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DUST FORMATION BY COLLIDING-WIND BINARIES

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RESUMEN

Imágenes infrarrojas de alta resolución recientes de las enigmáticas estrellas *cocoon* en el cúmulo del Quintuplete, muestran comas tipo "pinwheel". La inferencia de que las estrellas son binarias Wolf-Rayet con vientos en colisión evidencia cuán lejos ha llegado el estudio de la formación de polvo en los vientos, desde el primer descubrimiento de polvo de carbono calentado, alrededor de la clásica estrella WC9 Ve2-45 (WR 104). La formación de polvo atribuida a vientos en colisión es el proceso menos esperado y también el más difícil de entender. Evidencia directa de la conexión anterior comienza a estar disponible. En este trabajo revisaré estudios recientes y consideraré sistemas que muestran un rango de fenómenos de formación de polvo, incluyendo la prototípica formadora de polvo episódica WR 140 y la formadora de polvo variable WR 70, también largamente estudiada por Virpi Niemela y colaboradores.

ABSTRACT

The recent high-resolution infrared images of the enigmatic cocoon stars in the Quintuplet cluster showing them to have "pinwheel" tails, and the deduction that they are colliding-wind Wolf-Rayet binaries, shows how far the study of colliding-wind dust formation has come since the first discovery of heated carbon dust around the classical WC9 star Ve2-45 (WR 104) in the early days of infrared astronomy. The formation of dust is the least expected, and hardest to understand, process attributed to colliding stellar winds, and direct evidence of the connection is only now becoming available. I will review recent work and consider systems showing a range of dust-formation phenomena, including the prototypical epsiodic dust-maker WR 140 and the variable dust-maker WR 70, also long studied by Virpi Niemela and her colleagues.

Key Words: binaries: general — circumstellar matter — stars: individual (WR 70, WR 104, WR 140) — stars: winds, outflows — stars: Wolf-Rayet

1. THE INCIDENCE OF DUST FORMATION

Infrared observations show the wide prevalence of dust formation by evolved stars of different types: red supergiants, AGB stars, Novae, Type II Supernovae, Luminous Blue Variables, R Coronae Borealis (RCB) stars—and some Population I Wolf-Rayet stars. Of the last, dust formation is most common amongst the WC9 stars: of the 44 currently known WC9 stars (cf. van der Hucht 2006), about 36 show circumstellar dust emission. The uncertainty in the number comes from the difficulty of distinguishing the spectral energy distributions (SEDs) of weak dust shells from those of heavily reddened stellar winds when only JHK photometry, e.g. from the 2MASS survey (cf. Hopewell et al. 2005), is available—and observations need to be extended to longer wavelengths to resolve this.

Infrared photometric histories, some spanning more than two decades, show properties ranging from persistent dust formation at apparently constant rates (e.g., WR 104) to brief episodes of dust formation at regular intervals (e.g., WR 140 = HD 193793, P = 7.94 y.), and these two stars are considered to be the prototypes of *persistent* and *episodic* dust makers respectively. Intermediate behaviour is shown by WR 98a, which forms dust persistently, but at a variable rate (Williams et al. 1995).

The significance of dust formation is the difficulty of condensing dust grains near such hot stars (e.g., Williams, van der Hucht, & Thé 1987), so that local over-densities $\sim 10^4$ in the W-R winds are required (Cherchneff et al. 2000). These must be *large-scale, long-lived* structures to account for the observations that dust is formed asymmetrically, and that the process maintains its coherence over decades.

Evidence for large-scale structures comes from the spectacular spiral plumes ("pinwheels") of dust emission such as first observed around WR 104 by Tuthill, Monnier, & Danchi (1999) (cf. Figure 1). Pinwheels have been observed around WR 98a and WR 112 in the near-IR by Monnier, Tuthill, & Danchi (1999) and Monnier et al. (2007); and

