

Remarkable spectral variability in WR 104 (WC9): dust condensation in a hostile environment?

P. A. Crowther

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT

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ABSTRACT

We present new observations of the WC9 star WR 104 (Ve 2–45), collected in 1996 July at the 2.5-m Isaac Newton Telescope, which reveal unprecedented spectral and photometric variations. Relative to previous observations by Torres & Massey, we find a simultaneous visual fading by ~ 1.1 mag, plus the disappearance of high-ionization spectral features (He II, C IV) with low-ionization features (He I, C II) relatively unchanged. We interpret this behaviour as obscuration of the inner Wolf–Rayet wind by a dust cloud condensation, analogous to R CrB stars, and recently proposed to explain occasional eclipses in other WC9 stars. Non-LTE model calculations for the WC9 component indicate a cloud diameter $\gtrsim 60 R_{\odot}$ ($20 R_{*}$) – far smaller than in R CrB stars – probably formed at a radius beyond $300 R_{\odot}$ ($100 R_{*}$). We detect the definite presence of a companion OB star which may facilitate the necessary conditions for dust formation via shocks.

Key words: circumstellar matter – stars: individual: WR 104 – stars: Wolf–Rayet – dust, extinction.

1 INTRODUCTION

Dust is found in a variety of astrophysical environments, including the ‘mild’ conditions of carbon-rich asymptotic giant branch (AGB) stars and the ‘harsh’ environments of R Coronae Borealis (R CrB) stars and Wolf–Rayet (WR) stars (see review by Beck & Sedlmayr 1997), and is unique to late-type WC (WCL) stars in the latter (Williams 1995).

Williams, van der Hucht & Thé (1987) studied the permanent dust shells of many WCL stars, located at several hundred stellar radii from the central star, while Veen et al. (1997) have recently proposed that dust cloud condensations situated much closer to the star are responsible for the visual eclipses occasionally observed in WC9 stars (e.g. Massey, Lundström & Stenholm 1984). Deep eclipses observed in cooler R CrB stars are attributed to a similar cause, the cloud possibly being as close as 2 stellar radii (for a review see Clayton 1996). The formation, and persistence, of grains in these extreme environments represents a major problem, since temperatures are anticipated to exceed greatly the required condensation temperature of ≤ 2000 K. Shocks caused by pulsations (for R CrB stars) or wind–wind

collisions (WC stars) may provide the necessary conditions for dust formation (Usov 1991; Woitke, Goeres & Sedlmayr 1996).

WR 104 (Ve 2–45; Velghe 1957) is the brightest WR star in the mid-infrared as the result of a huge, circumstellar dust shell, the properties of which have been widely investigated (e.g. Allen, Swings & Harvey 1972; Williams et al. 1987). Speckle observations allowed Dyck, Simon & Wolstencroft (1984) to obtain a dust shell radius of $\geq 20\,000 R_{\odot}$, with a characteristic temperature of 200–1000 K (van der Hucht et al. 1996). Cohen, Barlow & Kuhl (1975) argued that most of the extinction was actually circumstellar, so that we may be viewing the WR 104 system edge-on. However, since the central star suffers from a substantial visual extinction ($A_V = 6.5$ mag; Pendleton et al. 1994), it is relatively faint in the visual ($v = 13.5$), and consequently optical spectroscopy has rarely been carried out.

In this Letter we present new spectrophotometry for WR 104 in Section 2, revealing unprecedented spectral and photometric changes, which we interpret in Section 3 as condensation of a dust cloud relatively close to the WC9 star. Constraints on this cloud are provided by non-LTE model atmosphere calculations.

2 DRAMATIC VARIABILITY IN WR 104

2.1 Spectroscopic observations

New observations of WR 104 were obtained with the 2.5-m Isaac Newton Telescope (INT), La Palma, using the Intermediate Dispersion Spectrograph plus the 235-mm camera and a 1024×1024 Tektronix CCD during 1996 July 20–21. Two overlapping settings, with exposures of 600 and 1200 s (blue) and 600 s (red), provided complete spectral coverage in the range $\lambda\lambda 3620$ – 6810 at a two-pixel spectral resolution of $3.0 \text{ \AA}$ using a 600 line mm^{-1} grating. Observations were de-biased, divided by a normalized flat-field, and optimally extracted using the PAMELA (Horne 1986) routines within FIGARO (Meyerdierks 1993). The spectra were wavelength-calibrated using Cu–Ar arc lamps. An absolute flux calibration was obtained by obtaining a short exposure of WR 104 and the flux standard BD + 33° 2642 on July 20 covering $\lambda\lambda 3610$ – 7020 , using a 5 arcsec wide slit (1.3 arcsec seeing) and 300 line mm^{-1} grating. No noticeable spectral variability was detected over the course of our data set, which commenced at UT 21:00 on July 20 and ended at UT 21:30 on July 21.

