Wolf-Rayet Stars
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The colliding-wind WC9+OB system WR 65 and dust formation by WR stars

P. M. Williams[1] & K. A. van der Hucht[2]
[1] *University of Edinburgh, Royal Observatory, Edinburgh, United Kingdom*
[2] *SRON Utrecht and University of Amsterdam, The Netherlands*

Observations of the WC9+OB system WR 65 in the infrared show variations of its dust emission consistent with a period near 4.8 yr, suggesting formation in a colliding-wind binary (CWB) having an elliptical orbit. If we adopt the IR maximum as zero phase, the times of X-ray maximum count and minimum extinction to the hard component measured by Oskinova & Hamann fall at phases 0.4–0.5, when the separation of the WC9 and OB stars is greatest. We consider WR 65 in the context of other WC8–9 + OB stars showing dust emission.

1 Identification of WR 65 as a colliding-wind binary

From 1.2–9.7-μm infrared (IR) photometry, Williams et al. (1987) found that WR 65 (LSS 3319), like most of the then-known WC9 stars, had a circumstellar dust cloud which, in this case, absorbed and re-emitted about 3% of its stellar flux in the IR.

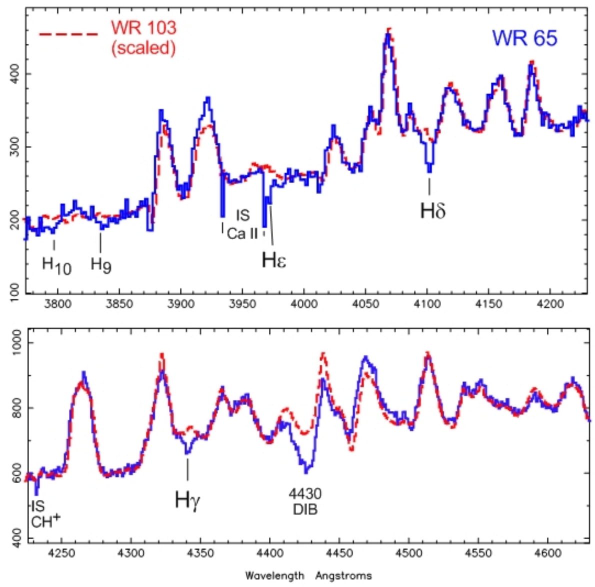

Fig. 1: Spectra of WR 65 and WR 103 observed with the ESO EMMI on the NTT. The interstellar lines in WR 65 are stronger on account of its higher reddening ($A_v \simeq 7.6$).

Spurred by the episodic formation of dust by the WC7+O5 binary WR 140 (Williams et al. 1990) at periastron when its components reached a critical separation, we suggested (Williams & van der Hucht 1992) that the persistent WC8–9 dust makers might also be binaries, but in circular orbits having stellar separations conducive to dust formation – as beautifully confirmed by the rotating dust 'pinwheel' made by the prototypical WC9 dust maker WR 104 (Tuthill et al. 1999) – and we began a spectroscopic survey of WC9 stars in the blue using the SAAO 1.9-m telescope and the ESO NTT to search for absorption lines attributable to OB companions. Amongst the WC9 stars found (Williams et al. 2005) to show Balmer absorption lines in their spectra was WR 65 (Fig. 1), making it a candidate SB2. From dilution of the WC9 emission-line spectrum, van der Hucht (2001) suggested that the OB star was 0.4 mag. brighter than the WC9 star.

Evidence that WR 65 might be a colliding-wind binary came from the variable X-ray emission observed by Oskinova & Hamann (2008). They fitted a $2T2N_H$ plasma model, and found that the column density to the 'hard' component varied with epoch, consistent with the movement of an embedded colliding-wind source in the WC9 wind.

We therefore examined the IR photometric history of WR 65. Besides the 1983 observations in Williams et al. (1987) and those by Pitault et al. (1983) in 1982, eight more sets of $JHKL$ photometry were observed at ESO during 1990–93 as part of another programme. Four of these observations were taken on successive nights in 1991 and the last of them shows brightening (0.09-mag. in JHK, less in L and M), suggesting a mini-outburst like those observed from WR 137 (Williams et al. 2001). Latterly, iJK_s were observed in the DENIS survey (Epchtein et al. 1999) in 1998 and JHK_s in the 2MASS survey (Skrutskie et al. 2006) in 1999. These J and K_s magnitudes are significantly brighter than any of the earlier J and K, suggesting occurrence of an IR maximum in 1998–99. For comparison with the L data, we determined [3.6] magnitudes from the pipeline-processed *Spitzer* IRAC frames observed in 2004 and 2012. We searched for a period in these rather sparse data following Lafler & Kinman (1965). As the dates of the DENIS and 2MASS K_s band observations were different from those of the [3.6] magnitudes, there is a small difference in the cadence of the K/K_s and $L/[3.6]$ datasets and we sought matching minima in the L–K statistic Θ from both of them. This is shown in Fig. 2, from which we adopt a tentative period of 4.8±0.2 yr.

