RevMexAA (Serie de Conferencias), **38**, 54–58 (2010)

WOLF RAYETS: INTERFEROMETRY OF HOT DUST

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RESUMEN

Las Wolf Rayets (WRs) son estrellas masivas calientes en sus últimas etapas evolutivas. Son indicadores prominentes de la formación de estrellas de gran masa y sus vientos masivos tienen influencia significativa en el medio interestelar. Es sabido que un pequeño pero significativo número de estas estrellas en la galaxia producen copiosas cantidades de polvo. Dado el hostil ambiente circunestelar, esto plantea preguntas interesantes. Las observaciones interferométricas y de abertura de máscara indican fuertemente que la binariedad juega un rol fundamental en la formación del polvo. Repasaré brevemente observaciones de alta resolución angular en el cercano y medio-infrarrojo que brindan una cierta luz sobre el polvo de las WRs.

ABSTRACT

Wolf Rayets (WRs) are hot massive stars at a late stage of evolution. They are prominent signposts for high mass star formation and their massive winds have significant influence on the interstellar medium. A small but significant number of these stars in the Galaxy are known to produce copious amounts of dust. Given the hostile circumstellar environment, this raises interesting questions. Interferometric and aperture masking observations strongly indicate that binarity plays a pivotal role in the dust formation. I will briefly review high angular resolution observations in the near- and mid-infrared which shed some light on dusty WRs.

Key Words: circumstellar matter — stars: Wolf-Rayet — techniques: interferometric

1. INTRODUCTION

Stars more massive than $\sim 40\ M_\odot$ will likely evolve through a Wolf-Rayet (WR) phase and a possible Luminous Blue Variable (LBV) phase before ending their lives as supernovae. Here I briefly review dust formation during the WR phase and high angular resolution observations thereof. Figure 1 from Davidson et al. (1989) roughly sketches the evolution of a massive star on the HR diagram. The LBV phase is known for short, massive and irregular episodes of explosive mass ejection of up to $10^{-4} - 10^{-5}\ M_\odot$ (Humphreys & Davidson 1994). The WR stage is mainly subdivided into the WN and WC phases, with strong Nitrogen and Carbon emission respectively (Smith 1968). Dust formation is strongly associated with the WC phase (see Crowther 2007 for a comprehensive review of WRs).

Of late, stars massive enough to pass through the WR stage have received attention as possible progenitors of soft gamma ray bursts (MacFadyen & Woosley 1999). In star-forming glaxies, massive stars dominate feedback to the ISM, and the spectacular emission features of WRs can dominate the continuum spectra. Even though in our Galaxy WRs only contribute a small fraction of the total dust, each individual dust-forming WR can produce up to $10^{-6}\ M_\odot$ per year of dust. Given such copious dust production, the lack of a complete picture of the physical conditions and chemical pathways for the formation of dust stands out.

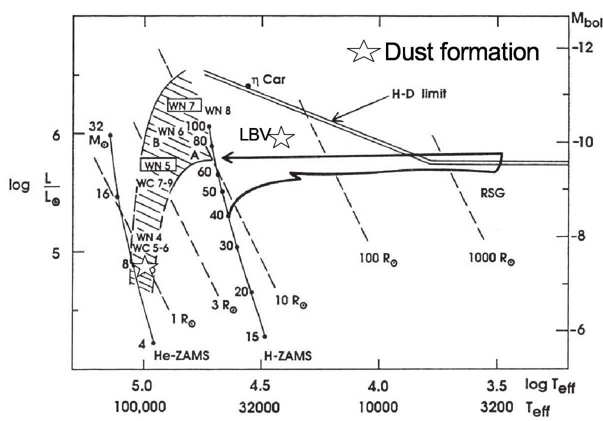

Fig. 1. Possible evolutionary path for a $\sim 40\ M_\odot$ star, adapted from Davidson et al. (1989). The empirical H-D limit beyond which Red Super Giants are not seen is indicated. Dust formation (indicated by star symbols) is associated with the LBV and the WC stages. The hatched region encompasses the WR phases.

