ACTIVE DUST FORMATION BY POPULATION I WOLF-RAYET STARS

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Abstract

We review studies of heated dust formation around Wolf-Rayet stars, observed in the near-IR with ground-based $JHKL'M$ photometry and in the IR with *ISO*-SWS spectroscopy. Episodes of fresh dust formation with intervals of the order of ten years has been discovered for three WC+O colliding wind binaries, episodic and variable persistent dust formation has been found for four other WC+O candidate binaries, and persistent dust formation is known for 19 WC8-9 stars. Of the last two categories two stars have been imaged in the near-IR, showing pin-wheels in the sky with rotation periods of the order of 1-2 yr. This suggests that perhaps all dusty WC stars are binaries.

Dust formation is the least understood of all phenomena associated with colliding stellar winds in WC+OB binaries, including non-thermal radio emission and variable X-ray and $\gamma-$ray emission. While the latter two phenomena are associated with the apex of the wind-wind collision cones, dust formation occurs in the wake of the collision cones, at distances of a few hundred stellar radii away from these hot evolved massive binaries. After formation, the dust is being carried away by the WC stellar winds and cools gradually to interstellar temperatures. The cooling dust radiation emission affects the wavelength regions where *FIRST* will observe.

Key words: Stars: Wolf-Rayet – Stars: dust formation

1. Introduction

Wolf-Rayet (WR) stars are characterized by strong He, N, C and O emission lines, originating in their hot stellar winds with terminal velocities $v_\infty \simeq 400$–$5000\,\mathrm{km\,s^{-1}}$, driving mass loss rates of the order of $\dot{M} = 10^{-5}\,\mathrm{M_\odot yr^{-1}}$. Both the emission-line spectrum and the free-free μm–cm continuum emission, causing an IR–radio 'excess' over a hot stellar photospheric spectrum, are formed within the WR winds; together with, in the case of some 26 WC stars, dust whose emission causes a further IR excess. The facts that among the WR sequences only WC stars have been observed to produce dust (and *not any* WN star), and that is has been established that the WC star dust is amorphous carbon (Williams *et al.* 1987a) are consistent with the large carbon abundance expected during the WC phase in the evolution of massive stars (Maeder & Meynet 1994).

Ground-based near-infrared photometry since the early 1970-ies has led to the discovery of this heated dust formation, primarily around WCL stars (Williams *et al.* 1987a), a astrochemical process which is not yet fully understood (Cherchneff *et al.* 2000).

In a near-IR photometric survey conducted during the past two decades by two of us (PMW and KAvdH), 145 WR galactic stars were monitored. The colour-colour diagram in Fig. 1 clearly separates the WR stars with heated circumstellar dust ($\sim 30\,\%$ of the galactic WC stars) from the non-dusty WR stars.

For the 26 WC stars known to have IR dust signatures, van der Hucht (2001) introduced as classification:

- WCd (persistent dust formation),
- WCvd (variable persistent dust formation),
- WCpd (periodic dust formation), and
- WCed (episodic dust formation).

Table 1 lists the dusty WC stars in those categories, and shows that primarily WC9 and WC8 stars carry the dust phenomenon. The only three known dust-free WC9 stars, WR 81, WR 88 and WR 92, have in their optical spectra anomalously weak O II emission lines and strong He II

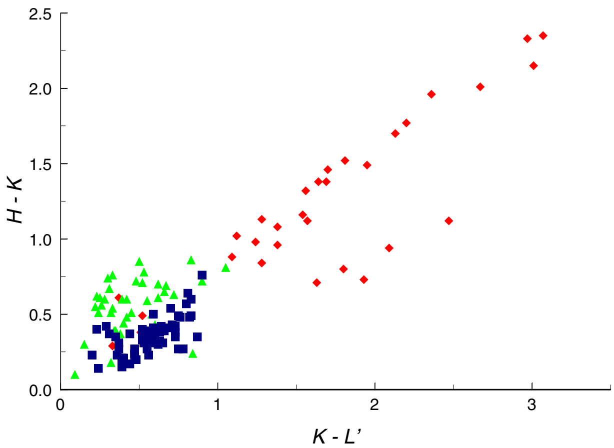

Figure 1. H–K versus K–L′ for 145 galactic WN (■), WC (▲) and WCd (♦) stars (from van der Hucht et al. 2001).