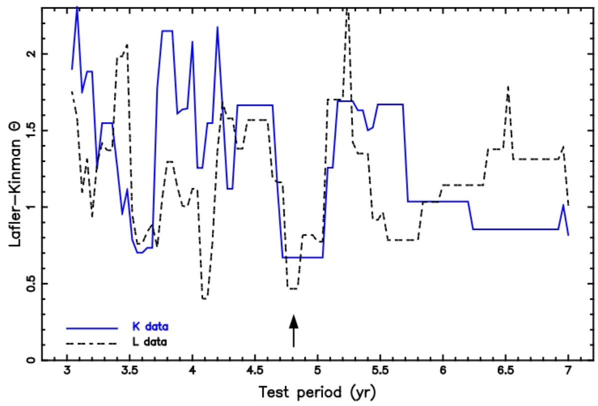

Fig. 2: Lafler-Kinman period search on K and L-band photometry with adopted 4.8-yr period marked (↑).

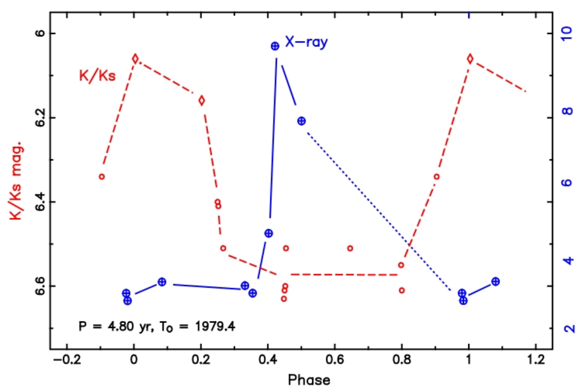

Fig. 3: IR K (○) and K_s (◇) photometry together with X-ray count rates (⊕) from Oskinova & Hamann (2008), all phased to a period of 4.8 yr and taking 1979.4 as zero. (The straight lines joining the observations are drawn just to guide the eye.)

The phased IR (K) magnitudes and X-ray count rates are plotted in Fig. 3 using our IR period of 4.8 yr and arbitrarily adopting $T_0 = 1979.4$, so as to place the brightest IR flux, the DENIS observation, at phase zero. The IR maximum is broad but poorly defined; more IR observations are needed to define the IR light curve and period. At minimum, the IR spectral energy distribution (SED) still shows dust emission. The X-ray emission remains faint during IR maximum, when the wind-collision source would have been most deeply buried in the WC9 wind. The rise to X-ray maximum corresponding to minimum column density to the 'hard' component occurs as the system approaches apastron, but the steepness of the rise suggests that we are observing it through a hole in the WC9 wind formed by the O star wind sweeping through our line-of-sight. Further X-ray observations are needed to define the light curve and map the wind-collision region (WCR). Above all, we need an orbit to allow a comprehensive picture to be developed. The period near 4.8 yr makes WR 65 a tractable source for a study on a reasonable time-scale; it is the only WC9 system known to have periodically variable dust emission (cf. Table 1).

Colliding stellar winds can also produce non-thermal radio emission, observable if the WCR lies sufficiently far out in the stellar wind, especially in wide, long period systems. The observable emission may vary during the orbit (Dougherty & Williams 2000) in systems of intermediate period. Our suggested 4.8-yr period lies in that range. The marginal 3.5-cm detection (0.37±0.14 mJy) by Leitherer et al. (1997) is consistent with the free-free emission from the wind of WR 65, 0.35 mJy, which we estimated by scaling the observed flux from γ Vel to the distance (3.3 kpc) of WR 65. The date of the observation corresponds to phase 0.31 on our suggested ephemeris, when the low X-ray flux implies that the wind extinction to the WCR and any non-thermal radio source is still high. We suggest that re-observation at a more favourable phase may well reveal non-thermal radio emission from WR 65.

