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EPISODIC DUST FORMATION BY WOLF-RAYET STARS: SMOKE SIGNALS FROM COLLIDING WINDS

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RESUMEN

Las observaciones infrarrojas realizadas durante las dos últimas décadas, han puesto en evidencia un grupo de estrellas Wolf-Rayet que episódicamente producen polvo en sus vientos. Cuando las observaciones han tenido suficiente continuidad en tiempo, se ha visto que los episodios de formación de polvo se repiten, a intervalos del orden de una década. Tres de estos episodios observados en el prototipo, WR 140, han sido relacionados a la interacción de los vientos de las componentes WC7 y O4–5 de esta binaria. Recientemente ha comenzado un segundo episodio en WR 137, otro sistema que contiene una estrella WC7. Nueva espectroscopía óptica de otros dos sistemas WC, que no se conocían previamente como binarios, y que han mostrado episodios de formación de polvo, indica la presencia de compañeras OB, sugiriendo que también pueden ser binarias. Otro sistema estrechamente relacionado a los anteriores, es la binaria de largo período WC9+B0I WR 70, cuya emisión de polvo es más compleja. Estos sistemas pueden arrojar nueva luz sobre la estructura de los vientos de las estrellas Wolf-Rayet.

ABSTRACT

It is evident from infrared observations made over the last two decades that there is a group of Wolf-Rayet stars which make dust episodically in their winds. In cases where observations have continued for long enough, it is seen that dust-formation episodes occur repeatedly, at intervals of about a decade. Three such episodes by the prototype, WR 140, have been observed and linked to the interaction of the winds of the WC7 and O4–5 components of this binary. A second episode by another system containing a WC7 star, WR 137, has recently begun. New optical spectroscopy of two other WC systems, not previously known to be binaries and which have showed dust-formation episodes, indicates the presence of OB companions and suggests that they too might be binaries. Closely related to these systems is the long-period WC9+B0I binary WR 70, whose dust emission is more complex. These systems can give new insights to the structure of Wolf-Rayet winds.

Key words: **BINARIES: GENERAL — DUST, EXTINCTION — STARS: WOLF-RAYET**

1. INTRODUCTION

Of all the phenomena caused by the collision of stellar winds in early-type binary systems, perhaps the most unexpected is the formation of circumstellar dust. In particular, there are the "smoke signals": the periodic formation of amorphous carbon dust (soot) by the WC7+O4-5 binary HD 193793 (WR 140). The processes of dust formation by hot objects like some Wolf-Rayet (WR) stars are still not understood, nor are the parameters that determine which of them make dust and which do not. However, the *episodic* formation of dust by some WR stars indicates that the values of these critical parameters in a particular object can vary so as to start and stop the condensation of dust grains. Consequently, analysis of these variations can provide insight to the operation of dust-formation processes in WR winds in general, as well as activity in particular systems.