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Table 1. WC stars: the incidence of heated CS dust per subtype (after Williams 1995).

type	persistent dust formation (WCd)	variable dust formation (WCvd)	periodic dust formation (WCpd)	episodic dust formation (WCed)
WC4			WR 19	
WC7			WR 137, 140	WR 125
WC8	WR 53, 113	WR 98a		WR 48a
WC9	WR 48b, 59, 65, 69, 73, 76, 80, 95, 96, 103, 104, 106, 112, 117, 118, 119, 121	WR 70		

Note: The WC9 stars WR 81, WR 88 and WR 92 did not show dust formation in two decades of IR photometric monitoring.

emission lines, as compared to WC9d stars (Williams & van der Hucht 2000).

Sizes and structure of those circumstellar dust envelopes have been measured in the near-infrared: by speckle interferometry for WR 104 (Allen *et al.* 1981; Dyck *et al.* 1984); by lunar occultation for WR 112 (Ragland & Richichi 1999); directly with *HST*-NICMOS for WR 137 (Marchenko *et al.* 1999); and by near-IR image-masking interferometry for WR 98a (Monnier *et al.* 1999) and WR 104 (Tuthill *et al.* 1999, 2001), who observed in the K-band heated dust diameters of the order of 150 AU.

2. Persistent dust formation

Persistent dust formation is a common feature for ~90% of the WC9 stars and ~50% of the WC8 stars in the sample ($K < 9$ mag) studied by Williams *et al.* (1987a).

ISO-SWS IR spectra (van der Hucht *et al.* 1996; Williams *et al.* 1998) given in Fig. 2 show the spectral energy distributions of three persistent WC8-9d stars: WR 104, WR 112 and WR 118. The SEDs are fairly smooth, apart from the ubiquitous interstellar 9.7-μm and 18-μm silicate absorption features and a narrow, probably also interstellar, absorption feature at 6.2 μ, attributed to aromatic compounds (Schutte *et al.* 1998).

Persistent dust formation appears to be a colliding wind effect in long-period ($100\,\mathrm{d} < P < 1000\,\mathrm{d}$) WC+OB binaries, as demonstrated by Tuthill *et al.* (1999, 2001) and Monnier *et al.* (1999) in time-series of high-spatial resolution near-IR imaging of WR 104 and WR 98a, respectively.

3. Episodic/periodic dust formation

Episodic and periodic dust formation has been observed among some seven WC8, WC7 and WC4 stars and appears to be a colliding wind effect in very-long-period

