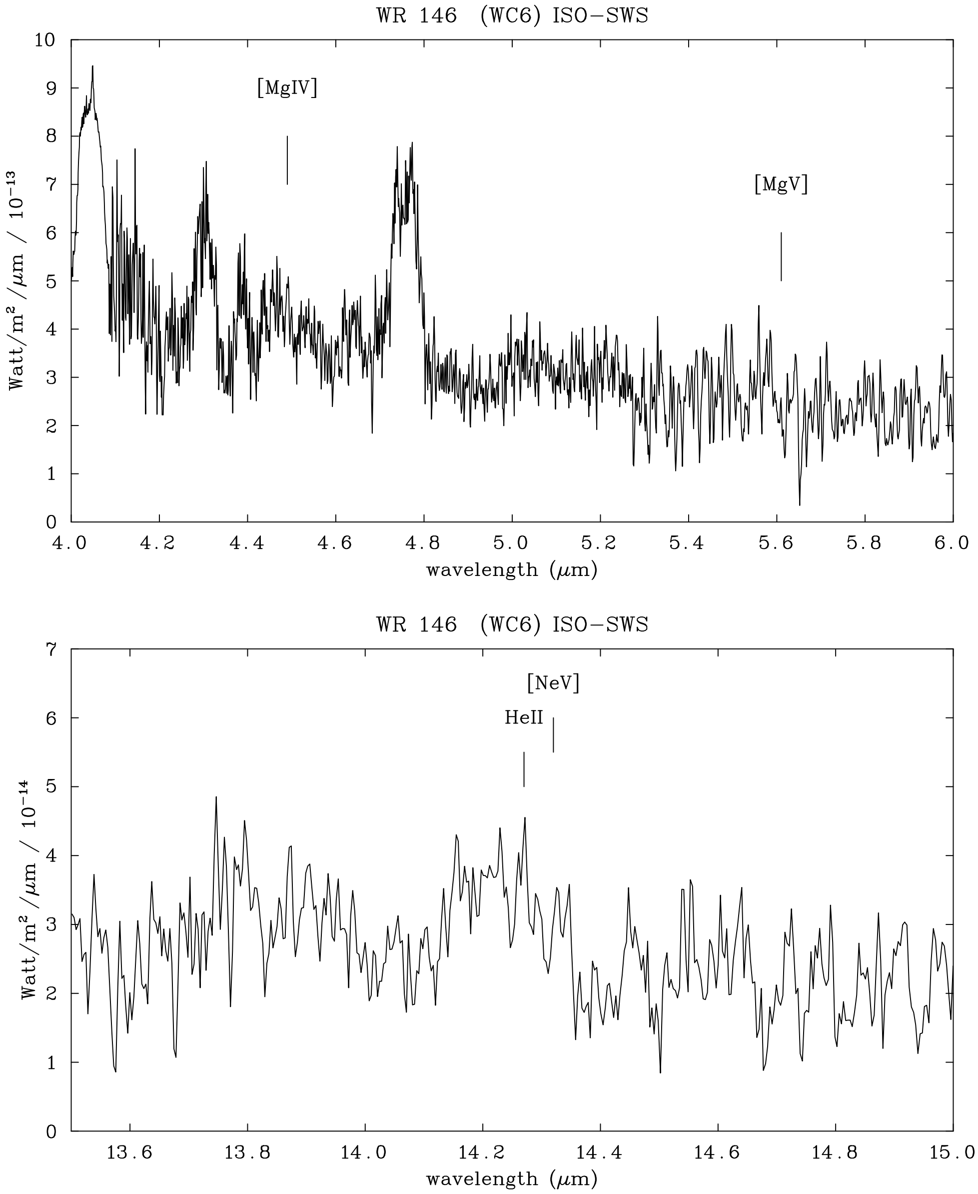


Figure 2. A section of the ISO–SWS spectrum of WR 146 in the region of the [Mg IV], [Mg V], and [Ne V] lines

