Evidence for Wind Anisotropies from Dust Formation by Wolf-Rayet Stars

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Abstract. The formation and survival of dust around stars requires a physical environment very different from that believed to hold anywhere in a Wolf-Rayet stellar wind. The observed facts of dust formation by Wolf-Rayet stars force the conclusion that their winds are not homogeneous. They also allow us to deduce the types of inhomogeneity, including clumps and large-scale high-density wakes produced in colliding-wind binaries, that allow the formation of dust.

1 Introduction: The Problem

We have long known from IR photometry that some Wolf-Rayet (WR) stars make dust in their winds. Because these winds are fast and dense enough to disperse the dust, causing it to cool and its emission to fade, persistent, strong IR emission from a WR star indicates persistent formation of new dust (Williams et al. 1987). A few WR stars show IR outbursts at intervals of $\sim$ a decade, indicative of episodic dust formation (e.g. Williams 1997). The significance of these phenomena lies in the great difficulty of forming dust in WR winds: heating of dust grains in the strong UV radiation fields of WR stars restricts dust formation to regions which, in a homogeneous WR wind of known mass-loss rate, are too rarefied by 3–4 orders of magnitude for dust to form (Cherchneff & Tielens 1995). Dust can only form in high-density structures of some sort. Here we consider the evidence for these.

2 Colliding-wind structures

As is often the case in astronomy, the best laboratories are provided by variable objects — such as the archetypal episodic dust-maker WR 140. This is a binary system comprising WC7 and O4-5 stars in a 2900-d orbit (Williams et al. 1990). Dust-formation episodes lasting a few months each recur with the same period, coinciding with periastron passage in the orbit. This phasing of dust formation to the binary orbit provides a crucial clue: the changes in physical conditions in the wind which determine when dust formation occurs must be related to changes with the orbital motion of some long-lived structure in the system. One which could provide the density enhancements required for dust formation is material compressed in shocks formed where the fast winds of the WC7 and O4-5 stars collide. Compression of the wind by

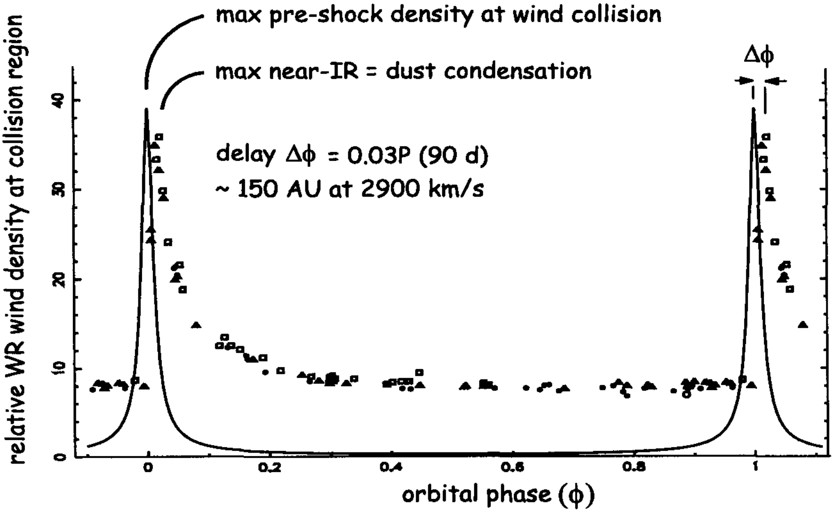

Fig. 1. Comparison of the orbital variation of Wolf-Rayet wind density at the wind-collision region (continuous line) with the observed K-band magnitudes (symbols) phased to the orbital elements.

a factor of ~ 10^3 can occur within the shock if the wind cools sufficiently by radiation (Usov 1991). However, the WC7 and O4-5 stellar winds in WR 140 collide and compress wind material all the time, so we then have to ask: what varies round the orbit so as to trigger dust formation for only ~ $0.02P$ during periastron passage? Consider the systematic variations in the *pre-shock* wind density near the interaction region. This region lies where the momenta of the WC7 and O4-5 winds balance and is much closer to the O4-5 star, whose mass-loss rate is ~ 60 times less than that of the WC7 star. Because the orbit is very eccentric ($e = 0.84$), the separation of the stars and the distance of the interaction region from the WC7 star vary strongly around the orbit. This is especially so around the time of periastron passage: for a very short time, the density of the WC7 stellar wind going into the shock (and being compressed by it) is ~ 50 times greater than that during most of the orbit (Fig. 1). The consequent "spikes" in the pre-shock density appear to be the clock that triggers the dust condensation.

