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# ISO-SWS spectrophotometry of galactic Wolf-Rayet stars: preliminary results*

**K.A. van der Hucht**[1], **P.W. Morris**[2,1], **P.M. Williams**[3], **D.Y.A. Setia Gunawan**[1], **D.A. Beintema**[2,4], **D.R. Boxhoorn**[4], **Th. de Graauw**[4], **A. Heras**[2], **D.J.M. Kester**[4], **F. Lahuis**[2], **K.J. Leech**[2], **P.R. Roelfsema**[2,4], **A. Salama**[2], **E.A. Valentijn**[4], **and B. Vandenbussche**[2,5]

[1] Space Research Organization Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[2] ESA-*ISO* Observatory, Villafranca del Castillo, Apdo 50727, E-28080 Madrid, Spain
[3] Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
[4] Space Research Organization Netherlands, P.O. Box 800, 9700 AV Groningen, The Netherlands
[5] Sterrenkundig Instituut, K.U. Leuven, Celestijnenlaan 200B, B-3001 Heverlee, Belgium

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**Abstract.** *ISO*-SWS spectra of seven late-type galactic Wolf-Rayet stars are discussed. A high resolution spectrum (2.3 – 29.6 $\mu$m, $\lambda/\Delta\lambda \approx$ 820 - 1700) of the WC8 star WR11 ($\gamma^2$ Vel) is shown and its Ne abundance is discussed. Medium resolution spectra ($\lambda/\Delta\lambda \approx$ 250 - 600) of the WC8-9 stars WR48a, WR98a, WR104, WR112 and WR118 show the broad circumstellar heated amorphous carbon dust emission feature and interstellar silicate and hydrocarbon absorption features.

**Key words:** stars: Wolf-Rayet – interstellar medium: extinction – infrared: spectroscopy

## 1. Introduction

Wolf-Rayet (WR) stars are characterized by strong emission lines which originate in their hot stellar winds, having velocities in the range $v_\infty$ = 1000 - 2500 km s$^{-1}$ and driving mass loss rates in the range $\dot{M}$ = $[2 - 10] \times 10^{-5}$M$_\odot$ yr$^{-1}$. For a review on WR stars, see van der Hucht (1992). The seven target stars of which we discuss here the *ISO*-SWS data are WR11, WR48a, WR98a, WR104, WR112, WR118 and WR147. Apart from the WC8+O9I object WR11 and the WN8 object WR147, all are late-type WC stars with heated amorphous carbon dust formed within their stellar winds (*cf.* Williams 1995). Table 1 lists some of their parameters.

*Send offprint requests to*: K.vanderHucht@sron.ruu.nl

* Based on observations made with *ISO*, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

## 2. Observations and reduction of data

The *ISO* mission is described by Kessler *et al.* (this issue). Table 1 summarizes the *ISO* revolution number, SWS observing mode, and range of spectral resolution for each target. Details on the SWS AOTs are described in the *SWS Observer's Manual* and by de Graauw *et al.* (this issue). Each spectrum was processed at the *ISO* Science Operations Center at VILSPA using software of the SWS Interactive Analysis (IA) package. This sofware was used to derive wavelength-calibrated spectrophotometry for each of the 48 detectors of the SWS grating sections. Details of the processing chain and calibrations may be found in de Graauw *et al.* (this issue), Schaeidt *et al.* (this issue), and Valentijn *et al.* (this issue). The final spectra were produced by rebinning the data of each detector to the expected resolution, scaling the flux densities to the median, and coadding the spectra with 2.0 or 2.5$\sigma$-clipping. These steps are done iteratively, treating each combination of detector block, aperture, and order separately, and inspecting up and down grating scans for memory and dark current effects. Further details on the data reduction will be given in a future publication.

## 3. Emission line features

The *ISO*-SWS spectrum of WR11 (WC8+O9I) shows (see Fig. 1) numerous expected He I, He II, C III and C IV emission lines. C II probably contributes to the corresponding He II transitions. All the C III transitions expected from hydrogenic approximation were accounted for in WR11. In addition we note the forbidden lines of [CaIV] 3.207$\mu$m, [SIV] 10.510$\mu$m, [NeII] 12.815$\mu$m and [NeIII] 15.554$\mu$m. Each of these forbidden lines is resolved in our spectrum, and generally exhibits the rectangular, flat-topped shape characteristic of saturation in the outer WR wind.