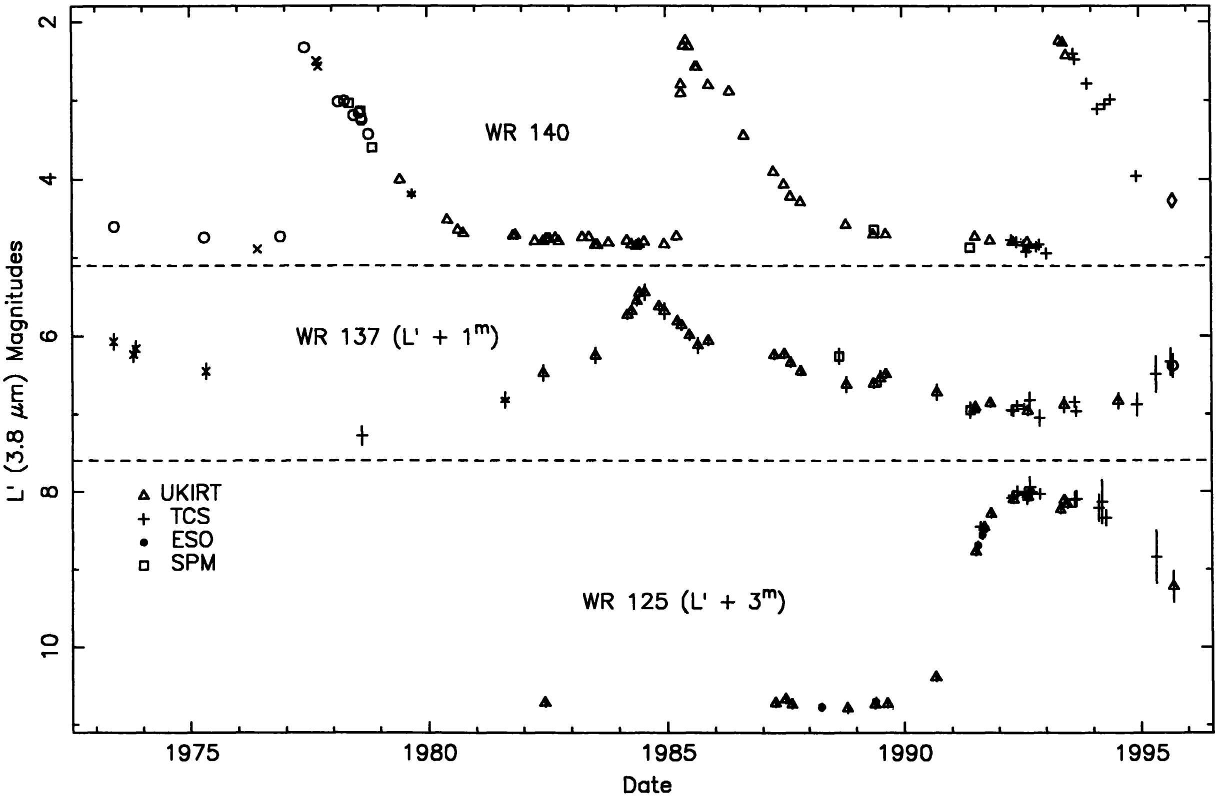

Fig. 1. Synoptic long-term 3.8 μm light curves of three Wolf-Rayet systems incorporating WC7 stars. Different symbols mark observations made at different observatories. For clarity, the data for WR 137 and WR 125 have been shifted as shown.

Certainly, the relation of the "smoke signals" from WR140 to its binary orbit has provided valuable clues. Dust formation in the wind of WR 140 occurs during periastron passage in the very eccentric ($e = 0.84$) orbit (Williams et al. 1990a, = W90). In this contribution, we will look first at the nature of the "smoke signals" and then at their message of activity in stellar winds. We take WR 140 as the prototype, and then look at the latest results from apparently similar systems.

2. THE "SMOKE SIGNALS" FROM WR 140

The signals from WR 140 are very conspicuous: a brightening of the infrared flux (e.g., by a factor of ten at 3.8 μm) over a period of weeks followed by a slow decline. Three such episodes have been observed —with maxima in 1977, 1985 and 1993 (Fig. 1). The period is 7.94 ± 0.03 years, so close to an integral number of years that some phases, including the rise to maximum, are poorly covered because the star is unobservable. Shown in the same figure are synoptic light curves of two other systems containing WC7 type stars, HD 192641 (WR 137) and WR 125, which will be discussed below.

The nature of the signals from WR 140 can be seen from the spectral energy distributions (SEDs) in Fig. 2. Both the infrared and radio fluxes vary, but at different phases. Although conspicuous in the infrared light curve, the additional flux at infrared maximum represents only a tiny fraction ($\sim$ 0.3%) of the total luminosity of the system. Comparison of infrared spectra observed at minimum and maximum shows that only the continuum level changed. The strengths of the emission lines did not change, implying that the wind temperature and density were unaffected. The shape of the infrared SED (Fig. 2), together with the 8–13 μm spectrum, confirm that the infrared excess comes from heated carbon dust. Modelling of the data (W90) showed that, at infrared maximum, $\sim 2.8 \times 10^{-8} M_{\odot}$ of dust was located $\sim$ 150 AU from the stars (which were separated by $\sim$ 2.5 AU at the time) and heated to $\sim$ 1100 K by absorption of $\sim$ 0.3% of the stellar UV-optical radiation. Light curves were observed at eight different infrared wavelengths in the 1–20 μm range, allowing determination of the dust mass and temperature and study of the temporal evolution of the dust cloud.