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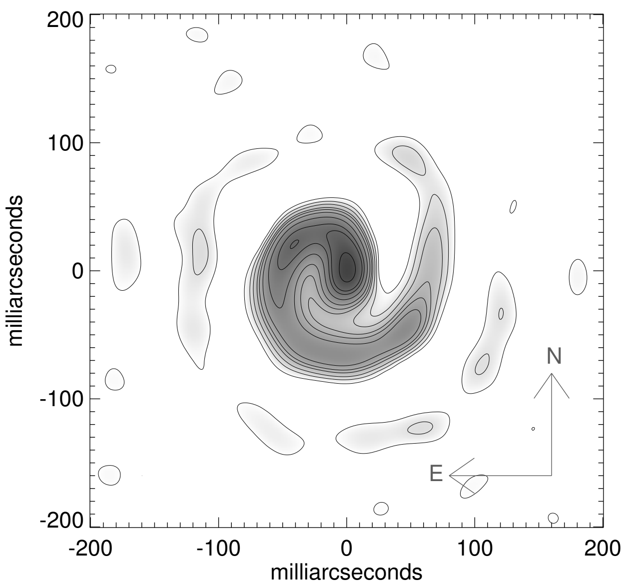

Fig. 1. Near-IR (2.27 μm) image of WR 104 observed and reconstructed using aperture-masking interferometry by Tuthill et al. (2003).

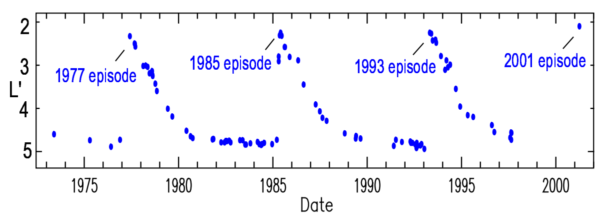

Fig. 2. L' (3.8 μm) light curve of WR 140 showing dust-formation epsiodes recurring with a period of 7.94 y.

around WR 112 in the mid-IR by Marchenko et al. (2002) and Marchenko & Moffat (2006). Recently, Tuthill et al. (2006) observed dust pinwheels around two of the "cocoon" stars, Q2 and Q3, in the Quintuplet cluster, suspected of being WC9 stars from their smooth mid-IR SEDs—*but still requiring spectroscopy showing W-R emission lines.* Asymmetric dust emission has also been observed around the episodic dust makers WR 137 (Marchenko, Moffat, & Grosdidier 1999) and WR 140 (Monnier, Tuthill, & Danchi 2002; Williams et al. 2004) and other dust-making WC stars (Marchenko & Moffat 2006; Monnier et al. 2007).

Evidence for the long lives of the wind structures come from the periodic repeatability of dust formation by episodic dust makers like WR 140 (Figure 2), and the multiple turns of the dust spiral around WR 112 observed in the mid-IR (12 μm) by Marchenko & Moffat (2006).

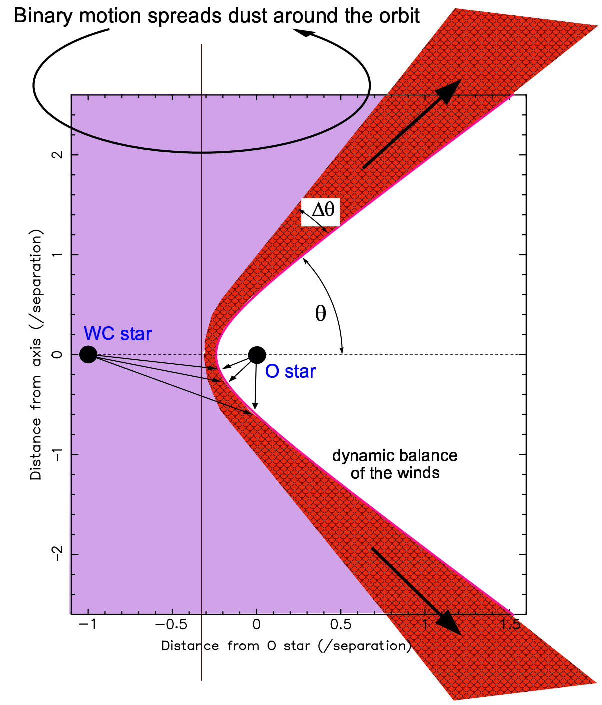

Fig. 3. Sketch of the CW region of a WC + O binary. The winds are separated by a contact discontinuity, where the dynamic pressures balance. This approximates to a cone whose opening angle, θ, depends on the ratio of the momenta of the two winds. On both sides of it are surfaces (width $\Delta\theta$) where the winds of the WC and O star are shocked. Only that of the WC star, in which dust condenses downstream, is shown here.