Tab. 1: Wolf-Rayet stars showing periodic dust emission. The IR photometric periods of WR 140 and WR 137 are supported by RV periods (Fahed et al. 2011; Lefèvre et al. 2005) and that of WR 98a by its pinwheel rotation (Monnier et al. 1999).

WCE (P/yr)	WC7 (P/yr)	WC8 (P/yr)	WC9 (P/yr)
HD 36402 (4.7)[a]	WR 140 (7.94)[b]	WR 98a (1.54)[c]	**WR 65** (∼ 4.8)
WR 19 (10.1)[d]	WR 137 (13.05)[e]	WR 48a (∼ 32)[f]	

Refs: [a] Williams et al. (2013); [b] Williams et al. (1990); [c] Williams et al. (2003); [d] Veen et al. (1998); [e] Williams et al. (2001); [f] Williams et al. (2012)

2 Relation to other persistent dust-making WC8–9 stars.

From their 'pinwheel' images of WR 104, Tuthill et al. (2008) showed that the dust was made by stars moving in a circular orbit and that the IR flux, and hence dust formation rate, did not vary with orbital phase. Also, the long-term (1982–1997) photometric history of WR 104 from 14 observations show a dispersion of only $\Delta K = 0.04$ mag. We have compiled long-term IR photometric histories of 12 other WC8–9 dust-makers. The only one to show systematic variability is WR 112 (CRL 2104), which may have a period near 12.3 yr (Fig. 4). This period is consistent with its dust 'pinwheel' and a plausible expansion velocity (Marchenko et al. 2002) with a revised distance ~ 2 kpc (Marchenko & Moffat 2007). The low orbital eccentricity inferred from its dust 'pinwheel' is consistent with the low amplitude of its IR variations compared with those ($\Delta K > 1$) of the high eccentricity binaries WR 140 (Fahed et al. 2011) and WR 19 (Williams et al. 2009).

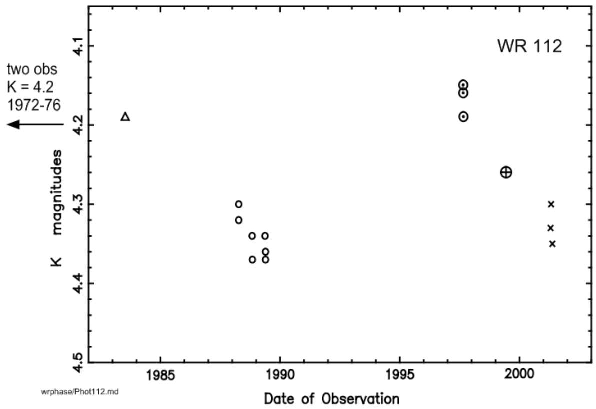

Fig. 4: Photometry of WR 112 from Williams et al. (1987) (△), new observations at ESO (∘) and with the Carlos Sánchez IR Telescope (⊙), from the 2MASS Catalogue (⊕) and by Kimeswenger et al. (2004) (×). We do not have dates for the earliest observations by Merrill & Stein (1976) and Allen et al. (1977).

The long-term photometry of another 'heavy' dust maker, WR 118, shows a dispersion $\Delta K = 0.11$ mag. but with no apparent periodicity. Two other dust-making WC9 stars found to have Balmer absorption lines (Williams et al. 2005), WR 59 and WR 69, have smaller dispersions in their photometric histories and we suggest that they are binaries in (near) circular orbits. The same might apply to other WC9 stars showing steady dust emission, which might be undetected binaries, especially if the WC9 stars are more luminous than currently thought, making it harder to detect composite spectra. There is a strong case for RV studies of these objects to search for orbital motion.

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Andy Pollock: Does the correlation between ΔK and e imply common physical conditions at periastron?

Peredur Williams: I think it is more a question of the contrast of conditions between periastron and the rest of the orbit.

Anthony (Tony) Moffat: In recent NIR surveys for Galactic WR stars, a large number of WC9 stars is showing up in the central part of the Galaxy. This may lead to a more significant source of dust in the Galaxy than thought previously. Do you agree?

Peredur Williams: Yes, there are dust makers amongst the newly discovered WC9 stars, but to get the significance of the contributions of WC9 stars to dust in the Galaxy, I would want to know the number of AGB stars in the same volume.