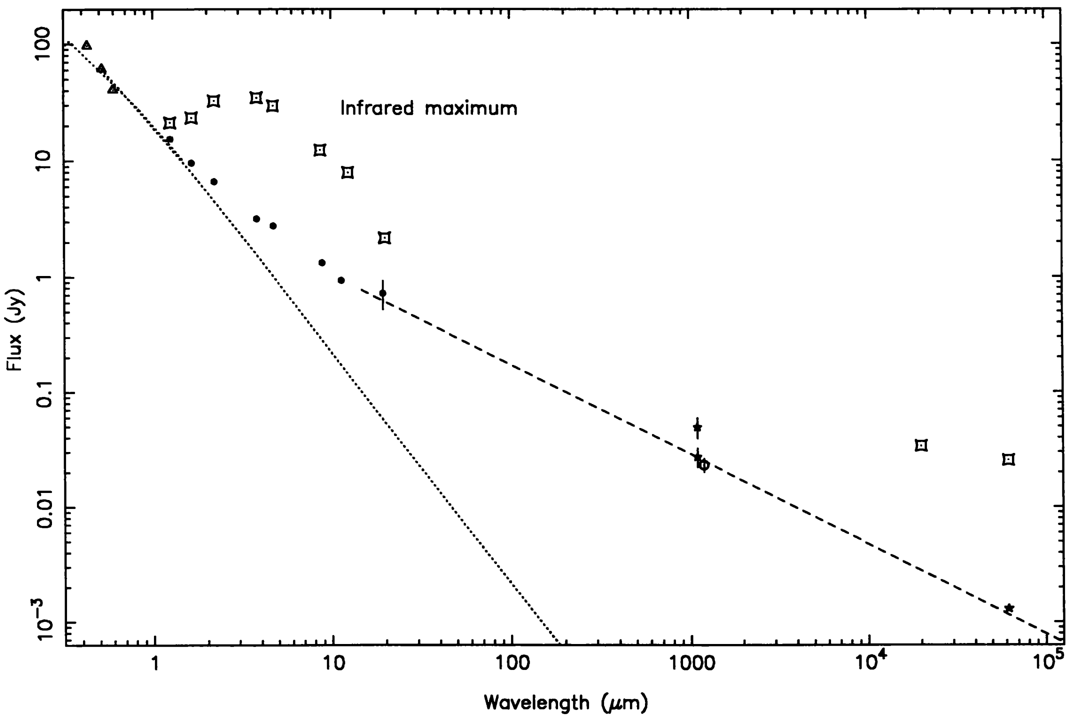

Fig. 2. Spectral energy distribution of WR 140 from optical to radio wavelengths. The points mark de-reddened fluxes from the optical (△), infrared (□ at maximum, • at minimum), millimetre (⋆) and radio (□ at maximum, ⋆ at minimum). The dashed line is a $\nu^{0.78}$ wind spectrum, the dotted line a hot photosphere for comparison.

It was shown from the rising infrared flux that dust condensed in the wind of WR140 for about 4 months. During this time, the dust-formation rate, $\sim 8 \times 10^{-8} M_{\odot}\ y^{-1}$, was about 0.13% of the total mass loss or 5% of the carbon being lost by the WR star. Because the dust formed in the wind, it was carried away from the stars —at a velocity slightly greater than the wind velocity owing to the effect of radiation pressure. Consequently, the stellar radiation heating the dust was increasingly diluted and the grains cooled soon after their formation. While dust formation continued, the dust being carried away in the wind was replenished with new, hot dust. When dust formation ceased and replenishment stopped, the average dust temperature fell sharply. This resulted in a fading of the infrared emission with a characteristic signature: the fading is steeper at the shorter infrared wavelengths.

3. THE MESSAGE FROM WR140

The significance of dust emission by WR140 and the other WR systems stems from the difficulty of condensing and growing dust grains near such hot stars. At the distance from the stars ($\sim$ 150 AU) at which the grains are observed, the density in an isotropic stellar wind carrying WR140's mass loss of $5.7 \times 10^{-5}\ M_{\odot} y^{-1}$ is $\sim 2 \times 10^{-19}$ g cm^{-3}. This is too low by several orders of magnitude to allow the processes in the proposed chemical pathway to the formation of carbon dust in WR stars (C $\rightarrow$ C_2 $\rightarrow$ carbon chains $\rightarrow$ monocyclic rings $\rightarrow$ polycyclic aromatic carbon (PAC) rings $\rightarrow$ fullerenes) discussed by Cherchneff & Tielens (1995) to occur. This density deficiency supports earlier inferences from considerations of classical grain growth (e.g., Hackwell, Gehrz, & Grasdalen 1979) that grain formation by WR140 cannot be isotropic nor widespread in the wind but occurs in density enhancements of some sort. There is now evidence that the winds of some WR stars are clumpy rather than homogeneous (e.g., Moffat & Robert 1994; Antokhin 1995) and, from polarimetry, that some are non-spherical and have disk-like structures (e.g., Schulte-Ladbeck 1995). A third category of density enhancement is that discussed at this Workshop: the wind-interaction regions ("wakes" or "ridges") in colliding-wind binaries (CWBs). Strong shocks occur where the winds collide, compressing the wind by a factor of four. Significant further compression, by up to $\sim 10^3$, can occur within the shock if the wind cools sufficiently by radiation (Usov 1991). Both the components of WR140 have winds with terminal velocities around 2900 km s^{-1}, making it a CWB and thereby accounting for its strong X-ray and non-thermal radio emission (W90,

