Are WC9 Wolf-Rayet stars in colliding-wind binaries?*

P. M. Williams [1], K. A. van der Hucht [2,3] and G. Rauw [4†]

[1]Institute for Astronomy, University of Edinburgh, United Kingdom
[2]SRON Netherlands Institute for Space Research, Utrecht, The Netherlands
[3]Astronomical Institute Anton Pannekoek, University of Amsterdam. The Netherlands
[4]University of Liège, Astrophysics Institute, Belgium

Abstract: We present results from a spectroscopic search for massive companions to dust-making Galactic WC9 stars as a step to testing the paradigm that dust formation in these systems requires colliding winds to produce over densities. We find evidence for OB companions to the WC9 stars WR 59 and WR 65, but not WR 121 or WR 117. We identify lines of N III-V and possibly N II in the spectrum of WR 88, one of the few Galactic WC9 stars which do not make circumstellar dust, and suggest that WR 88 is a transitional WN–WC9 object and less evolved than the other WC9 stars. On the other hand, the possible identification of a strong emission line at 4176Å in the spectrum of WR 117 with Ne I suggests that this star is more evolved than other WC9 stars studied.

1 Wolf-Rayet dust formation and binarity

Infrared observations over the last 30+ years have shown that WC-type Wolf-Rayet stars make dust, but the mechanism for this is still not understood. Studies have shown that dust formation by WR stars requires that their winds contain regions of significantly higher density. These can be provided by shocks in colliding stellar winds (Usov 1991) if the WR stars are members of massive binary systems. Observational support for this process comes from the infrared light curve of the episodic WC7+O5 dust-maker WR 140, which makes dust very briefly during periastron passage when the pre-shock wind density is highest (Williams 1999), and from the rotating 'pinwheels' of heated dust formed by the persistent dust-makers WR 104 (Tuthill, Monnier & Danchi 1999) and WR 98a (Monnier, Tuthill & Danchi 2000), which are considered to be binaries observed at low inclination angle. The presence of heated dust around most WC9 stars then prompts the question: are all dust-making WC9 stars colliding-wind binaries? As a step to answering this question, we observed (Williams & van der Hucht 2000, Paper I) a selection of WC9 stars with the 1.9-m telescope at the SAAO and found absorption lines attributable to companions to the WC9 stars in the spectra of WR 104 and WR 69. We also

*Based on data collected at the European Southern Observatory (La Silla, Chile)
†Research Associate FNRS (Belgium)

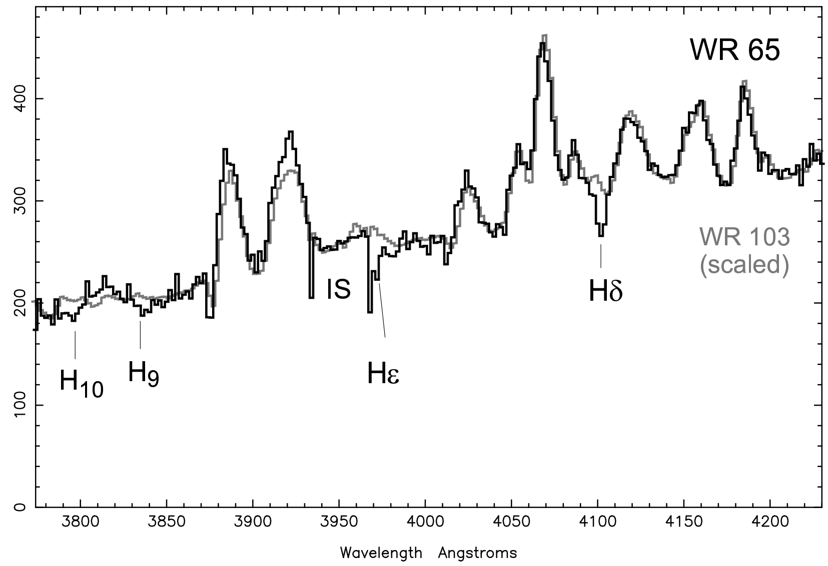

Figure 1: The spectrum of WR 65 compared with that of WR 103 (grey), scaled to match that of WR 65. Balmer lines H_{10}, H_9, $H\epsilon$ (in the wing of interstellar Ca II H) and $H\delta$ are clearly visible in WR 65.

found spectroscopic differences between two non-dusty WC9 stars and the dusty stars in our sample, suggesting a compositional difference having a bearing on dust formation.