2. COLLIDING-WIND BINARIES

2.1. *The CWB connection*

The connection between dust formation and colliding-wind binary (CWB) interactions came first from WR 140, whose dust-formation epsiodes coincide with periastron passage (Williams et al. 1990) in the very eccentric orbit of its WC7 and O4-5 components, both of which have fast stellar winds. Usov (1991) showed that part of the WC wind entering the wind-wind collision shock near the stagnation point between the stars can cool very efficiently and reach a density $\simeq 10^3$ times its pre-shock value, providing cool, dense material within which dust could condense. The configuration is sketched in Figure 3; reality is more complicated, as can be seen from the hydrodynamic models of, e.g., Folini & Walder (2002) and Walder & Folini (2003). The brief episodes of dust formation by WR 140 at periastron are related to spikes in the pre-shock wind density ($\simeq 50\times$) when the stars are at their smallest separation. Further evidence for a CWB connection comes from the pinwheel systems, interpreted as continuously formed dust which is blown out in a plume and spread around its orbital plane by a binary observed at a relatively low inclination angle. The thickness of the dust plume is determined by the opening angle of the wind interaction region (θ in Fig. 3), which depends on the ratio of the momenta ($\dot{M}v_\infty$) of the WC and companion winds. The clincher is the observed rotation of the pinwheels. Tuthill et al. (2003) presented images of WR 104 at six epochs, which show rotation of the system with a period of 243.5 ± 3.0 days. From the uniformity of the pinwheel rotation, they deduced that the orbit of WR 104 was circular. The lack of significant variation in the IR flux from WR 104 over the years suggests that dust formation occurs at a constant rate, which is probably a consequence of its circular orbit and constant separation of the components—in contrast to WR 140.

From images observed at three epochs, Monnier et al. (1999) showed that the pinwheel around the variable dust-maker WR 98a rotates with a period of 565 ± 50 days. From near-IR photometry, Williams et al. (2003) derived $P = 564 \pm 8$ days and, from the colours, showed that the variation was caused by periodic variation in the dust-formation rate; so WR 98a may have an eccentric orbit. The morphology of the pinwheel differs in the three images: that observed near maximum dust formation (photometric $\phi = 0.93$) is more compact than that observed near minimum ($\phi = 0.50$), presumably because there is more hot dust near the star—but modelling of the system is necessary to explore this.

Harries et al. (2004) have developed 3-D radiative transfer models of the WR 104 pinwheel which provide an excellent fit to the observations. They derived a dust creation rate of $8 \pm 1 \times 10^{-7}$ $M_\odot \mathrm{y}^{-1}$ and constrained the opening angle of the wind interaction region to $\theta \simeq 40°$. They found that the radial temperature gradient of the dust differed from the $r^{-0.4}$ dependency expected for grains in radiative equilibrium with geometrically diluted starlight owing to shielding by dust, especially in the first turn of the spiral. This makes the dust in the second turn cooler than otherwise, accounting for the observation that, in the near-IR, the pinwheel emission is dominated by dust in the first turn (e.g., Figure 1). To observe the more distant dust, we need to go to longer wavelengths. A fine comparison comes from images of WR 112 observed at 18 μm by Marchenko et al. (2002) and in the near-IR by Monnier et al. (2007), which show similar structures on scales of a few arcsec and a few $\times$ 100 mas respectively, being outer and inner spiral turns from the same system.

2.2. *Are all Wolf-Rayet dust makers CWBs?*

Of the episodic dust makers, WR 140 and WR 137 have spectroscopic orbits (Marchenko et al. 2003; Lefèvre et al. 2005) with periods in excellent agreement with those derived from dust formation. The variable dust maker WR 70 is known to be an SB (Niemela 1995) but has, so far, defied orbital analysis—see below.

For the persistent dust makers, we have only indirect evidence. There is the rotation of the pinwheels around WR 104, WR 98a and Q3, which is hard to explain *except* in terms of binary rotation. Of them, only WR 104 has a spectroscopic companion (e.g., Crowther 1997) and Q3 needs spectral classification.

Chapman et al. (1999) and Monnier et al. (2002) have observed non-thermal radio emission from WR 98a, WR 104 and WR 112, which is a good diagnostic of colliding stellar winds. Radio observations of other WC9 persistent dust makers yield only upper limits on their fluxes (Chapman et al.), but this does not rule out binarity because non-thermal radio emission can be extinguished by free-free absorption in the winds if the binaries are too close (Dougherty & Williams 2000), or if the configuration of the binary at the time of observation is unfavourable—as happens with WR 140 for part of each orbit.