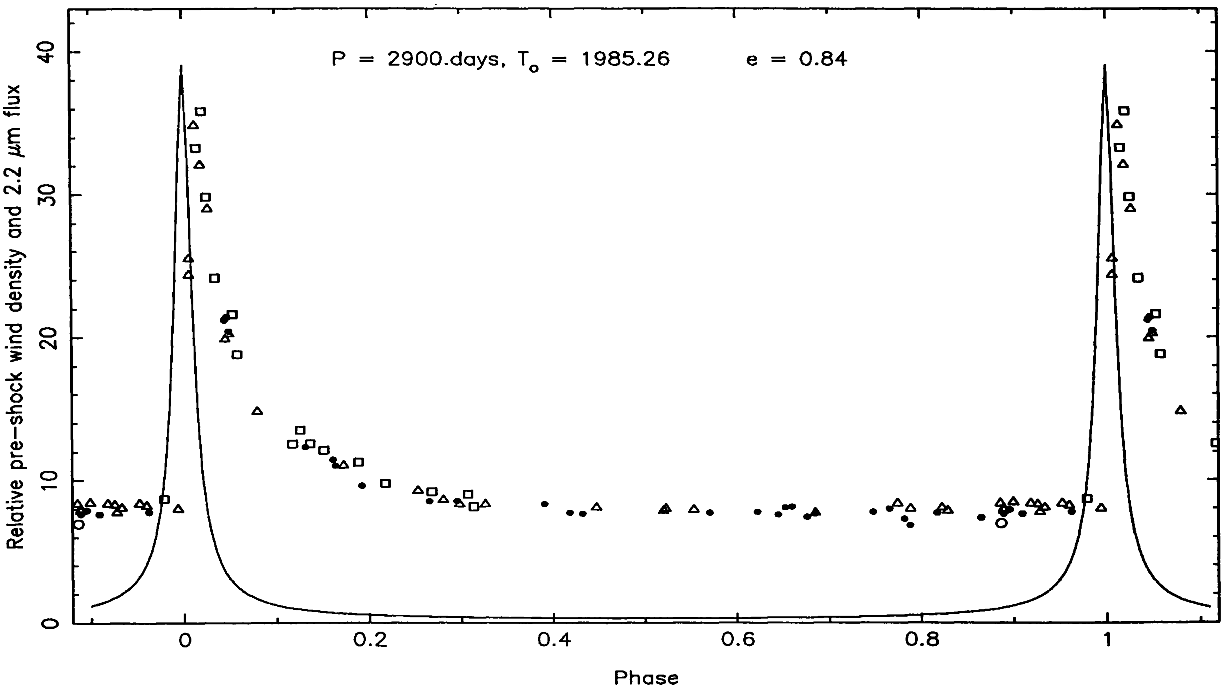

Fig. 3. The density (continuous line) in the Wolf-Rayet stellar wind at the position of the wind-wind interaction region as a function of orbital phase. The density is relative to that at a distance from the WR star equal to the semi-major axis of the orbit. Plotted against the same phases are 2.2 μm fluxes (symbols, different for observations from different cycles) from the K magnitudes.

Eichler & Usov 1993). Colliding-wind effects also appear to provide the clumping required for dust formation.