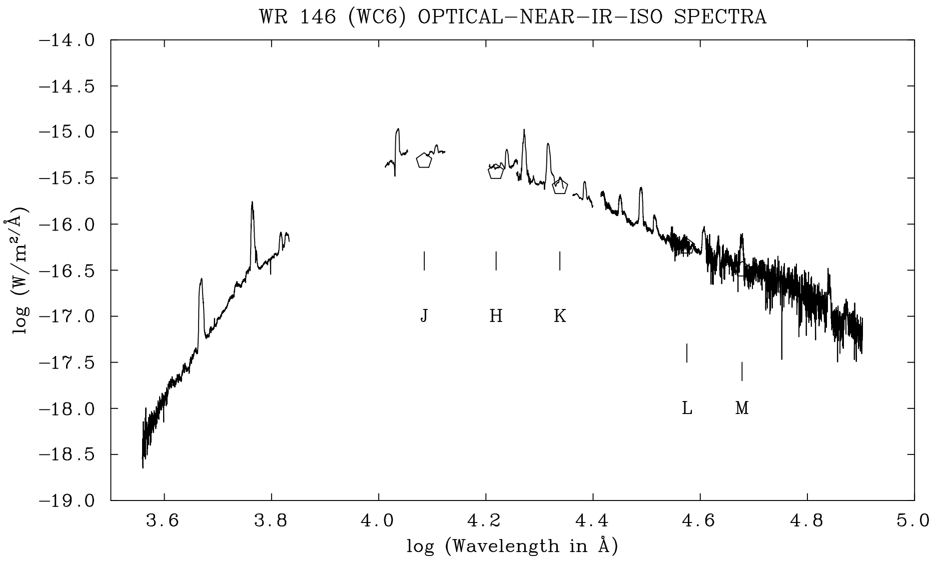


Figure 3. The optical–near-IR (SWS) spectrophotometry of WR 146, together with *JHKLM* photometry from Dougherty et al. (1996).

3. The Neon Abundance in WR 146

As noted above, the neon abundance in WR stars can only be determined from analyses of observed ground-state fine-structure lines of [Ne II], [Ne III], and [Ne V] which occur in the ISO–SWS wavelength range. These transitions are formed at critical densities $\sim 10^5$ cm^{-3}, at very large radii in the wind ($\sim 1500 R_*$) in the constant, terminal-velocity regime. For such a circumstance Barlow, Roche & Aitken (1988) have shown that an analytical expression for the 2-level-atom line-formation process can be derived to yield an accurate determination of the ionic fraction, γ_i, for a given neon line. Full details are given in Barlow, Roche & Aitken (1988) and Willis et al. (1997), and are summarized as follows. For a measured fine-structure line intensity I_{ul}, from a star at a distance D, the ionic fraction γ_i is derived from the expression:

$$\gamma_i = \frac{2D^2 I_{ul}}{\pi \gamma_e^{0.5} A^{1.5} h\nu_{ul}} \times C$$

where the parameter C depends only on the assumed electron temperature (typically $\sim 10^4$ K) and atomic data for the transition; γ_e is the mean number of electrons per ion, and the mass-loss-rate parameter A is given by:

$$A = \frac{\dot{M}}{4\pi \mu m_{\rm H} v_\infty}$$

For WR 146 we measure a line intensity in the [Ne III] 15.55-μm emission of 0.94×10^{-14} W m^{-2}. Using this and the wind properties summarized above yields a ionic density for Ne^{2+} of $\gamma_{\rm Ne^{2+}} = 2.9 \times 10^{-3}$. With an abundance ratio of C/He = 0.15 derived for WR 146, the Ne^{2+} abundance ratio by number is then:

$$\frac{Ne^{2+}}{He} = 3.4 \times 10^{-3}$$

Our SWS spectrum of WR 146 shows no wind emission in either [Ne II] 12.81μm or [Ne V] 14.32μm, implying that the contribution of these ions is negligible. Further the lack of Ne V implies that $Ne^{3+} \leq Ne^{2+}$, and indeed our non-LTE models for a WC6 suggest Ne^{2+} is the likely dominant ion, so we set an upper limit for the Ne^{3+} contribution of $Ne^{3+} = Ne^{2+}$, to obtain the following bound on the neon abundance in WR 146:

$$3.4 \times 10^{-3} \lesssim \frac{Ne}{He} < 6.8 \times 10^{-3}$$

This range is compatible with the predicted value of $\sim5\times10^{-3}$ from evolutionary models (Maeder 1991).