The processes of compression and cooling in the shocks sufficient to allow dust formation by WR 140 have been modelled by Usov (1991). However, dust cannot condense until the compressed wind material has been carried far enough away from the stars so that the grains are not heated to sublimation by the stellar radiation field: a distance ~ 150 AU. Assuming the compressed material moves with the wind terminal velocity ~ 2900 km s^{-1}, this introduces a delay of $\sim$ 90 days between the times of maximum pre-shock wind density (at periastron passage) and maximum dust formation — consistent with the observed phase difference ($\Delta\phi \sim 0.03P$) between maximum pre-shock density and infrared (K band) maximum (Fig. 1).

Extension of the WR 140 paradigm to other dust-makers requires demonstration that they are colliding-wind binaries with appropriate stellar and orbital properties. Spectroscopic companions to some episodic and persistent dust-makers have been found (Williams 1997, Williams & van der Hucht 1996) but determination of orbits will be difficult given the broad emission lines of WR stars and the apparently long periods of episodic dust makers indicated by their IR light curves.

3 Clumps small and large

Some dust-making WR stars (e.g. WR 121) show brief optical occultations by $\sim 10^{-14}$ $M_\odot$ dust clumps forming in the line of sight (Veen et al. 1998). Also, the fading light curves of two of the episodic dust-makers, WR 48a and WR 137, show "mini" infrared outbursts and fadings indicative of minor ($\sim 10^{-9}$ $M_\odot$) episodes of dust formation $\sim$ years after the major outbursts. Whether these phenomena represent part of a continuum of condensing clump masses or come from different processes is an open question.

References

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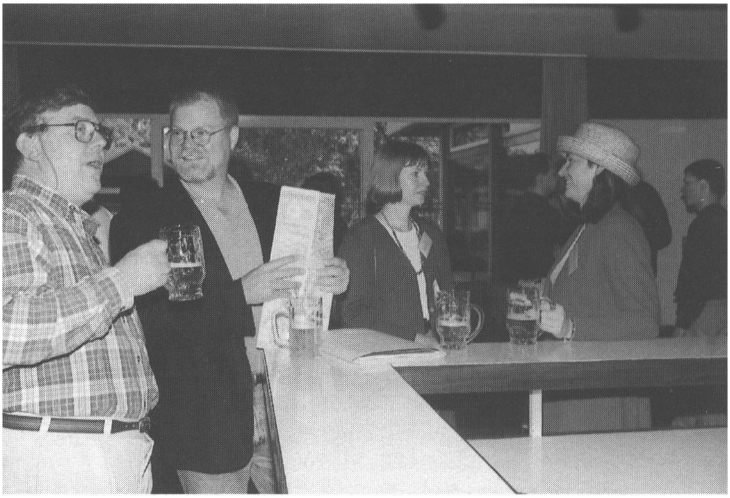
Discussion

G. Koenigsberger: Is it enough to have an increased WR wind density in the wind-wind shock region during periastron or do you need an increased mass-loss rate to form dust?
P. Williams: I have not modelled this aspect; it would help a little, but since the WR 140 system is so wide, even at periastron, any enhanced mass loss is likely to be smaller than in most other systems considered.

J. Bjorkman: Can you use the colour information in the photometry to estimate the maximum dust temperature as a function of time? Is this temperature consistent with constant velocity expansion of the dust?
P. Williams: Yes. The dust temperature falls as the emission fades when dust formation ceases. The cooling and fading of the emission from WR 140 are slower than expected from simple dispersion by the stellar wind, perhaps due to continued grain growth after condensation.

D. Massa: Do you see any evidence for IR spectroscopic features that might tell you what sort of dust is being formed?
P. Williams: No, the spectral energy distribution is smooth; we see no dust features, only interstellar features.



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