The question is: which of these clumping effects varies systematically during the orbit of WR 140 so as to trigger dust formation for ~ 0.02P around periastron passage? The winds collide all the time, so the answer must lie in the pre-shock wind density near the interaction region. Because the orbit is so eccentric ($e = 0.84$), the separation of the stars and pre-shock wind density vary drastically around the orbit, especially near the time of periastron passage, when the pre-shock density at the interaction region in an isotropic wind is about two orders of magnitude greater than that during most of the orbit (Fig. 3). These "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). The dust formation itself may not occur until the compressed material has been carried sufficiently far down along the wind contact surface for grains not to be heated to sublimation by the stellar radiation field. For a distance ~ 150 AU from the stars and a velocity ~ 2900 km s^{-1}, this introduces a delay of ~ 90 days ($\sim 0.03P$) between the times of maximum interaction (at periastron passage) and maximum dust formation. This is consistent with the observed phase difference between maximum pre-shock density and dust formation (Fig. 3).

Another possibility comes from the inference by White & Becker (1995) from the radio light curves that the wind of the WC7 star is concentrated in a disk inclined to the orbital plane of the binary. The O star passes through this disk twice during the orbit, producing two maxima of different size in the wind-wind interaction. One of these, at $\phi \sim 0.7$, was identified as the cause of the maximum in the non-thermal radio emission and the other, at $\phi \sim 0.002$, proposed as the trigger for dust formation. White & Becker pointed to the slightly later phase than periastron passage at which the O star passed through the disk as a reason for preferring their model to the spherical wind model. However, the difference of ~ 6 days is small compared with the uncertainties in the epoch of periastron passage and the ~ 90-day delay as the compressed material reached the dust condensation radius. A definitive test may be provided in the future by the identification of a system having a much lower orbital eccentricity than WR 140, which might show two episodes of dust formation per orbit corresponding to two passages through a disk. Also, a quantitative model of the proposed WR 140 disk is required to compare the density contrasts provided by passing through it and by the eccentric orbital motion.

In either event, the message is that dust formation by WR 140 is periodically triggered when sufficiently

TABLE 1

PROPERTIES OF EPISODIC DUST-MAKING WR STARS

WR	HD	Spectrum	Binarity	Dust Maxima	Period	Other phenomena
140	193793	WC7+O4-5	SB2, orbit	1977, 1985, 1993	7.94y	X-ray, non-T radio
137	192641	WC7+?	SB1?	1984	~13y	secondary episodes
125		WC7+O9		1993	> 15y	X-ray, non-T radio
70	137603	WC9+B0I	SB2	1979	> 6y	IR eclipse 1992
19		WC4+O		?1987	> 8y	
48a		WC8-9		1979	> 16y	secondary episodes

dense material is incorporated in the wind collision region and then compressed to high enough density. We now ask whether this model has wider applicability.

4. OTHER EPISODIC DUST-MAKING WR STARS

Apparently similar signals to those from WR 140 have been observed from five other Wolf-Rayet systems, whose properties are summarised in Table 1. The outburst from another WC7-based system plotted in Fig. 1, WR 125, is seen to have about the same amplitude as that from WR 140 but to have occurred more slowly, taking about two years to reach maximum. The rising light curves at different wavelengths have been studied and modelled in terms of the effects of a growing reservoir of cool dust, while hot dust continued to condense (Williams et al. 1994). As in the case of WR 140, the newly formed dust cooled as it was carried away in the wind. However, dust condensation by WR 125 continued for so long that the earliest dust to condense cooled so much that it no longer emitted in the near infrared. At this stage, the effects on the infrared emission of the cooling of the dust as a consequence of its dispersal and of the continued condensation of hot dust were in balance. Consequently, the rising light curve flattened, as seen in the L' light curve in Fig. 1. The behaviour after maximum is not well defined, but it is evident that the emission is now (1995) fading at a rate comparable to that of WR 140.

Although WR 125 is not a confirmed CWB like WR 140, there is strong circumstantial evidence for its being one. Recent spectroscopy of WR 125 in the blue has revealed absorption lines attributable to an O9 companion (Williams et al. 1994). Also, this star shows strong X-rays (Pollock 1987) and variable non-thermal radio emission (Williams et al. 1992). Like that from WR 125, the radio emission from WR 125 can be modelled in terms of a synchrotron source which suffered increasing circumstellar wind extinction prior to the dust-formation episode. It is also apparent from the infrared light curve that, if the variations are periodic, the period is rather long. If the fading of the dust emission continues at a similar rate to that of WR 140 —which is plausible, given their similar wind velocities— then the 3.8 μm flux should return to its base level in mid-1997. The interval between the 1982 observation and the more frequent observations since 1987 would then not have been long enough for an earlier dust-formation and cooling episode to have occurred, so any previous episode must have finished no later than mid-1982, implying a period of at least 15 years if the eruptions are indeed periodic.