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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		

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

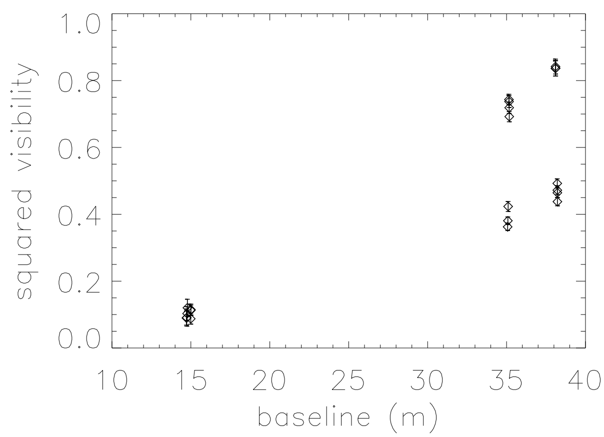

Fig. 2. WR 137: Squared visibilities obtained in the H band with the IOTA interferomter in July 2005.

2. INTERFEROMETRY OF DUSTY WOLF-RAYETS

Dust formation in WRs is almost exclusively seen in the WC sub-type (van der Hucht et al. 2001), signalled by a large IR excess. About 10% of known WRs produce dust, the majority of which are late type WC stars (see Table 1). Long term IR photometry (Williams et al. 1987) has led to considerable insights on the nature of dust production. The IR light curves fall into “periodic”or “persistent” categories. The regular rise and fall of the periodic category reveals the presence of a binary system. The favored mechanism for dust production in this case is a WR-O/B binary system wherein the wind-wind collision zone is the dust-forming region, with bursts of dust formation happening at periastron passage (Usov 1991).

2.1. *Periodic dust formation*

The archetypal periodic dust producers are WR 137 and WR 140. A spectroscopic orbit has been determined for WR 140 (Marchenko et al. 2003) and extensive work has been done in the radio on synchrotron emission from the wind collision zone, e.g., Dougherty et al. (2005), leading to a fairly detailed understanding of the dust formation zone in this system. Monnier et al. (2004) determined the position angle and separation of this WR-O/B pair using long-baseline IR interferometry with the IOTA instrument (now defunct). These parameters, used in conjunction with radio data, enable modeling of the inclination of the orbit as well (Dougherty et al. 2005b). IR interferometry has been making steadily increasing impact in the study of massive binaries; the recently determined astrometric orbit for γ^2 Velorum, the closest WR-O/B binary (albeit non-dusty), with the SUSI interferometer (North et al. 2007), is a case in point.

WR 137, on the other hand, has not been spectroscopically resolved and no orbit has been determined, though the 13 year periodicity of the IR light curve indicates the binary period. We have attempted interferometric observations of both WR 140 and WR 137 with the ultimate goal of determining the astrometric orbit. In addition to adding to the handful of WRs with directly measured masses, this would also help constrain better the physical conditions prevailing in the dust-production zone. The main challenges for dust formation scenarios are: i) obtaining the physical conditions necessary for forming dust in the vicinity of these extremely hot (> 40,000 K) stars and ii) establishing the chemistry of the dust nucleation and grain growth (Crowther 2003 and references therein).

We used the 3-beam IONIC combiner on IOTA to obtain visibility and closure phase data on WR 137 in July 2005 (Figure 2) on baselines ranging up to 38 m in the H band. We were able to resolve the binary and preliminary estimates put the separation at 9.8±0.6 mas with a brightness ratio of 0.81±0.2. The non zero closure phases (Figure 3) help us constrain the position angle at 295±1.3 degrees measured E of N from the brighter to fainter star. Along with a measurement with the Keck interferometer (80 m baseline, K band) in 2004 and recent measurements (2008) in the visible with the PAVO combiner at CHARA (650−950 nm, up to 200 m baselines with closure phases; P. Tuthill PI) we should be able to fit an astrometric orbit to WR 137. Considering that

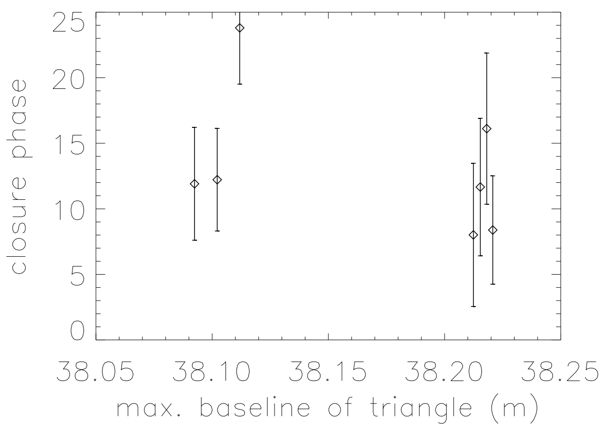

Fig. 3. WR 137: Closure phases obtained in the H band with the IOTA interferometer in July 2005. The maximum baseline in each triangle involved is plotted on the X-axis.

both WR 140 and WR 137 are headed towards periastron phase in 2010 with the associated episode of dust production, determining the orbital parameters of the binary take on added importance.