2.2 Comparison of spectroscopy with previous observations of WR 104

We present our INT spectrophotometry of WR 104 in Fig. 1, and contrast it with flux-calibrated observations of WR 104 presented by Torres & Massey (1987). WR 104 has clearly undergone a dramatic fading plus a spectral change to (apparently) lower ionization between the two observations. Spectroscopy from Torres & Massey (1987) reveals a normal WC9 spectrum, except for relatively weak emission lines. Their blue spectroscopy ($\lambda\lambda 3420$ – 4730) was obtained with the 1.5-m Cerro Tololo Inter-American Observatory (CTIO) telescope on 1982 February 18 and 1983 April 24,

while their red spectra ($\lambda\lambda 4350$ – 6900) were obtained at an unknown earlier epoch at the 4.0-m CTIO telescope (see Torres & Conti 1984). Cohen & Kuhl (1977) presented earlier spectroscopy of WR 104 which compares relatively closely to that of Torres & Massey (1987).

In contrast, our observations reveal a spectrum in which high-ionization (He II and C III–IV) features are either absent or extremely weak, while features from low-ionization stages (He I and C II) are relatively unaffected. We illustrate this in Table 1, where measurements of the principal emission-line features are compared. Of the high-ionization stages, the average equivalent widths from the INT are only 6 per cent ($\sigma=2$ per cent) of the strength of the CTIO data sets, in contrast to 47 per cent ($\sigma=15$ per cent) for low-excitation lines. While the widths of the latter had remained constant, the FWHM (C III $\lambda 5696$) reduced from

Table 1. Emission-line strengths (equivalent widths in $\text{\AA}$) measured in our INT observations of WR 104, plus those from CTIO observations by Torres & Massey (1987), where high- and low-ionization features are marked accordingly.

Spectral Ion	Feature λ ($\text{\AA}$)	CTIO 1982-83	INT 1996	INT/CTIO	
C II	4267	9.5	2.7	0.28	Low
C III	4325	8.0	<0.5	<0.06	High
C III	4647-51	46.7	4.0	0.09	High
He II	4686	11.4	<0.8	<0.07	High
O III	5592	2.6	0.2	0.07	High
C III	5696	64.9	3.5	0.05	High
C IV	5801-12	22.2	<0.1	<0.01	High
He I	5876	17.7	10.3	0.58	Low
C II	6578-82	53.0	32.3	0.61	Low
He I	6678	7.1	3.9	0.55	Low
C III	6727-62	18.9	<1.0	<0.05	High
C II	6780-91	15.3	5.0	0.33	Low

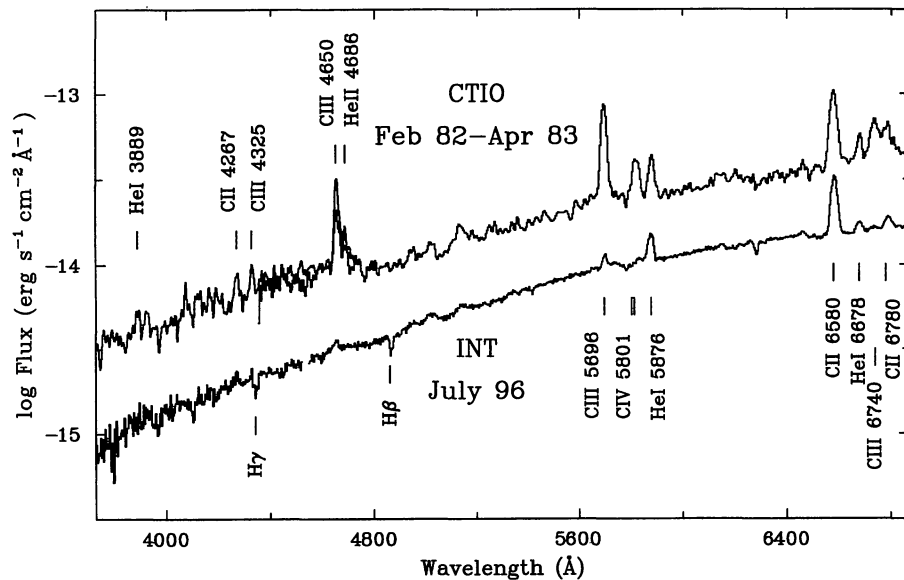


Figure 1. Comparison of spectrophotometry of WR 104 obtained at the INT in 1996 July with observations presented by Torres & Massey (1987) from 1982 February–1983 April, showing its dramatic spectroscopic and photometric variability.