The status of the third system plotted in Fig. 1, WR 137, as a binary is still uncertain: Annuk (1995) derived orbital elements from the C III-IV λ4650 emission feature and several absorption lines, but Underhill (1992) did not find systematic radial velocity changes nor spectroscopic features attributable to a companion in her 1986–1991 dataset. Clearly, more observations are needed, particularly over the next few years because the spectroscopic period derived by Annuk (5680 days) is somewhat longer than that ($\sim$ 4700 days) indicated by folding the infrared light curve. As seen in Fig. 1, the fading of the emission after the maximum in 1984.5 has been slower and more irregular than that from WR 140. The relative slowness in the initial decline is attributable to the fact that the wind carrying away the dust formed by WR 137 is slower (1900 km s^{-1}, Eenens & Williams 1994) than those ($\sim$ 2900 km s^{-1}) of WR 125 and WR 140. The irregularities, which are not well defined owing to incomplete coverage, suggest that there may have been three or four secondary episodes of dust formation. If these episodes were triggered by wind-collision effects, they imply that the density structure of WR 137's wind is more complex than that of WR 140.

Another star showing secondary episodes of dust formation is WR 48a. This star was discovered by Danks et al. (1983) while its infrared flux was rising to a maximum in 1979. Its fading since then has been monitored and small ($\Delta K \sim 0^{m}.25$) secondary outbursts were observed in 1990 and 1994. Unfortunately, owing to its heavy reddening and proximity to a bright star, there is little optical spectroscopy of WR48a and no information as to its status as a binary.

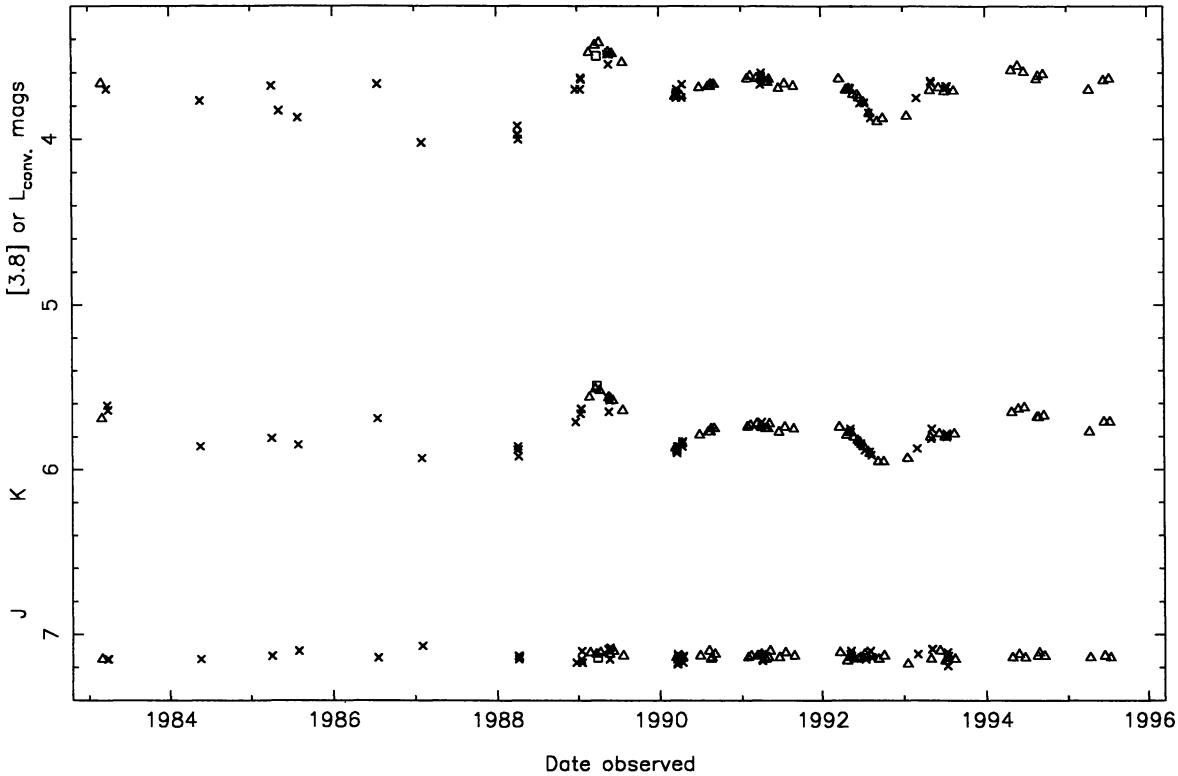

Fig. 4. Light curves of WR 70 (HD 137603) at 3.8 μm (from L' and L converted using an empirical colour equation), K and J.