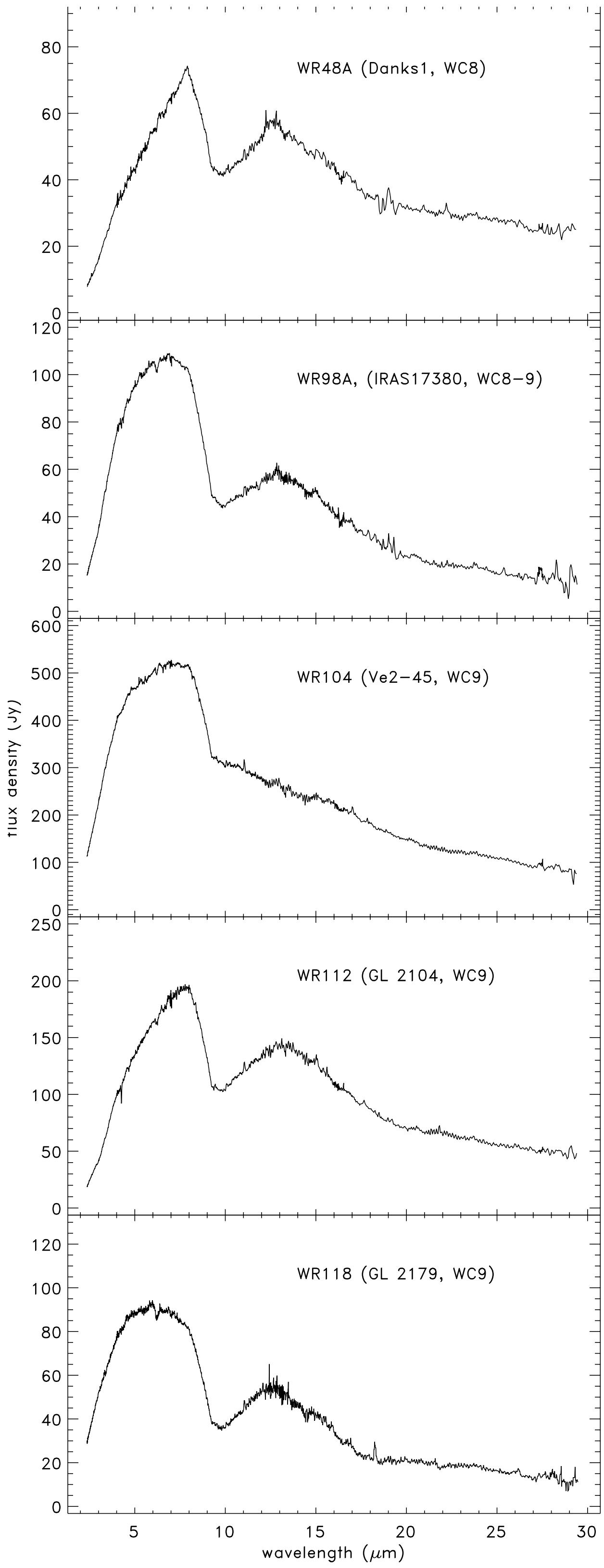

Figure 2. ISO-SWS spectra of the late-type WCd stars WR 48a, WR 98a, WR 104, WR 112, and WR 118 (from van der Hucht et al. 1996).

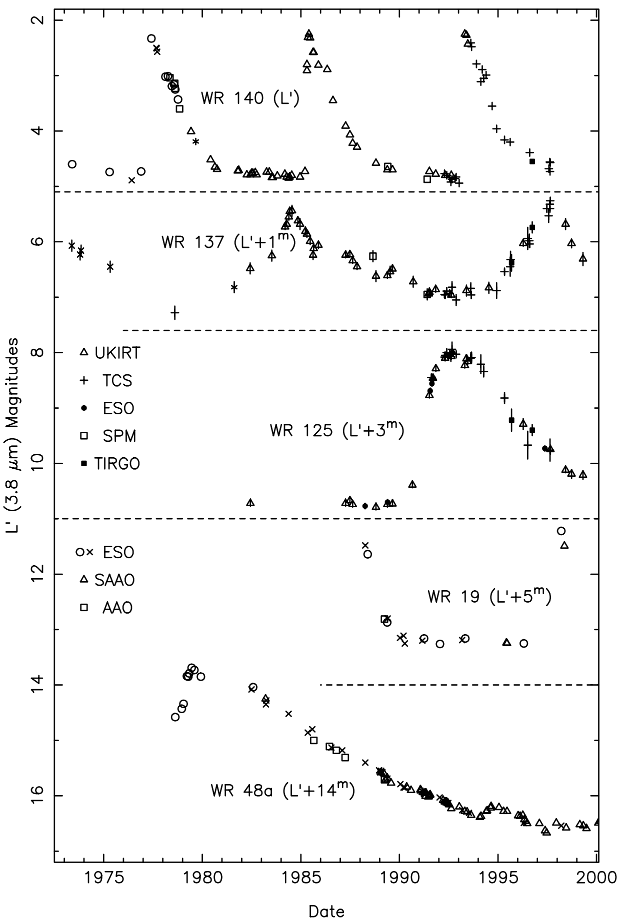

Figure 3. Near-IR L'-band (3.8 μm) light curves of five dusty WC stars, presumably all eccentric WC+O colliding wind binaries, with dust formation during periastron passage.

(1000 d $< P <$ 10000 d) eccentric WC+OB binaries during periastron passage (Williams 1999, 2001).

ISO-SWS IR spectra (van der Hucht *et al.* 1996; Williams *et al.* 1998) show in Fig. 2 the spectral energy distributions of two episodic/periodic WC8-9d stars: WR 48a (WC8ed) and WR 98a (WC8-9vd). The latter was discussed by Williams *et al.* (1995).

Near-IR L'-band (3.8 μm) light curves of five periodic and episodic dust forming WC stars are given in Fig. 3:
- The upper panel shows the archetype WR 140 (WC7pd +O4-5), for which Williams *et al.* (1987b, 1990) discovered that the IR maxima occur around periastron passage of this highly eccentric ($e = 0.84$) binary. WR 140 has three IR-maxima covered, while a fourth IR maximum is expected in Spring 2001.
- The second panel from above shows WR 137 (WC7pd +O9) with two maxima covered (Williams *et al.* 2001). A part of its *ISO*-SWS spectrum is shown in Fig 4.
- The IR light curves of WR 125 (WC7ed+O9) have been discussed by Williams *et al.* (1992, 1994).