**Table 1.** Target stars

| WR | name | type | $v$ [mag] | $A_v$ [mag] | $d$ [kpc] | $T^c{}_{\rm dust}$ [K] | $v_\infty$ [km/s] | *ISO* revolution | SWS AOT | spectral resolution |
|---|---|---|---|---|---|---|---|---|---|---|
| 11 | $\gamma^2$ Vel | WC8+O9I | 1.74 | 0.12 | 0.45 | no dust | $1450^d$ | 180 | SWS01 | 820 - 1700 |
| 48a | Danks 1 | WC8 | (16.8) | 8.6 | 3.9 | var. | | 79 | SWS01 | 250 - 600 |
| 98a | IRAS 17380-3031 | $WC8\text{-}9^a$ | $(19.7)^a$ | $(12.5)^a$ | $3^a$ | var. | | 94 | SWS01 | 250 - 600 |
| 104 | Ve2-45 | WC9 | 13.54 | 7.09 | 1.58 | ∼1100 | $1200^e$ | 99 | SWS01 | 250 - 600 |
| 112 | GL 2104 | WC9 | 18.8 | 13.2 | 1.2 | 960 | | 102 | SWS01 | 250 - 600 |
| 118 | GL 2179 | WC9 | 22.0: | 13.98 | 3.7 | 1410 | | 108 | SWS01 | 250 - 600 |
| 147 | AS 431 | WN8 | 14.89 | $12.79^b$ | $0.63^b$ | no dust | $900^b$ | 40 | SWS06 | 1000 - 2600 |

Notes: Catalog data are from van der Hucht *et al.* (1988) unless stated otherwise; $v$: in narrow-band photometric system of Smith (1968) and Lundstrom & Stenholm (1984), with $A_v$ = 1.11 $A_V$. Values between parentheses are Johnson $V$ magnitudes; $a$: Cohen *et al.* (1991); $b$: Churchwell *et al.* (1992); $c$: $T$ of circumstellar heated amorphous carbon dust formed in WC wind, from Williams, van der Hucht & Thé (1987); $d$: Eenens & Williams (1994); $e$: Torres, Conti & Massey (1986).

