**FULL TITLE**

ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION**

**NAMES OF EDITORS**

Dust Formation in Massive WR+O Binaries: Recent Results

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Abstract. The massive, luminous Population I Wolf-Rayet stars can be considered as stars with the highest known sustained mass loss rates. Around 10% of WR stars may form carbon-rich dust in their dense and inhomogeneous winds. Though we are yet to find how dust is formed in such an extremely hostile environment, we have made substantial progress over the past decade. Here we discuss the results of recent high-resolution mid-infrared imaging of a sample of the most prodigious WR ‘dustars’. This allows one to map rapidly changing dust-forming regions and derive some basic properties of the freshly formed dust.

1. The Wolf-Rayet ‘Dustars’

The hot, massive Population I Wolf-Rayet stars are the evolved descendents of O-type stars. WR stars live on the verge of exploding as Supernovae (even hypernovae), thus providing vitally important information about the very final stages of massive star evolution, possibly leading to Gamma-Ray Bursts. The extremely luminous ($L \gtrsim 10^5 L_\odot$) and hot ($T_{\text{eff}} \gtrsim 20000$ K) hydrostatic cores of WR stars drive fast dense winds: average mass-loss rates $\dot{M} \sim 10^{-4} M_\odot/\text{yr}$ and terminal velocities $v_\infty \sim 1000 - 4500 \text{km/s}$. There are three evolutionary-successive WR phases: WN, WC (carbon-rich, dust-producing class we are going to discuss here), and WO. Even though present-epoch dust production output for all Galactic WC stars is $\lesssim 1\%$ of the total Galactic rate [Dwek 1985, Cohen 1991], the dust-generating WC stars are regarded as outstanding for three main reasons: (i) The absolute rate of dust production is extraordinarily high, reaching $\dot{M} \sim 10^{-6} M_\odot \text{yr}^{-1}$ [van der Hucht et al. 1987, Williams 1995] in some stars. (ii) The dust is formed in a hot, extremely hostile environment, posing a formidable theoretical problem. (iii) In the early (age-1 Gyr) universe, WR stars could be very common, but unique sources of dust, along with subsequent dust-generating SN events, since WR stars evolve much more rapidly than any lower-mass stars, commonly associated with dust production in the ‘modern’ universe. It is not clear how much (and what kind of) dust can be produced in a SN explosion [Dwek 2004]. However, it is quite clear that the copious amounts
of the carbon-rich dust produced in the WC winds may survive for at least \( \sim 10^2 \) years \cite{Marchenko2002}, thus effectively reaching (and enriching) the ISM.

Two basic processes of dust formation prevail among the WC stars:

(i) ‘single’ channel: constant, sustained formation in single WC stars, only of the coolest (WC9,10 and some WC8) subtypes. The IR emission excess, arising from re-radiation of stellar UV photons by the hot dust and superposed on an underlying hotter stellar emission component, is in the form of \( \sim \)black-body radiation at \( T_d \sim 1000-1600\,K \) from a shell with inner critical diameter \( \sim 0.5 - 1.5 \times 10^3 R_\star \) (see Zubko 1998 and references therein). Presumably, the winds of hotter single WC stars are too rarified to form dust at a distance where the UV radiation has dropped sufficiently to allow dust formation to occur. In any case, even in cool WC stars, a smooth wind flow will not form dust; clumping is required for efficient grain growth \cite{Cherchnev2000}. Apparently, it cannot be excluded that the ‘single’ channel might ultimately involve a binary companion and thus a strong wind-wind collision zone to facilitate the dust formation.

(ii) ‘binary’ channel: episodic formation in binary WC + O systems with eccentric orbits, and almost constant dust formation in WC+O binaries with \( \sim \)circular orbits (‘pinwheel nebulae’: see \cite{Tuthill1999}). The key factor here is the compression by wind-wind collision involving H-rich material from the O-star and the C-rich WC wind. This allows dust formation to occur, which is dramatically enhanced at each periastron passage. Among the some 7 systems in which episodic dust formation has been detected so far \cite{Williams1995}, all have (confirmed or suspected) long periods of several years, with no preference for hot- or cool-type WC stars. Presumably, the dust is formed relatively far downstream along the shock interface, where the temperature has fallen sufficiently from the initially extremely high values of \( 10^6-7\,K \). The shock cone wraps around the weaker-wind O-star, so that IR dust emission should arise in a preferred direction far beyond the O-star, as seen from the WR star.

Hot \( (T \leq 1500\,K) \) circumstellar WR dust was only recently spatially resolved around some WC+O binaries \cite{Tuthill1999, Monnier1999, Marchenko1999, Monnier2002}. All the above-cited near-IR observations have targeted the hottest dust only. The apparent sub-arcsecond sizes of the barely resolved hot dust regions made next to impossible any direct application of quantitative models. The first mid-IR \( (\lambda\lambda 8 - 18\,\mu m) \) images of the spatially-resolved dust cloud around WR112 \cite{Marchenko2002} provided data on: (a) the temperature profile in the envelope, proving that, as anticipated, the temperature follows a thermal equilibrium profile; (b) the characteristic size and chemical composition of the dust grains, finding amorphous carbon as a main constituent of dust particles of a \( \sim 0.5\mu m \) characteristic size; (c) the absolute rates of dust formation, up to \( \dot{M}(\text{dust}) \sim 6 \times 10^{-7} M_\odot \, yr^{-1} \). Unusually large, sub-micron, dust particles were found in independent surveys \cite{Chiar2001, Yudin2001}.
2. Colliding-Wind Prototypes WR137 and WR140