Here we report a follow-up of that study, based on medium-dispersion ($\sim$ 1Å) spectra observed with EMMI on the ESO NTT in 2001 June. We used Grating 3 at two settings, centred near 4000Å ('violet') and 4150Å ('blue'), to search for $H\gamma$ and higher-n Balmer and He I absorption lines indicative of OB companions. For our candidates, we included the WC9 stars noted as having diluted emission-line spectra in the VIIth Catalogue (van der Hucht 2001). Because $H\gamma$ and $H\delta$ lie close to emission lines, we found that $H\epsilon$ and H_9, which are located in clearer regions of the spectrum, were good diagnostics despite their relative weakness.

We discovered Balmer absorption lines in our EMMI spectra of WR 59 and WR 65, but not in those of WR 121 or WR 117. The 'violet' spectrum of WR 65 is shown in Fig. 1, where it is compared with the spectrum of WR 103, a well-observed, 'typical' WC9 star. The 'blue' spectrum showed $H\gamma$ absorption. Our spectra of WR 59 are similar to those of WR 65, but also show weak absorption on top of the 4025Å He I + He II and 4472Å He I profiles, and also possibly He I at 4387Å. From the apparent absence of He I absorption in WR 65, its companion may be of earlier subtype than that in WR 59 but further work, using synthetic composite spectra, is needed to estimate strengths of He II lines to classify the companions. Together with Paper I, we have spectroscopic companions to 4/11 WC9 systems observed. Our results suggest we should detect any OB companions at least as luminous as the WC9 stars. The three WC9 stars with known luminosities have $-4.16 \geq M_v \geq -4.97$ (VIIth Catalogue), so there could still be undetected main-sequence OB companions.

Confirmation that the absorption lines do come from a companion require observation of RV shifts attributable to orbital motion. We re-observed WR 69, found to have a companion in our SAAO spectroscopy, and found that there was indeed a relative shift in RVs (absorption – emission) between SAAO and ESO observations, making this star a prime candidate for an orbital analysis.

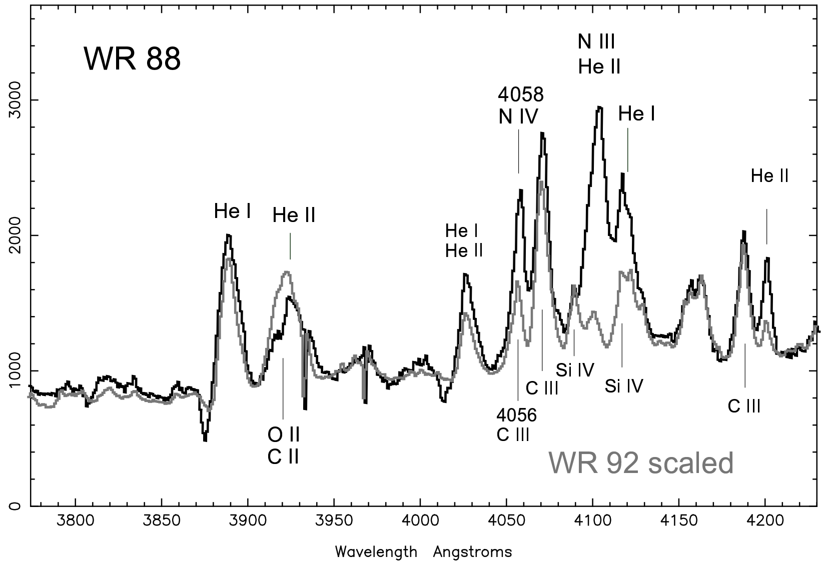

Figure 2: Part of the spectrum of WR 88, compared with that of another dust-free WC9 star, WR 92 (grey), scaled to match the C III lines in WR 88. From comparison of the He II lines, we believe most of the 4101Å line comes from another ion, which we suggest is N III, while from comparison of the C III lines, we suggest that N IV is a major contributor to the line at 4058Å.