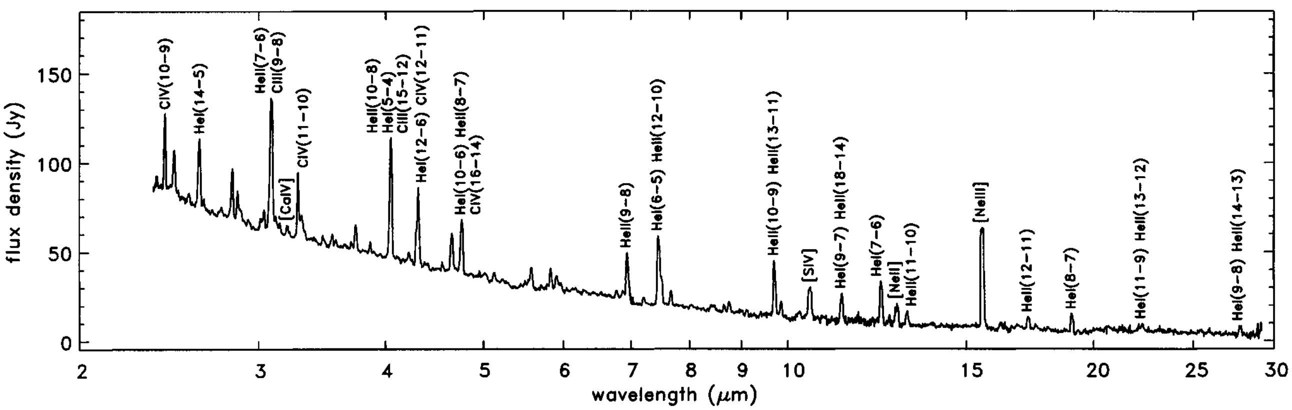


**Fig. 1.** *ISO* AOT-SWS01 (speed 4) spectrum of the WC8+O9I star WR11 ($\gamma^2$ Velorum)

### 3.1. Wind terminal velocities of WR11 and WR147

The forbidden Ne lines in the spectrum of WR11 and WR147 are ideal for measuring the wind terminal velocities because of their strength and the fact that they are easily justified as arising in the outer-most layers of the wind where the wind terminal velocity has been reached (*cf.* Barlow *et al.* 1988). After correcting for the instrumental broadening using unresolved Ne lines in the spectrum of NGC 7027, we measure the Ne lines of WR11 to have widths (HWZI) corresponding to $v_\infty$ = 1540±30 km s$^{-1}$. The corrected [SIV] 10.51$\mu$m line gives 1560±25 km s$^{-1}$, while the [CaIV] 3.21$\mu$m line gives a lower value of 940±100 km s$^{-1}$, indicating that the latter line is formed where the wind of WR11 is still accelerating. The mean value $v_\infty$ = 1550 km s$^{-1}$ is in good agreement with the value measured 1520±200 km s$^{-1}$ from a groundbased [NeII] 12.8$\mu$m observation by Barlow *et al.* (1988), and is somewhat larger than the value measured from the He I line-profile at 2.058$\mu$m, as quoted in Table 1.

For WR147, we find $v_\infty$ values of 960±20 km s$^{-1}$, 980±20 km s$^{-1}$, and 950±50 km s$^{-1}$ when measured from the [NeIII] 15.5$\mu$m, [SIV] 10.5$\mu$m, and [CaIV] 3.21$\mu$m lines, respectively, in reasonably good agreement with the value of 900 km s$^{-1}$ given by Churchwell *et al.* (1992).

### 3.2. The Ne/He abundance ratio of WR11

The Ne-abundance of WR11 was addressed by Barlow *et al.* (1988), based on the [NeII] measurements of Aitken *et al.* (1982) and the [NeIII] data of van der Hucht & Olnon (1985). Rather than normalizing the Ne lines to the He I 12.37$\mu$m line as done by van der Hucht & Olnon, the detailed analysis by Barlow *et al.* relied more heavily on determinations of the mass-loss from the 5 GHz radio flux of WR11, the $He^+/He^{++}$ balance in the 12 $\mu$m region from the He recombination lines, and the C/He abundance. Barlow *et al.* found a Ne/He number ratio of $1.0 \pm 0.35 \times 10^{-3}$, only a factor 1.8 above initial cosmic levels, and a factor of 5 lower than predicted by evolutionary models (*cf.* Maeder & Meynet 1994). By adapting a number of corrections based on the Barlow *et al.* analysis to the simplified theory of Aitken *et al.* for the fine-structure lines, it is possible to obtain similar results; this will be demonstrated in a future paper. For the present, we find that the [NeII] 12.8$\mu$m and [NeIII] 15.5$\mu$m line strengths are in very good agreement with the measurements of Barlow *et al.* and van der Hucht & Olnon, differing by only 7% at most. The He I 12.37$\mu$m line is some 20% weaker than measured by Aitken *et al.* ($F_{12.37} \simeq 2.67 \times 10^{-14}$ W m$^{-2}$ in our spectrum), which increases the Ne/He abundance by roughly