The long-period, colliding-wind binaries WR 137 and WR 140 can be used as textbook examples of the ‘binary’ channel of dust production. WR140: this long-period (P=7.93 y), highly eccentric (e=0.881: Marchenko et al. (2003)) binary serves as a prototype for studies of wind-wind collision phenomena in massive binaries. Its repeatable, giant near-IR outbursts (Williams et al. 1990) are related to periastron passages, i.e. the intervals when the O star companion ploughs through the densest regions of the WR wind. Additional compression of the WR outflow in the wind-wind collision zone allows the shocked gas to cool rather quickly, thus creating favorable conditions for condensation of dust which eventually leaves the system. Indeed, after the 2001 periastron passage Monnier et al. (2002) detected slowly moving clumps of dust. The recent VLBA (S. Dougherty, these proceedings), UKIRT (P. Williams, these proceedings) and IOTA3 (Monnier et al. 2004) imaging helped to establish a relation between the 2001 dust ejecta and the wind-wind collision zone wrapped around the O star. Our high-quality λ12.5μm images obtained with Michelle/Gemini-North in November, December 2003 show concentric dust arcs around WR 140 which can be unequivocally linked with the 1993 and 2001 dust formation episodes (Fig. 1). Combined with the independently acquired near-IR images, these data may allow one to confirm the preliminary conclusions about the properties of dust in WR 140, i.e. the presence of fairly large dust grains with a characteristic size a ~ 0.1μm (Marchenko et al. 2003).

The massive long-period binary WR 137 was recognised as a periodically variable IR source by Williams et al. (1985) and included in the category of dust-producing WR+O binaries (Williams et al. 2001). Thirteen years after the 1984 dust-production maximum, alarmed by the rising near-IR flux (Williams 1996), we took H,K images with NICMOS2/HST (Marchenko et al. 1999) to find that, roughly one year after the 1996 periastron passage the system ejected a ~0.25” dust cloud at P.A.~ 110° and a bright clump at P.A.~ −70°, right along the plane corresponding to orientation of the equatorially-enhanced wind of the WR component (Harries et al. 2000). Taking the λ12.5μm images in 2003 (Fig. 1) we find that the dust clouds continue to expand along the directions outlined by the 1997/1998 NICMOS2 images, with the main outburst going SE. There is
no doubt that the equatorially-enhanced mass loss in the WR component plays a leading role in shaping the outcoming dust cloud.

3. Mid-IR Survey of Dustars with Gemini

Finishing our mid-IR survey of the WR ‘dustars’ in 2004, we find a spectacular dust envelope around WR48a (Fig. 2). This presumably binary system underwent a major dust-formation outburst in 1979 followed by relatively small secondary outbursts in 1990 and 1994 \cite{Williams1996}. Can the bright knots in Fig. 2 be related to the secondary events? If not, then what else can influence the dust production rate at the particular (and repeatable from orbit to orbit) orbital phases?

Comparing the second-epoch image of WR112 (Fig. 3) taken on July 2004 to the image from May 2001 \cite{Marchenko2002}, we find clear signs of slow expansion of the broken dust spiral. The rate of expansion allows us to estimate the distance to WR112: $d = 2.0^{+1.7}_{-0.8}$ kpc, assuming $v_\infty = 1200 \text{ km s}^{-1}$. We reinforce our previous conclusion that dust may survive in the hostile environment of the WR wind for a long time, up to $10^2$ years.

Six other ‘dustars’: WR 76, WR 80, WR 95, WR 98a, WR 106 and WR 121 - were not resolved in the $\lambda12.3\mu m$ images taken with TReCS/Gemini-South.

![Figure 2. The $\lambda12.3\mu m$ image of WR48a obtained with TReCS/Gemini-South in March 2004.](image)
We use the excellent sky coverage of 2MASS \footnote{http://www.ipac.caltech.edu/2mass/releases/allsky/} to conduct a galaxy-wide census of WR stars, adding to the 227 sources listed in \cite{vanderHucht2001} all the recently discovered Galactic Center objects (see the compilation in \cite{vanderHucht2003}). Working with the J-H vs. H-K diagrams of appropriately de-reddened sources and combining them with the K vs. J-K distributions, we were able to isolate the known population of WR ‘dustars’ (Wood et al. 2003) and find one new dust-producing source, WR102e. Overall, there is no statistically significant difference between the known binary and presumably single WR ‘dustars’: $< J - H >_{\text{single}} = 0.95 \pm 0.09$, $< H - K >_{\text{single}} = 0.90 \pm 0.05$, while $< J - H >_{\text{binary}} = 0.76 \pm 0.17$, $< H - K >_{\text{binary}} = 0.83 \pm 0.10$. Slightly bluer color indices of the binaries can be explained by the presence of a luminous, hot companion.

![Figure 3. The $\lambda 12.3\mu m$ image of WR112 obtained with TReCS/Gemini-South in July 2004.](image)

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