Hot companions have been observed in spectra of the episodic dust makers WR 19 (Veen et al. 1998a) and WR 125 (Williams et al. 1994); and, of a sample of ten WC9 stars, WR 59, WR 65 and WR 69 (Williams & van der Hucht 2000; Williams, van der Hucht, & Rauw 2005). Radial velocity studies are needed to search for orbital motion.

2.3. *Are dust eclipses related to CWB dust?*

In addition to its infrared emission, dust formation in WC stars manifests itself by eclipses at optical wavelengths, caused by episodic obscuration of the starlight by clumps of dust in the line of sight (e.g., Veen et al. 1998b; Marchenko et al. 1998; Kato et al. 2002a,b), similar to those of the RCB stars.

In most cases, there are not enough observations to determine a pattern to the eclipses, but Kato et al. (2002a) found a "quasi-period" of 241 d. in observations of WR 104, close to the rotation period (243.5 d.) of the pinwheel. Given the low orbital inclination ($i = 11° \pm 7°$) and small opening angle ($\theta \simeq 40°$) of the wind-interaction region, we do not expect the main dust plume to cross the line of sight but this result could indicate more complex structure. To test this, Kato's data were augmented with observa-

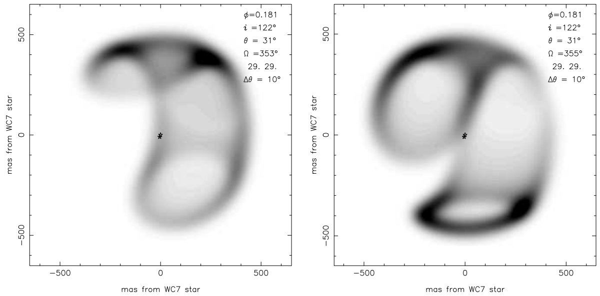

Fig. 4. Model images of WR 140 for CWB dust formation during $\phi = 0.99$–0.01 showing the difference in spread of dust for orbital eccentricities $e = 0.88$ (L) and 0.94 (R). The emission is optically thin and we see limb brightening of the hollow structures. The ellipses at the ends of the dust features are the projections of the bases of the CW region at phases when dust-formation starts and finishes.

tions in the All-sky Automated Survey[2] (Pojmanski 2002). Searches in the composite ten-year (1994–2004) dataset do not reveal periods near 243 d., and it is probable that the dust eclipses are stochastic phenomena.

2.4. *Location of dust relative to the CW region*

The next stage in the study of CWB dust formation is comparison of the locations of the dust and the CW structure. This is difficult for the pinwheels: the stars in WR 104 have an angular separation of ~ 1 mas and provide a challenging target for interferometry. Meanwhile, we now know enough about the orbit of WR 140 for comparison with the dust images. There have been several SB orbit solutions, most recently by Marchenko et al. (2003). The binary itself was resolved by Monnier et al. (2004), who measured the stellar separation and position angle (PA) at $\phi = 0.297$. From high-resolution imaging of the non-thermal radio emission, Dougherty et al. (2005) demonstrated that the WR 140 system rotates clockwise on the sky, and derived $i = 122°$ and $\Omega = 353°$, completing the specification of the orbit. Thus we can calculate the orientation of the CW structure on the sky at any time.

At periastron, the WC7→O4-5 star axis projected on the sky has $PA = 323°$ (i.e., the O4-5 star is NW of the WC7 star), and any dust formed at this phase should be displaced in this direction. From the IR light curves, we know that WR 140 makes dust for $\simeq 0.02P$ of its orbit near periastron so, instead of a pinwheel, we would expect to see only an arc of dust having an angular extent determined by the rotation of the PA in $0.02P$. Owing to the

[2] `http://archive.princeton.edu/~asas/`

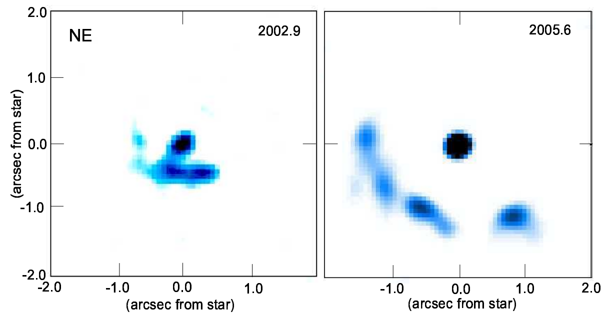

Fig. 5. Images of WR 140 at 3.99μm observed with UIST on UKIRT in 2002 November and 2005 July showing expansion of dust cloud.