2.2. *WRs with Persistent Dust*

The episodic dust production in some WRs immediately provides some indication of an underlying binary. But several dusty WRs show persistent IR excess (see Table 1), posing a puzzle. While dust formation in the massive winds of single WRs might be possible (Cherchneff et al. 2000), finding the right conditions (higher density, lower temperatures and shielding from the UV radiation) in the immediate environment of these hot stars is a challenging task. Optical depths of the order of unity are achieved well into the fully developed wind, where the electron temperature is of the order 10^4 K, and Carbon (assumed to be the primary dust constituent) is fully ionised, making dust grain formation a formidable challenge.

The interferometric technique of aperture masking in the near IR, primarily with the Keck telescope, has made significant impact in this area by providing diffraction-limited images of fairly high dynamic range. For example, WR 98a and WR 104 are resolved into rotating "pinwheel" nebulae at milliarseconds scale (Tuthill et al. 1999; Monnier et al. 1999). More recently, the enigmatic "cocoon" stars in the Galactic Center have also been resolved into pin-wheel spirals using this technique (Tuthill et al. 2006). The regular period of rotation is an immediate indicator of an underlying close binary, with dust formation in the colliding winds. Though the central binary remains unresolved, long-term monitoring of the pinwheel nebulae have revealed much about the physical conditions and geometry of the archetypal WR 104 system. Tuthill et al. (2008) presents a six-year, 10-orbit data set of aperture masking images from which a wealth of detail is extracted. Binary parameters like the orbital period, eccentricity, inclination to the line of sight are constrained and elements of the dust-formation scenario like the angular outflow velocity, distance from the wind stagnation point to the dust peak and the entanglement of the WR and O/B winds are also discussed.

The caveat remains, however, that only a handful of peristently dusty WRs have been imaged with high-angular resolution techniques (see also Marchenko & Moffat 2007). We carried out VLTI MIDI observations of WR 106 and WR 95 (Rajagopal et al. 2007), two late type WC stars with IR excess from dust, but no evidence for binarity. Williams et al. (1987) derives dust shell sizes and dust mass estimates from fitting the IR SED for these and a number of other dusty WRs. Our main goal was to directly resolve the sizes of the dust shells, and probe for clues to the dust formation mechanism. The observations were primarily carried out with a 45 meter baseline in the 8–13 μm MIDI band, yielding spectrally dispersed visibilities at $\sim$ 10 mas resolution. To supplement this study we also carried out 10.7 μm observations with the Keck telescope, probing scales of $\sim$ 40 mas. For the latter, an innovative "segment-tilting" method (Tannirkulam et al. 2005) was used wherein groups of the Keck mirror-segments were combined to form sub-apertures and the resulting speckle frames were analyzed to extract high resolution information akin to the aperture-masking technique in the near-IR.

Figure 4 shows the MIDI visibilities and corresponding gaussian sizes as a function of the wavelength. Both dust shells were clearly resolved by the MIDI baseline. We then used a radiative transfer model of a spherical shell based on these visibility profiles to arrive at the basic dust shell parameters (Figure 6: for details see Rajagopal et al. (2007)). The initial parameters for our model were based on Williams et al. (1987). For WR 106, we arrive at an inner dust shell radius of 280 $R_\star$ ($\sim$ 20 AU, assuming a distance of 2.3 Kpc). The results are similar for WR 95. The dust composition was assumed to be amorphous C (Williams et al. 1987). We obtain the best agreement to the measured visibilities and the SED (from the optical to the far-IR, obtained from the literature) for a uniform grain size of $\sim$ 0.5 μm and an optical depth of 0.015 at 10 μm. The dust