Another southern star whose dust emission was discovered serendipitously is WR 19. Only the fading of the infrared emission has been observed, so the date for its maximum given in Table 1 is a conjecture based on the dust temperature when it was first observed and an estimate of its cooling rate (Williams et al. 1990b). This star has the earliest spectral subtype of any dust-making Wolf-Rayet star known. New spectroscopy with the 1.9-m Radcliffe telescope of the SAAO in 1995 shows the presence of hydrogen (Hβ–Hϵ) and helium absorption lines in its spectrum, indicating the presence of an early-type companion to the WC4 star. This star deserves a spectroscopic study to search for orbital motion.

The third southern system which may be related to WR 140 is the WC9+B0I binary HD 137603 (WR 70). Niemela (1995) estimated a mass ratio M(WC9)/M(B0I) of 0.45 from the anti-correlated radial velocities of the absorption and λ4652 emission features but did not find an orbit, suggesting a long period for the system. The WC9 component has a wind of 1150 km s^{-1} (Eenens & Williams 1994) and the B0I component is expected to have a wind of $\sim$ 1500 km s^{-1} (Prinja, Barlow, & Howarth 1990), making WR 70 another long-period CWB. The infrared data differ from those of the other stars in showing dust emission all the time: the offset of the K and L' light curves in Fig. 4 indicates $(K - L')$ colours in the range $1.9 - 2.2$, always significantly redder than that ($\sim$ 0.6) of a dust-free WR system adjusted to the interstellar reddening of WR 70. Comparison of the light curves in J, K and L' shows that the dust emission varies while the underlying star (which determines the J magnitudes, cf. the SED in Fig. 2 of Williams, van der Hucht & Thé 1987), does not vary significantly. Two features are well defined by the light curves. There was a maximum in early 1987 which resembles the dust formation episodes of WR 140 in that the dust was hotter (i.e., $(K - L')$ bluer) while the flux was rising than when it was falling. This indicates that there was a short-lived increase in the rate of dust formation for a few months. While this was taking place, there was more newly formed hot dust than usual, giving a higher average dust temperature and bluer $(K - L')$ colour. When the rate of dust formation fell again, there was for a while a higher proportion of cooling dust giving a redder $(K - L')$ colour. The second feature is the broad minimum at the end of 1992. The fading during 1992 was not accompanied by a reddening in $(K - L')$, implying that it was *not* caused by a temporary lull in dust formation and the cooling of the existing dust. The implication is that part (~ 20%) of the heated dust must have been eclipsed —presumably by a sufficiently thick body of cold dust on the outskirts of the system. Clearly, we have another complex system whose density structures may be related to colliding-wind compression, and an important step in unravelling it must come from determination of its orbit.

5. CONCLUSION AND ACKNOWLEDGMENTS

It was the analysis of the infrared light variations of WR 140 that led to the demonstration that this system was indeed a binary, leading in turn to the study of its colliding winds and their X-ray and radio emission. We know much less about the other stars in Table 1 but they all share at least one property with WR 140 and could make up a class of long-period CWBs. The study of the conditions allowing the formation of circumstellar dust will give unique information on the results of wind collision in these systems.

The long-term infrared photometry underpinning this project was observed from the United Kingdom Infrared Telescope (UKIRT), European Southern Observatory (ESO), South African Astronomical Observatory (SAAO), Carlos Sánchez Telescope (TCS) of the Instituto Astrofísica de Canarias, Observatorio Astronómico Nacional at San Pedro Mártir (SPM) and Rothney Astrophysical Observatory (Calgary), for which I thank particularly Tom Geballe and UKIRT Service Observers, Karel van der Hucht and Patrice Bouchet, Mark Kidger and TCS Service Observers, Patricia Whitelock and colleagues at the SAAO, Mauricio Tapia and Sean Dougherty. The studies of individual stars will be reported in detail elsewhere.

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