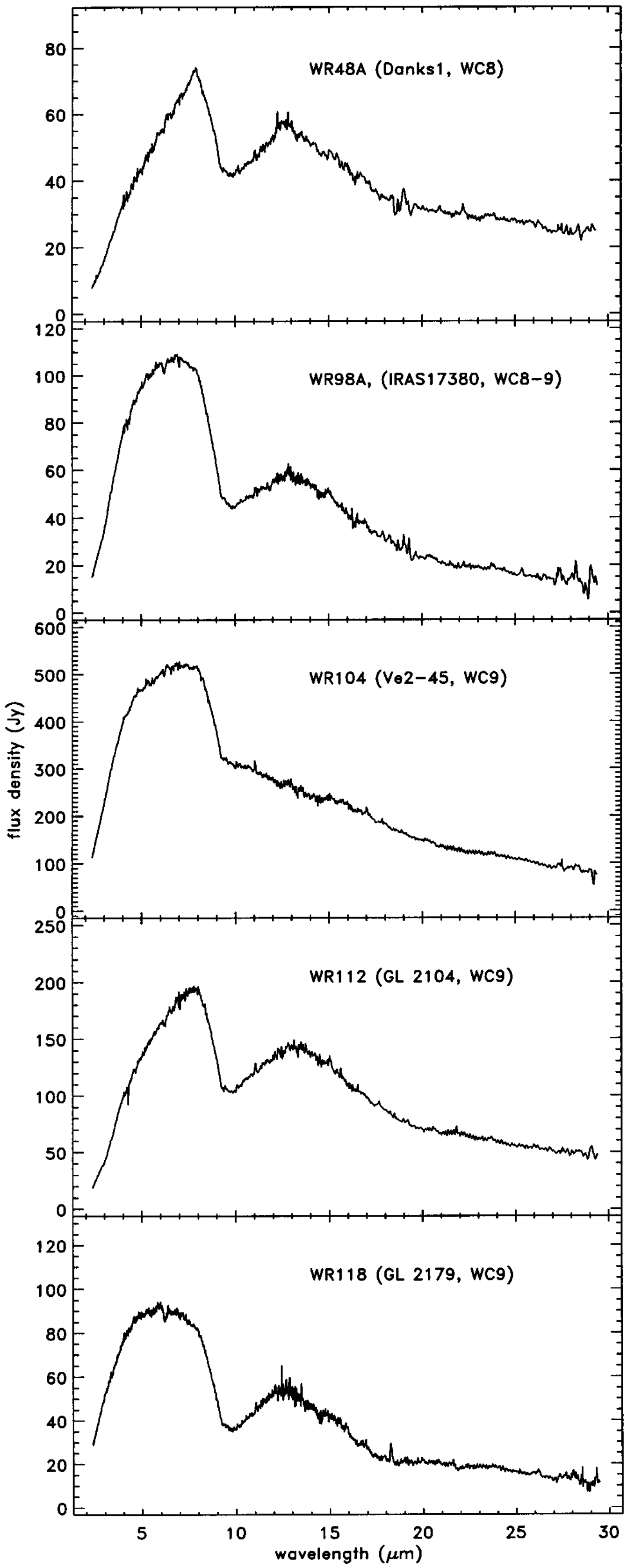


**Fig. 2.** *ISO* AOT-SWS01 (speed 2) spectra of the late-type WC stars WR48a, WR98a, WR104, WR112, and WR118

the same amount in the approach of Aitken *et al.* to a Ne/He number ratio of $1.2 \pm 0.35 \times 10^{-3}$. This is still a small ratio compared with the predicted Ne/He abundance. While no [NeIV] transitions occur in the 2 – 45 $\mu$m region, we do not find the highest-probability transtions of [NeV] at 8.99 $\mu$m or 24.1 $\mu$m. We have searched our spectrum for forbidden and allowed lines of Mg which would provide evidence for $^{22}$Ne conversion to $^{25}$Mg and $^{26}$Mg by $\alpha$-particle capture, but we detect no Mg lines. We seek to confirm the evolutionary abundances of WR11 with additional diagnostics avialable to us with our spectral coverage, and will extend our analyses to other WR stars in our SWS observing program.

## 4. Heated carbon dust

Heated ($\sim$ 1000 K) circumstellar carbon dust spectral features, superposed on stellar wind *free-free* emission, are a common phenomenon for late-type WC stars at infrared wavelengths: 90% of the WC9 stars and 50% of the WC8 stars display heated dust. This dust dominates the IR spectrum completely and veils the underlying stellar wind spectrum. In most cases the IR dust characteristics are constant with time, at least over the last 25 or so years. This implies that heated carbon dust is constantly being replenished within those WC stellar winds. In some cases dust formation is variable or even periodic, modulated by orbital motion in WC+OB binaries (*cf.* Williams 1995). Our IR photometric monitoring program shows that the level of dust formation in WR104, WR112 and WR118 has remained steady over the last two decades. The dust emission from WR98a varies on a short time-scale (Williams *et al.* 1995). In contrast, the hot dust shell formed by WR48a in 1978-1979 has faded (Williams & van der Hucht 1994) as the dust, being carried away by the stellar wind, has cooled from $\sim$1000 K in 1979 to $\sim$300 K as seen in our *ISO* observation.