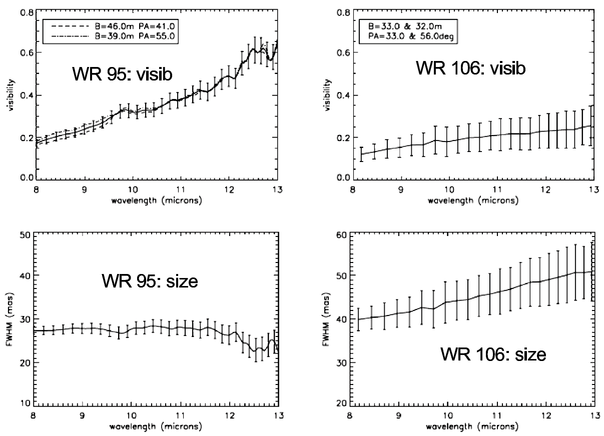

Fig. 4. Visibilities and corresponding gaussian sizes from the VLTI MIDI combiner for WR 95 and WR 106.

density profile is proportional to r^{-2}. We were able to resolve WR 106 (but not WR 95) with the Keck single aperture as well (Figure 5). We account for this in the model by introducing an over-dense region starting from the inner-edge radius (R_{in} out to about $14R_{in}$. At the angular scales probed by MIDI, the spherical geometry is probably justified and the derived inner radius gives us rough estimate of the distance from the dust to the central star.

The most significant result from this work is the proximity of the dust to the hot central object. In fact, the temperature profile we derive (Figure 6) indicates that the dust is close to sublimation ($\sim$ 1200 K or so), despite adopting a rather low photospheric temperature of 20,000 K for the WR star (see Crowther 2003). This, coupled with the large grain sizes indicated by our measurements enhance the puzzle of dust production in these stars. Dust appears to be forming under fairly extreme conditions. This may suggest a colliding wind binary; though we stress that there is no direct evidence yet. A further clue comes from the long-term aperture-masking study of a number of persistently dusty WRs. Monnier et al. (2007) finds evidence from a surface brighness relation in the near-IR bands that the underlying near-IR emission mechanism is the same for these objects.

3. DISCUSSION

To conclude, we seem tantalisingly close to establishing that all dusty WRs are in fact colliding-wind systems. But numerous issues remain. The next logical step would be to use multiple-baseline interferometry or other high resolution techniques to directly or parametrically image a number of these objects which are within the sensitivity and resolution

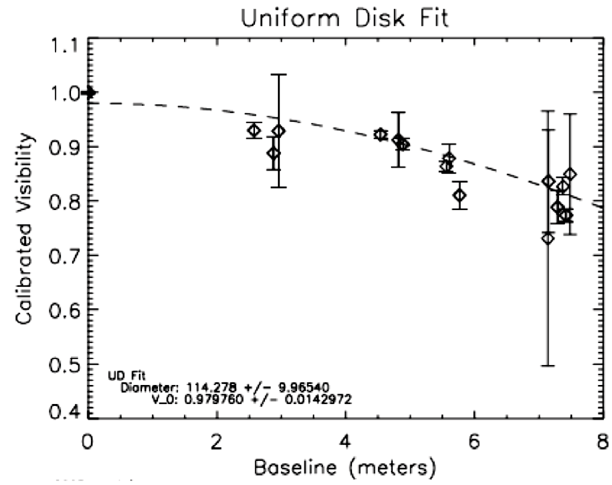

Fig. 5. Visibilities from the "segment-tilting" experiment on WR 106 from the Keck-I telescope, showing a resolved dust shell. A uniform disk fit is indicated.

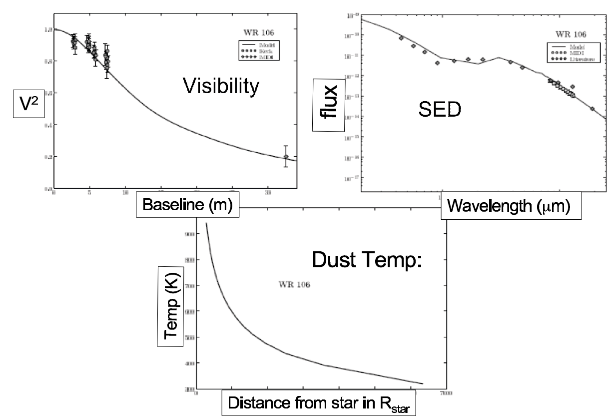

Fig. 6. The radiative transfer model for the spherical shell around WR 106: Clockwise from the top left: (1) The fit to the visibilities, the short baselines are from the Keck measurement. (2) The model SED compared to measurements from MIDI and the literature. (3) The dust temperature profile.