4. SWS Results for γ^2 Velorum (WC8+O9I), HD 192103 (WC8), and WR 147 (WN8)

Estimates of the neon abundance in three other WR stars based on ISO–SWS (AOT1) spectroscopy, which can be compared with the result above for WR 146, have recently been reported by Morris et al. (1997) to which the reader is referred. The conclusions are summarized as follows:

In γ^2 Velorum (WC8+O9I) WC8 wind emision is observed in [Ne II] 12.81μm and [Ne III] 15.55μm, with similar line intensities to those used by Barlow, Roche & Aitken (1988). The deduced neon abundance depends critically on the adopted mass-loss rate for the WC8 star. Morris et al. (1997) use the value $\dot{M} = 0.9 \times 10^{-6}\, M_{\odot}\,\mathrm{yr}^{-1}$ from the optical polarization data from St Louis et al. (1988) to estimate that neon is overabundant by a factor of 10–20 in the WC8 star.

In HD 192103 (WC8) strong [Ne III] 15.55μm is observed, but neither [Ne II] 12.81-μm nor [Ne V] 14.32-μm emission. Using wind parameters for this star from the literature a neon overabundance of a factor of ≥ 4 is estimated.

In WR 147 (WN8) strong [Ne III] 15.55-μm wind emission is observed, but again neither [Ne II] nor [Ne V] wind emission is apparent. Morris et al. (1997) estimate a neon overabundance of a factor of about 3 in the WN8-star wind – a surprising result. Furthermore, they deduce a ratio of H/He = 0 for the WN star, which they suggest could well be a post-LBV candidate. It is suggested that, for this star, rotational mixing is exposing initial He-burning products and an enhanced neon abundance before the star has entered a fully-fledged WC phase.

5. Discussion

The neon abundances we have derived to date from our ISO–SWS spectroscopy for WR 146 (WC6), γ^2 Velorum (WC8), and HD 192103 (WC8) are enhanced over the normal cosmic value by factors of 4–20. These are generally consistent with the predictions of the massive-star evolution models which predict an overabundance of neon (through ^{22}Ne production in Galactic stars) of about a factor of 10 for the WC phase (Maeder 1991). The difference between the new result for γ^2 Velorum and the earlier (near solar) value from Barlow, Roche & Aitken (1988) lies in the adopted mass-loss rate for the WC8 component. The value used by Morris et al. (1997) is a factor of $\sim$3 lower than the revised 'radio-flux' rate, based on the new distance to γ^2 Velorum from HIPPARCOS parallax data (van der Hucht et al. 1997), used in the earlier analysis, and is consistent with the mass-loss rate derived by Stevens et al. (1996) from ASCA X-ray data of the colliding-wind emission from the binary system.

The apparent good agreement between the enhanced neon abundances derived for the WC stars analysed to date and the evolutionary-model predictions gives strong support to the hypothesis that massive stars may be the main source of s-process elements with atomic mass $A \leq 100$, as suggested by Prantzos et al. (1992), Baraffe et al. (1992), and Meynet & Arnould (1992). In these papers the reaction involving the destruction of ^{14}N leading to $^{22}\mathrm{Ne}(\alpha, n) \rightarrow ^{25}\mathrm{Mg}$ is considered the main the source of neutrons which are captured into iron-peak elements. In addition, Maeder & Meynet (1993) have suggested that WC stars may be responsible for the observed excess of neon in galactic cosmic rays, through the injection of processed material by their strong winds. The enhanced neon abundance we have derived for WC stars adds support to this scenario.

The enhanced neon abundance in the WN8 star in our sample is a rather surprising result. In current evolution models, the exposition of enhanced Ne is not expected until the star has 'peeled down' sufficiently to expose initial He-burning products, which simply by mass-loss stripping is not expected until the WC phase. The high neon abundance in WR 147 suggests that, for this WN8 star, some additional process is operating to expose the processed material, and we suggest this is due to enhanced rotational mixing in this star.

Finally, further determinations of the neon abundance in a larger WC-star sample will be made in the near future as our SWS data become fully reduced for HD 165763 (WC5), HD 156385 (WC7), HD 117297 (WC8), and HD 164270 (WC9). Although too faint for ISO, it would be very important to secure mid-IR spectra of WC and WO stars in low-metallicity galaxies (e.g., SMC). In these environments the evolutionary models predict an even greater enhancement of neon ($\sim$100$\times$) in the WC/WO phase through the production of ^{20}Ne via α-capture in advanced helium burning. Hopefully future IR satellite missions can address this issue.