27 to 17 Å. In addition, Balmer absorption features (H β and H γ) are conspicuous in our INT observations, indicating the presence of an OB companion (see Section 2.3). From the appearance of WR 104 during 1996 July, the resulting classification is WC11, following the recent quantitative scheme of Crowther, De Marco & Barlow (1997).

Substantial evidence for previous spectral variability exists from published spectroscopy of WR 104. Indeed, the red CTIO observations of Torres & Massey (1987) reveal considerably stronger C III λ 4650 and He II λ 4686 profiles than in their blue data (see also Lundström & Stenholm 1984a). Allen et al. (1972) remarked that the C II λ 4267 profile was the most prominent spectral feature in their blue observations (also true for the INT data set), yet Torres & Massey (1987) and Williams & van der Hucht (1996) show emission features from higher ionization stages (e.g. C III λ 4069, 4325) which are equally strong. Despite the limited data sets available, WR 104 has clearly displayed various degrees of spectral variability over the past 20 years, with the nearest spectroscopy to our own obtained by Williams & van der Hucht (1996) one year earlier.

Regarding the photometric history of WR 104, we compare narrow-band photometry (Smith 1968) obtained here with previous measurements in Table 2. For spectrophotometric data sets, synthetic photometry was obtained by convolving each data set with suitable Gaussian filters. Our data imply a fading by $\Delta v = 1.07$ mag and an increase in colour index of $\Delta(b-v) = 0.24$ mag. Unfortunately, we are unable to discuss the possible optical photometric variability further, owing to the scarcity of photometric observations, although we note that no evidence exists for significant near-infrared variability (Williams et al. 1987; van der Hucht et al. 1996).

2.3 A binary nature for WR 104?

Several WC + O binaries are known to form dust episodically at periastron, where the interaction between their winds is at its greatest, as discussed by Usov (1991, 1995). Cohen et al. (1975) and Cohen & Kuhl (1977) proposed a possible binary nature for WR 104, since its emission lines were observed to be weaker than in other WC9 stars. Further evidence for a binary nature for WR 104 has been presented by Williams & van der Hucht (1996), who identified weak hydrogen Balmer absorption features in its blue spectrum, which we confirm by their clear appearance in our INT data set (Fig. 1). We have obtained an estimate of the dilution from the companion by comparing the strengths of selected V -band optical emission lines (from Torres & Mas-

sey 1987) with those in WR 103 (HD 164270), and find $W_{\lambda}(\text{WR 104})/W_{\lambda}(\text{HD 164270}) = 0.33$ ($\sigma = 0.01$), indicating WR:OB $\sim 1:2$, supporting the results of Cohen & Kuhl (1977).

WR 104 is considered to be a possible member of Sgr OB1 (Lundström & Stenholm 1984b), which lies at a distance modulus of 11.0 mag (Humphreys 1978). The interstellar and circumstellar reddening towards WR 104 is $E(B-V) = 2.1$ mag (Pendleton et al. 1994). Our observations support this high reddening, since a combination of the observed colour index $(b-v) = 1.65$ mag with $(b-v)_0 = -0.20$ mag (obtained from our theoretical flux distribution in Section 3.1) reveals $E(B-V) = 2.25$ mag (following Turner 1982). Assuming the former value, the systemic absolute magnitude for WR 104 is $M_v = -4.5$ mag based on the spectrophotometry of Torres & Massey (1987) and assuming WR:OB $\sim 1:2$ in the v band; we find $M_v^{\text{WR}} = -3.3$ mag and $M_v^{\text{OB}} = -4.1$ mag, the latter consistent with a late O or early B dwarf (e.g. Vacca, Garmany & Shull 1996).

3 INTERPRETATION OF VARIABILITY

What is the cause of the observed variability in WR 104? Could we merely be observing the WC9 component occulted by the OB star? From a spectroscopic point of view this is certainly feasible, although the corresponding photometric change would be ≤ 0.4 mag from the relative brightness of the OB companion to the WC9 star (Section 2.3), and we will show that the region obscured is much larger than the disc of the companion. We are therefore left with the possibility that, as in R CrB eclipses, additional dust must be obscuring the system, an idea which we shall now pursue.