of current instruments. Radio interferometry has also added much to the knowledge of physical conditions in the wind collision zone. However the chemistry of dust formation within the colliding-wind model remains unknown. Since the WC winds have little hydrogen, the dust-formation needs hydrogen-free chemistry. The O/B companion could possible contribute H into the mix, but the mixing scenario for the winds is complex (Tuthill et al. 2008). Zubko (1998) sketches a possible pathway to grain growth through carbon-ion accretion, but the nucleation itself is not addressed. Cherchneff et al. (2000) discuss grain nucleation and growth in a H-free, single WR wind environment, but the large grain sizes indicated by various measurements pose difficulties. The best attempts at this problem currently fall short of establishing the first links in the chain of dust nucleation and grain growth. Clearly much remains to be done in this challenging area.

Zinneker: *Are there any relevant Spitzer observations of dust composition in these late type WC stars?* — I can't recall any specifics on dust composition from Spitzer. I think there is a Spitzer measurement which claims to find dust around a WN star, which would involve very different make-up from the amorphous C we assume here.

Miroshnichenko: *Is the dust formation in "persistent" dusty WRs continuous? What is the fate of the dust formed around WR stars?* — Yes, apparently the orbits are tight enough for wind-collision (assuming that is the mechanism) to form dust for most of the period. Presumably, the dust survives and cools in the outer environs (this could affect the light curves of the ensuing SNe).

Trunkovsky: *What is the possibility of some similarity in the mechanism of dust formation in AGBs vs WRs, despite their great differences?* — I would say there are certainly many more differences than similarities.

REFERENCES

Cherchneff, I., Le Teuff, Y. H., Williams, P. M., & Tielens, A. G. G. M. 2000, A&A, 357, 572

Crowther, P. A. 2003, Ap&SS, 285, 677

_________. 2007, ARA&A, 45, 177

Davidson, K., Moffat, A. F. J., & Lamers, H. J. G. L. M., eds. 1989, IAU Colloq. 113, Physics of Luminous Blue Variables (Dordrecht: Kluwer)

Dougherty, S. M., Beasley, A. J., Claussen, M. J., Zauderer, B. A., & Bolingbroke, N. J. 2005, ApJ, 623, 447

Dougherty, S. M., Pittard, J. M., & O'Connor, E. P. 2005, in Massive Stars and High-Energy Emission in OB Associations, ed. G. Rauw, Y. Nazé, R. Blomme, & E. Gosset, 49

Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025

MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262

Smith, L. F. 1968, MNRAS, 138, 109

Marchenko, S. V., et al. 2003, ApJ, 596, 1295

Marchenko, S. V., & Moffat, A. F. J. 2007, ASP Conf. Ser. 367, Massive Stars in Interactive Binaries, ed. N. St.-Louis & A. F. J. Moffat (San Francisco: ASP), 213

Monnier, J. D., Tuthill, P. G., & Danchi, W. C. 1999, ApJ, 525, L97

Monnier, J. D., Tuthill, P. G., Danchi, W. C., Murphy, N., & Harries, T. J. 2007, ApJ, 655, 1033

Monnier, J. D., et al. 2004, ApJ, 602, L57

North, J. R., Tuthill, P. G., Tango, W. J., & Davis, J. 2007, MNRAS, 377, 415

Rajagopal, J., et al. 2007, ApJ, 671, 2017

Tannirkulam, A., Monnier, J., Ireland, M., Tuthill, P., Harries, T., & Cohen, R. 2005, Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 8383

Tuthill, P. G., Monnier, J. D., & Danchi, W. C. 1999, Nature, 398, 487

Tuthill, P., Monnier, J., Tanner, A., Figer, D., Ghez, A., & Danchi, W. 2006, Science, 313, 935

Tuthill, P. G., Monnier, J. D., Lawrance, N., Danchi, W. C., Owocki, S. P., & Gayley, K. G. 2008, ApJ, 675, 698

Usov, V. V. 1991, MNRAS, 252, 49

van der Hucht, K. A., Williams, P. M., & Morris, P. W. 2001, The Promise of the Herschel Space Observatory, ed. G. L. Pilbratt, J. Cernicharo, A. M. Heras, T. Prusti, & R. Harris (ESA-SP 460; Noordwijk: ESA), 273

Williams, P. M., van der Hucht, K. A., & The, P. S. 1987, A&A, 182, 91

Zubko, V. G. 1998, MNRAS, 295, 109