2 Spectral diversity: an evolutionary sequence?

We observed in Paper I that the spectra of two WC9 stars (WR 81 and WR 92), which had never (in 20+ years of IR photometry) shown dust emission, differed from the other WC9 stars in having weaker O II (relative to C II), and stronger He II lines, suggesting a compositional difference. Previously, Torres & Conti (1984) had found that the spectrum of the dust-free WC9 star WR 88 differed from those of the other WC9 stars in having stronger He II and weaker C II lines. We re-observed WR 88 with EMMI to see if its O II/C II ratio resembled those of WR 81 and WR 92 in being lower than in dust-forming WC9 stars. Our spectra of WR 88 (the 'violet' spectrum is compared with that of WR 92 in Fig. 2) confirmed the strengths of the lines at 4101Å and 4200Å but other He II lines, e.g. those near 3968Å and 3923Å, are not stronger. We deduce that most of the 4101Å feature in WR 88 must come from another ion, for which we propose multiplet 1 of N III. Multiplet 6 of N III could contribute to He II line at 4200Å and we observe multiplet 17 at 4379Å in our 'blue' spectrum. The 4650Å C III line is stronger and broader in WR 88 and does not have the P-Cygni absorption component seen in WR 92, possibly due to the strong N III 4640Å multiplet. We confirm the identification of the 4603Å line with N V as we also see the 4619Å line of the same multiplet. As shown in Fig. 2, WR 88 appears to have N IV 4058Å blended with C III 4056Å, which is much weaker in WR 92.

We examined the 10-Å resolution spectra of WR 88 and WR 92 in the Torres & Massey (1987) atlas and observed other differences, e.g. the presence in WR 88 of the N IV 5200Å and 7117Å and N V 4933-45Å lines seen in WN stars (cf. Hamann, Koesterke & Wessolowski 1995). We may also be seeing some N II lines in WR 88, but this needs confirmation with higher resolution spectroscopy.

We conclude that WR 88 either has a WN companion or is of a previously unobserved transitional WN–WC9 type, and prefer the latter alternative since the N lines have comparable widths to the C lines, suggesting formation in the same wind. This would make WR 88 less evolved than WR 92 and WR 81, and even less evolved than the dust-making WC9 stars.

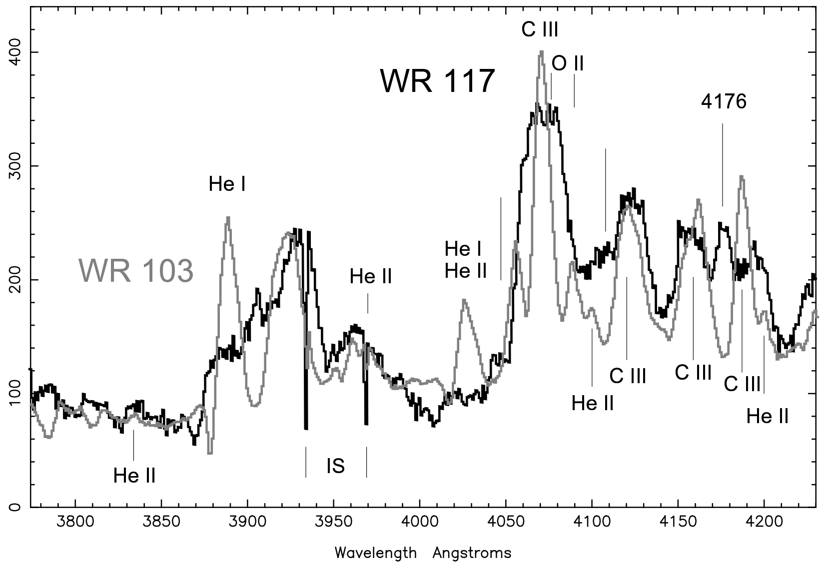

Figure 3: Spectrum of WR 117, compared with that of WR 103 (grey). Note the weakness of the He I lines in WR 117, and the line at 4176Å.

While WR 88, WR 92 and WR 81 appear to be less evolved than most of the WC9 stars, we found one star to be apparently more evolved: WR 117. We had time to observe only a 'violet' spectrum (Fig. 3), which appears to be significantly different from that of WR 103. The lines in WR 117 are broader than in WR 103, but comparisons with another broad-lined WC9 star, WR 53 (Paper I), and the WC8 star WR 135 (Torres & Massey), show similar differences. The feature at 4176Å does not appear to coincide with ions usually seen in WR stars, and we identify it with the $2p^5(^2P^o_{3/2})3p$–$2p^5(^2P^o_{3/2})8d$ array of Ne I (van Hoof 1999). We urgently need spectroscopy in the red to confirm the presence of Ne I, which would make WR 117 more evolved than other WC9 stars. The apparent evolutionary sequence exemplified by WR 88 → (WR 81, WR 92) → (WR 103 etc) → WR 117 needs to be tested by full spectroscopic analyses.

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