3.1 Temporary dust formation close to WR 104?

Veen et al. (1997) have recently presented a study involving the temporary formation of a dust cloud that represents occultations of up to ~ 1 mag in other WC9 stars. Unfortunately the duration of the 1996 July occultation of WR 104 is unknown. Indeed, the only comparable eclipse depth to WR 104 that Veen et al. (1997) analysed was a 1980 occultation of WR 103 ($\Delta v = 1.2$ mag) for which a dust cloud condensation was proposed at a radius of $\sim 150 R_{\odot}$. The observed colour change of $\Delta(b-v) = 0.24$ mag for WR 104 suggests that the dust grains are large [$0.15 \mu\text{m}$ according to calculations carried out by Veen (private communication)] as expected theoretically (Rawlings & Williams 1989).

The spectroscopic variability of WR 104 provides important information relating to the dimensions of such a dust cloud. However, we first need to estimate the physical properties of the WC9 stellar wind. To date, no Population I WC9 stars have been the subject of a detailed analysis. We have therefore used the iterative, non-LTE technique of Hillier (1990) to derive the approximate physical properties of the WC star based on the spectroscopy of Torres & Massey (1987).

A detailed description of the analysis technique is given by Crowther, Hillier & Smith (1995), while additional information for WCL stars is provided by De Marco & Crowther (in preparation). We assume spherical symmetry, homogeneity, a wind velocity of 1220 km s^{-1} (Howarth & Schmutz

Table 2. Photometric history of WR 104, including our measurements of the spectrophotometric observations of Torres & Massey (1987), who noted that the continuum flux levels of their blue and red spectra disagreed by 10 per cent (apparent from Fig. 1).

Source	Epoch	v mag	$(b-v)$ mag
Smith (1968)	1964-1966	13.54	1.31
Torres & Massey (1987)	1982-1983	13.68	1.41
This work	1996	14.75	1.65

1992), $M_p = -3.3$ mag, a light ratio of WR:O=1:2 in the v band and C/He=0.5, O/He=0.1 by number. We derive approximate parameters $T_* \sim 45$ kK ($T_{\text{eff}} = 35$ kK), $R_* = 3 R_\odot$, $\log L/L_\odot = 4.6$ and $\log \dot{M}/(M_\odot \text{ yr}^{-1}) = -4.5$ for the WC9 star using He I $\lambda 5876$, C III $\lambda 5696$ and C IV $\lambda 5801-12$ as spectral diagnostics, allowing for the contamination of the OB star. In contrast, Williams et al. (1987) estimated a stellar radius a factor of 5 larger for WR 104. We also find significant differences compared with the only previous non-LTE study of WR 104 by Howarth & Schmutz (1992), since they assumed that WR 104 was single, was composed purely of helium and had a stellar temperature of only 30 kK.

By considering the regions of the stellar wind over which different spectral features are formed, we are now able to estimate the size of the dust cloud. In Fig. 2 we present line formation regions for helium (He I $\lambda 5876$, He II $\lambda 4686$) and carbon (C II $\lambda 4267$, C III $\lambda 5696$, C IV $\lambda 5801-12$). The (highly obscured) features from high-ionization stages are formed close to the stellar core ($\lesssim 5R_*$), while the (partially obscured) lines from low stages are formed at significantly greater distance ($5-30R_*$). Therefore we propose that the observed variability in WR 104 is as a result of dense condensation of dust grains in a cloud with diameter $\gtrsim 20R_*$ ($60 R_\odot$). Thus the dust cloud appears to be relatively small, unlike the huge condensations producing very deep eclipses in R CrB stars (see the review by Clayton 1996).

Since the permanent outer dust shell of WR 104 appears relatively constant (van der Hucht et al. 1996), it must be regularly replenished, probably via dust clouds carried out at high velocity by the WC stellar wind. The frequency of such clouds must be fairly high, although eclipses would be observed infrequently along a particular line of sight. Veen et al. (1997) estimated that condensations take place typically every week, with a recurrence time-scale of 5 yr along