high orbital eccentricity ($e = 0.881$, Marchenko et al. 2003), the binary and CW system swing round by 167° in $0.02P$, from $PA = 13°$ at $\phi = 0.99$ to $PA = 206°$ at $\phi = 0.01$. The arc of dust formed by the CW region would be greater than this, depending on the opening angle, extending from $PA \simeq 50°$ (NE) to $PA \simeq 170°$ (SSE). A model dust distribution for $\phi = 0.18$, using the known orbital elements and reasonable values of θ and $\Delta\theta$ is shown in Figure 4 (left).

The observed distribution of dust about WR 140 is rather different. Monnier, Tuthill, & Danchi (2002) imaged WR 140 twice in 2001 and found the dust to lie in several features around the star, mostly to the S and E. Further images at wavelengths between 2μm and 19μm were observed during 2001–2005 by a consortium including Tony Marston, Watson Varricatt, Sergey Marchenko, Tony Moffat and the writer. Despite the variety of instrumentation (on UKIRT, Gemini N, Hale and WHT), and data reduction software, the images are rather similar, with most of the dust to the S and E (cf. Figure 5). Preliminary results were presented at the MSIB meeting (Williams et al. 2004). The features show linear expansion at rates consistent with the wind velocity. Extrapolation back to the star suggests that the dust to the E was formed before that to the S, which is consistent with the model only if the system rotated by $\sim 270°$ during dust formation. This could occur if the orbital eccentricity was rather greater than that derived from the RVs (cf. Figure 4 [right]) or if the condensation continued for longer than $0.02P$. Also, the absence of dust to the NW of the star suggests that the condensation rate is not uniform, but least at periastron, perhaps because the reduced separation of the components results in radiative braking of the WC7 wind. So, more work is needed before we have a direct comparison of imaged dust and a

CWB—and WR 140 may not be a good test owing to its extremely eccentric orbit.

3. OUR MUTUAL FRIEND HD 137603 = WR 70

The WC9 + B0I system WR 70 is a mutual friend, which has frustrated us for decades! Working with Virpi, Golombek (1983) derived a RV orbit from the absorption line spectrum having a period near 50.5 d. but noted that more work was required. At the Elba meeting, Niemela (1995) showed that WR 70 was a SB2 having a mass ratio $M(\mathrm{WC9})/M(\mathrm{B0}) = 0.45$, and remarked that the RV data would be compatible with a longer period, ~ 1200 d. Also, WR 70 was found to vary in the IR, and the orbital studies prompted long-term monitoring. Preliminary results (Williams, van der Hucht, & Marang 2003) showed it to be a persistent dust maker with semi-regular ($P \simeq 1045 \pm 60$ d.) bursts of additional dust formation and *abrupt breaks* in dust formation. With the addition of further photometry, the strongest dust-formation periodicity is at 1061 d. This might be related to the longer periodicity in the RV variations; there is no evidence for a period near 50.5 d. in the IR data.

We can speculate that this is a triple system with dust formation triggered by the "outer" orbit—but it deserves further study to solve for the orbits and then the modulation of the dust formation.

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DISCUSSION

N. Przybilla - Do you see any features resembling the classical interstellar absorption features in the visual during dense occultation episodes?

P. Williams - The only spectroscopy during an eclipse I know of is that by Paul Crowther of WR 104 which I don't think showed any difference in interstellar features.

A. Willis - Are there IR/mid IR spectra of the dust in, say, WR 140, to determine the chemical composition of the dust? Are there any PAH seen – I would expect it not since there should be no hydrogen in the WC wind!

P. Williams - Yes, the mid-infrared spectra of WR 140 during dust formation are featureless – no sign of the graphite feature at 10.5 micron or any PAH lines, not surprisingly.

C. Cappa - Which are the dust temperatures?

P. Williams - The dust temperature nearest the stars is about 1200 K. It falls off to about 400 K in the furthest features observed.

C. Cappa - Is it possible to detect molecular gas in the "pinwheel" nebulae?

P. Williams - Molecular gas like CO, C_2, or CN has not been observed from these systems – they are not like the carbon stars. What some spectra show are features near 6.4 and 7.7 microns which are associated with carbon-carbon bands.

As the LOC could find no mariachis, Virpi (first floor balcony) enjoys a performance of floor gymnastics by Javier.