References

Baraffe, I., El Eid, M.F., Prantzos, N., 1992, A&A, 258, 357

Barlow, M.J., Roche, P., Aitken, D.A., 1988, MNRAS, 232, 821

Crowther, P.A., Hillier, D.J., Smith, L.J., 1995, A&A, 293, 172

de Graauw, Th., Haser, L.N., Beintema, D.A., et al., 1996, A&A, 315, L49

Dougherty, S.M., Williams, P.M., van der Hucht, K.A., Bode, M.F., Davis, R.J., 1996, MNRAS, 280, 963 van der Hucht, K. A., Schrijver, H., Stenholm, B., et al., 1997, New Astronomy, 2, 245

Kessler, M., Steinz, J.A., Anderegg, M. E., et al., 1996, A&A, 315, L27

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

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

Maeder, A., 1983, A&A, 120, 130

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

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

Meynet, G., Maeder, A., Schaller, G., Schaerer, D., Charbonnel, C., 1994, A&AS, 103, 97

Meynet, G., Arnould, M., 1992, in Nuclei in the Cosmos, eds. F. Kappeler & K. Wissak (IoP, Bristol), p. 487

Morris, P. W., van der Hucht, K. A., Willis, A. J., Dessart, L., Crowther, P. A., Williams, P. M., 1997, in ISO's View on Stellar Evolution, eds. R. Waters, C. Waelkens & K. A. van der Hucht (Kluwer, Dordrecht), in press

Prantzos, N., Hashimoto, M., Nomoto, K., 1992, A&A, 234, 211

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

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

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

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

Discussion

Puls: Since you reproduce the predicted neon abundance very well, you can say that the mass-loss rate you use is probably okay; then what is the performance number for this star?
Willis: This one doesn't have a *very* high mass-loss rate: $\sim 2\times 10^{-5} M_\odot$ yr^{-1}. For the luminosity, the performance number is probably around 10–15, not 100.
Venn: You have to worry about the ionization corrections; do you also have to worry about isotopic corrections?
Willis: No, not at all. We cannot separate out ^{22}Ne and ^{20}Ne in the [Ne III] 15.55μm lines, since the isotopic wavelength shift is too small. The analysis just gives the total Ne abundance, which is consistent with the evolutionary model prediction of enhanced ^{22}Ne.
Langer: Just a comment; to use the rotational mixing to explain the neon abundance in the WN8 star WR 147 is a bit tricky. One expects there to be mixing of helium-burning products to the surface, then one should get these transition WNC stars.
Maeder: The results shown by Allan are important not only for studies of stellar evolution, but also of Galactic cosmic rays. The people studying these cosmic rays are able to determine the isotopic ratio ^{22}Ne/^{20}Ne, and the value they get is always a big problem. If the high neon abundance reported here is

confirmed then WC stars could be cosmic-ray injectors, since most cosmic rays come from the inner regions of the Galaxy, where WC stars are concentrated.

Howarth: Compared to the early work by Barlow et al., the reconciliation of the γ^2 Vel neon abundance with theory arises essentially through a reduction in the mass-loss rate. What was the basis for that reduction?

Willis: The radio mass-loss rate, interpreted in the normal way (i.e., assuming helium to be singly ionized in the radio-emitting region), formerly gave about $9 \times 10^{-5} M_\odot$ yr^{-1}; the polarization measurements reported by Nicole [St.-Louis] give about $1 \times 10^{-5} M_\odot$ yr^{-1}, a factor 9 smaller, compared to a general difference of a factor 3 between radio and polarization results. The analysis of X-ray colliding-wind effects that Ian Stevens and I carried out gave $3 \times 10^{-5} M_\odot$ yr^{-1}, and seemed reasonably constrained.

The new HIPPARCOS distance changes the radio mass-loss rate from 9 to $3 \times 10^{-5} M_\odot$ yr^{-1}, which still leaves the neon abundance out by a factor of 4–5. What Pat [Morris] is saying is that you can explain this if there's some extra peculiarity about γ^2 Vel, and we don't know if that's true; but the polarization mass-loss rate gives the 'right' result, for example. Things are better (or worse, depending on your point of view) when you realise that the X-ray mass-loss rate is also reduced by a factor of 3 in consequence of the new HIPPARCOS distance, and now agrees with the polarization value.

You have to ask why there might be some peculiarity about the radio emission from γ^2 Vel, and I don't know the answer to that, except that we do know there's strong colliding-wind X-ray emission. It may be that the X-rays are ionizing up the gas in the radio-emitting region.

Schaerer: I understand that there are new radio measurements which bring down the mass-loss rate by a factor of two or so.