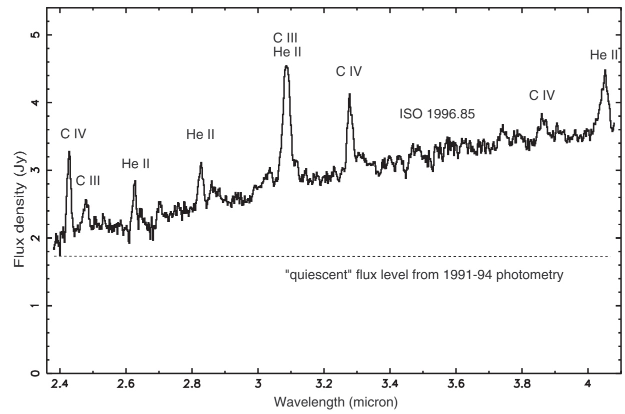

*Figure 4. ISO-SWS spectrum of WR 137 observed on 1996 November 6. The broken line represents the flux level determined from 1991-94 photometry. The emission features (*He II *and transition arrays of* C III *and* C IV*) are identified by their principal quantum numbers (from Williams et al. 2001).*

- The IR light curves of WR 19 (WC4pd+O9.6) have been discussed by Veen *et al.* (1998).

Table 2 lists all seven cases of know episodic/periodic dust making WC+OB binary systems. Thus, IR photometric monitoring provides an unique way of discovering very-long-period binaries which otherwise would have been unnoticed.

4. Galactic Center WCd stars

The Galactic Center (GC) region proves to be an area rich in WR stars. The *VIIth Catalogue* lists within 50 pc from the GC 15 WNL and 11 WCL stars, discovered at near-IR wavelengths by Blum *et al.* (1995); by Krabbe *et al.* (1995) in the Galactic Center Cluster; by Figer *et al.* (1999) in the Quintuplet Cluster (AFGL 2004); and by Cotera *et al.* (1999) in the Arches Cluster (near the radio emission region G 0.12+0.02); although some of them are questioned by Paumard *et al.* (2001). Earlier classifications of

Table 2. Episodic/periodic dust making WC+OB binary systems (after Williams 2001).

WR	spectrum	P (yr)	orbit	dates of IR maxima and notes
19	WC4pd+O9.6	10.1		(1987,) 1997-8
48a	WC8ed			1979, also mini eruptions
70	WC9vd+B0I		SB2	1989
98a	WC8-9vd	1.51	ast*	rotating dust pinwheel
125	WC7ed+O9			1992
137	WC7pd+O9	13.05	SB2	(1971,) 1984, 1997
140	WC7pd+O4-5	7.94	SB2	(1970,) 1977, 1985, 1993

*: astrometric orbit ($i = 35° \pm 6°$) indicated by rotating dust pinwheel (Monnier *et al.* 1999).

so-called He I stars have been revised by Crowther (private communication) in the *VIIth Catalogue* into WN9-11 stars. In the meantime, the number of WR stars discovered in the GC region has increased with seven additional WNL stars (Genzel *et al.* 2000: 13S SE, 16CC and MPE−8.3,–5.7; Paumard *et al.* 2001: ID 180, IRS 7E2, HeI N3 and HeI N2). Moreover, near the GC five additional WCL stars may be present, of which the heated circumstellar dust radiates strongly in the near-IR and masks their WC IR emission line spectra, thus preventing proper spectral classification. Preliminary classifications coin them *cocoon* stars (Moneti *et al.* 2001) or *DWCL?* stars (Figer *et al.* 1999).

5. Are all WCd stars binaries?

As listed by van der Hucht (2001), eighteen WC9 stars, four WC8 stars, three WC7 stars and one WC4 star are known with persistent or episodic/periodic thermal IR excesses indicative of heated circumstellar amorphous carbon dust formation (Williams 1999). Of the episodic and periodic cases it has been established that their heated dust is being formed in the wake of the colliding wind cones of WC4+O, WC7+O and WC8+O binaries. Of this phenomenon WR 140 is the prototype (Williams *et al.* 1990). Thanks to repeated high-spatial resolution IR observations (image-masking interferometry) Tuthill *et al.* (1999, 2001) and Monnier *et al.* (1999) managed to resolve the circumstellar dust shells of, respectively, WR 104 (WC9pd+B0.5V) and WR 98a (WC8-9vd), and to derive, from the observed rotation of their pinwheel images, orbital periods ($P = 243$ d and 565 d, respectively) of the low-inclination WC+OB binaries revolving within those dust spirals. Those discoveries make it very likely that all other apparently single WC9d and WC8d stars owe their heated circumstellar dust signatures also to colliding WC+OB wind effects, as suggested previously by Williams *et al.* (1995). Thus, the majority of the known WC9 stars ($\gtrsim 60$ %) and WC8 stars ($\gtrsim 55$ %) could actually all be WC+OB binaries.

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