As expected, the *ISO*-SWS spectral energy distributions of WR48a, WR98a, WR104, WR112, and WR118 (Fig. 2) are dominated by an emission feature of heated circumstellar amorphous carbon dust, cut by the 9.7 $\mu$m interstellar silicate absorption feature (see next section). The *ISO*-SWS data of WR104 have been modelled following Williams, van der Hucht & Thé (1987), but using new optical constants for amorphous carbon grains, from Colangeli *et al.* (1995). Correction for IS extinction followed the law of Rieke and Lebofsky (1985). We find that $T_{grain}$ ranges from 1050 to 200 K going from inner to outer dust shell radii, and that the total carbon dust mass is about $10^{-5}$M$_{\odot}$.

## 5. Interstellar absorption: hydrocarbons, silicates, ice

Sandford *et al.* (1991, 1995) and Pendleton *et al.* (1994) observed the WC9 stars WR104, WR112, WR118 and WR121 with the *IRTF*-CGAS at resolution 800-3000 and discussed notably the hydrocarbon 3.38-3.42 $\mu$m absorption features, comparing them with the 9.7 $\mu$m silicate feature. They found $A_V/\tau_{9.7}$ = 14.4 and $A_V/\tau_{3.4}$ = 260 for the local ISM.

Apart from WR11, our target stars are heavily reddened (see Table 1) and *ISO*-SWS spectra show silicate and some hydrocarbon *absorption* features:

**Table 2.** Interstellar absorption features

| WR | $\tau_{3.38-3.42}$ litt.[a] | $\tau_{3.38-3.42}$ t.s. | $\tau_{6.2}$ | $\tau_{9.7}$ litt.[b] | $\tau_{9.7}$ t.s | $A_v^c$ [mag] |
|---|---|---|---|---|---|---|
| 11 | - | - | - | - | - | |
| 48a | - | .02 - .03 | .04 | - | .53 | 8.5 |
| 98a | - | .02 - .03 | .04 | - | .62 | 9.9 |
| 104 | .02 -.02 | .02 - .02 | .04 | .32 | .36 | 5.8 |
| 112 | .037-.044 | .02 - .02 | .04 | .65 | .64 | 10.2 |
| 118 | .05 -.052 | .04 - .03 | .06 | .71 | .65 | 10.4 |
| 147 | - | ? - ? | ? | - | .77 | 12.3 |

Notes: $a$: Sandford *et al.* 1995; $b$: Roche & Aitken 1984; $c$: $A_V/\tau_{9.7}$ = 14.4 (Sandford *et al.* 1995) and $A_v$ = 1.11 $A_V$ (Lundström & Stenholm 1984); t.s.: this study.

- 3.4 $\mu$m (although marginally): CH stretching and deformation modes in $CH_2$ (3.42$\mu$m) and $CH_3$ (3.38$\mu$m) groups in saturated aliphatic hydrocarbons (Pendleton *et al.* 1994, Tielens *et al.* 1996). Optical depth values for the 3.4 $\mu$m feature are in reasonable agreement with literature values (Table 2).
- 5.5 $\mu$m: metal carbonyl (C=O) stretching mode (Tielens *et al.* 1996);
- 6.2 $\mu$m: C double bonds (Cohen *et al.* 1989) or OH stretching and bending variations of $H_2O$ (Cohen *et al.* 1989). Since we do not observe a 7.7 $\mu$m feature and this normally goes with the 6.2 feature (Cohen *et al.* 1989), $H_2O$ is the more probable identification, although the absence of the corresponding 3 $\mu$m feature is puzzling.
- 6.8 (6.6-6.7) $\mu$m: CH stretching and deformation modes in $CH_2$ and $CH_3$ groups in saturated aliphatic hydrocarbons (Cohen *et al.* 1989).

Very pronounced is the interstellar 9.7 $\mu$m silicate absorption feature. Optical depth values for the 9.7 $\mu$m feature are in reasonable agreement with literature values (Table 2). The red-wing of the 9.7 $\mu$m feature shows much structure, notably a sharp peak at 11.0 $\mu$m, possibly due to crystalline silicate. The 18 $\mu$m silicate absorption feature is best seen in WR118.

Whether all mentioned absorption features are entirely interstellar or have a circumstellar contribution, is still a question to be settled.

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