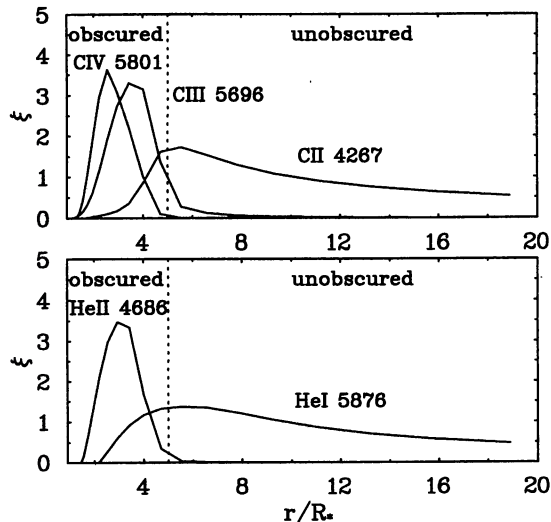


Figure 2. Line formation regions for selected optical carbon and helium lines from our WC9 model atmosphere in terms of the stellar radius ($R_* = 3 R_\odot$). ξ is defined (Hillier 1987) so that its integrated area is normalized to unity. We have indicated the approximate boundary (dotted line) between lines that are obscured during eclipse ($< 5R_*$) and those that are relatively unaffected.

one line of sight. The probable edge-on dust shell geometry of WR 104 may lead to more frequent eclipses, as suggested from the abundance of spectral variability reported in the literature.

3.2 Grain formation in very harsh conditions

Most theoretical effort on dust condensation around stars has related to carbon-rich (and H-rich) AGB stars, the envelopes of which are dense and cool enough to allow for the nucleation of polycyclic aromatic hydrocarbon molecules as dust precursors. Beck & Sedlmayr (1997) conclude that dust formation in WC winds is impossible in a spherical, homogeneous outflow, which is actually assumed in our present analysis! For the large circumstellar dust shells of WCL stars, low densities (Williams et al. 1987) may be overcome by shocks produced by the interaction of stellar winds in a WC + OB system, in an analogous manner to R CrB stars (Usov 1991; Woitke et al. 1996). However, very little quantitative work has been carried out to date (see Cherchneff & Tielens 1995), and other dusty WC9 stars (e.g. WR 103) show no evidence for a luminous companion.

Veen et al. (1997) require the formation of dust clouds very close to the intense UV radiation field of the WR star to reproduce the observed eclipses, where conditions are *far* from ideal. For example, at a radius of $100R_*$ ($300 R_\odot$) from the WC9 component of WR 104, which is twice the distance derived by Veen et al. for the deep eclipse of WR 103, our wind model predicts $T_e \sim 7500$ K ($\log N_e \sim 8.5 \text{ cm}^{-3}$) with a wind composed of *singly ionized* helium, carbon and oxygen! Soon beyond this region the electron temperature reaches its asymptotic value, so that 10 times further out the predicted wind temperature has still only dropped to $T_e \sim 7000$ K ($\log N_e \sim 6.5 \text{ cm}^{-3}$), with helium now on the point of recombining to a neutral state. Of course, in a strongly clumped or shocked outflow, large departures from these parameters will be achieved. Clumped winds are now well established in WR winds (Moffat 1996), and may provide the opportunity for more favourable conditions for nucleation and grain growth via shielding.

The presence of carbon ions in the dust condensation zone would significantly influence the standard model for dust formation, since it is based on neutral monomers. The nucleation of carbon from ionized precursors has not yet been investigated (Beck & Sedlmayr 1997). Should the necessary temperature and density conditions be met via clumping or shocks, amorphous carbon dust formation¹ requires the presence of *non-pure* carbon molecules (heterogeneous nucleation), probably involving hydrocarbons (Rawlings & Williams 1989). Since hydrogen is not present in the stellar wind of the WC9 component, perhaps the H-rich wind of the OB star is necessary to facilitate such chemistry?

In summary, we suggest that the observed variability of WR 104 can be naturally explained through the occultation

¹The presence of amorphous carbon has been deduced in WR 104 by Williams et al. (1987). An emission feature at $7.7 \mu\text{m}$ identified as a carbonaceous carrier by Cohen, Tielens & Bregman (1989) was not confirmed in recent *ISO* spectroscopy (van der Hucht et al. 1996).

of the system by a dust cloud condensation, with a measured dimension $\gtrsim 20R_*$, (probably) taking place beyond $100R_*$, with the permanent dust shell at a radius of $(3000-300\,000)R_*$ (Williams et al. 1987). Intensive spectroscopic and photometric monitoring of WR 104 should be keenly sought, despite its visual faintness, and would provide further constraints on (i) the precise region in which the dust cloud forms, (ii) the period and orientation of the WC9 + OB system, and (iii) the (still uncertain) role played by the OB star in dust formation.

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