Radio and Infrared Properties of Dust-Enshrouded Wolf-Rayet Stars

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Abstract. This paper discusses our ongoing efforts to characterize dust-enshrouded Wolf-Rayet (WR) stars in the radio and infrared. We have used the Very Large Array to measure the broadband radio spectrum of WR stars in suspected binary systems and discovered non-thermal emission, which is usually attributed to colliding winds. In addition, infrared imaging using aperture masking interferometry on the Keck-I telescope has resolved the dust shells around a number of WR stars with K-magnitudes brighter than \( \sim 6 \). Although this admittedly small study suffers from selection bias, we note that all the dust-enshrouded WR stars with radio detections show evidence for colliding winds, supporting the theory that wind compression in a binary system is necessary for efficient dust production. A consequence of this hypothesis is that virtually all WC8-10 stars must be in binaries, since most are dusty. Single-star and binary stellar evolution models will have to be modified to accommodate this observational result if confirmed.

1. Introduction

The relationship of binarity to dust production for Wolf-Rayet (WR) stars is controversial. Most will agree that the physical conditions around single WRs are unfavorable for dust production (e.g., Cherchneff & Tielens 1995; Le Teuff et al. 2001) due to the intense radiation field, low hydrogen content, and rapid density decrease in the fast expanding winds, although some mechanisms have been proposed (Zubko 1998). The realization that WR 140 was an eccentric binary system naturally explained the observed non-thermal radio emission and episodic dust production in terms of colliding winds, with high gas compression at periastron catalyzing dust creation (Moffat et al. 1987; Williams et al. 1990; Usov 1991).
But are colliding winds necessary for dust production around WR stars? Dust-enshrouded WR stars have been classified as either “variable” or “persistent” dust-producers, based on the variability of IR flux (Williams & van der Hucht 1992). While the variable dust producers can be easily understood in terms of WR 140-style colliding wind systems, the binary nature of the persistent dust producers has been unknown until more recently. Diffraction-limited infrared imaging with the Keck-I telescope revealed that spiral-shaped dust shells, “pinwheel” nebulae, surround two of the dustiest WR stars (WR 104, WR 98a), most likely created through the colliding winds of a WR+OB binary system in a close orbit (Tuthill, Monnier, & Danchi 1999; Monnier, Tuthill, & Danchi 1999). These observations have led to a more unified picture of the dusty Wolf-Rayet stars in terms of interacting wind (binary) systems. On the one hand, WR 140 and other episodic emitters consist of eccentric systems with $\gtrsim 10$ year orbits, while WR 104 and WR 98a have more circular (circularized?) orbits with periods $\sim 1$ year. But are all dusty sources somewhere on this continuum of binary orbits, or could some of them be single stars?

In this paper, we give a progress report including preliminary results of our work to detect non-thermal emission from pinwheel nebulae and our search for more pinwheel nebulae in the infrared.

2. New Radio Observations

We used the Very Large Array (VLA) to measure the broadband spectra of three dust-enshrouded Wolf-Rayet systems, WR 104, WR 98a, and WR 112, at wavelengths of 1.3, 2, 3.6, 6, & 21 cm. At the time of our observations, WR 112 was the only dust-enshrouded WR star to have a radio detection (Leitherer et al. 1997; Chapman et al. 1999), and our programme was designed to improve upon the sensitivity limits of previous surveys by factors of 3 to 10, with a goal of $\sim 100 \mu$Jy point-source sensitivity. In addition, another 12 sources have been observed with the Australian Telescope Compact Array with somewhat less sensitivity.

Preliminary results of observations from 1999 September and 2000 February are shown in Figure 1. We have clearly detected WR 104 and WR 98a for the first time, at the higher frequencies. Together the two observing sessions cover 5 wavelengths for each star. Unfortunately, we could not study each star at all wavelengths during each epoch, but repeated observations at certain wavelengths confirm that the fluxes did not change dramatically between observations. Full details will be included in a future paper.

We draw the important conclusion that these sources all show evidence for non-thermal emission. The straight dashed lines in Figure 1 show the expected power law slope ($\alpha \sim 0.6$) for a pure (thermal) wind source, and our data does not show the expected increase with frequency (e.g., Leitherer & Robert 1991). In addition, WR 104 and WR 98a both show a dramatic drop in flux at 21 cm where the non-thermal emission should be bright, likely caused by free-free absorption. The radio photosphere is expected to be well outside the non-thermal emission region at these wavelengths, and such absorption is observed at long wavelengths for WR 140 (White & Becker 1995), although a detailed understanding is geometry-dependent.
We fitted a simple two-component model to the data, consisting of thermal wind (spectral index $\alpha = 0.6$) and non-thermal ($\alpha = -0.5$) components, where we account for free-free opacity, $\tau_\nu \propto \nu^{-2.1}$ (as Chapman et al. 1999). The results of fits to the WR 112 and WR 98a data have been included in Figure 1, and the 6 cm optical depths are reported in the legend. Based on the long wavelength turnover, the optical depth of the wind appears higher for both WR 98a and WR 104, than for WR 112 at this epoch. This could mean that the binary separation of WR 112 is larger than for WR 98a and WR 104, or that we are viewing the system through a “hole” in the wind. For instance, if the OB-type companion was in front of WR 112, then we would view the shock collision zone through the OB-wind rather than the denser WR wind; this kind of effect has also been seen in WR 140 (White & Becker 1995).

The variability of the WR 112 radio flux reported in Chapman et al. (1999), and further supported by our new data, indicates an eccentric orbit and/or an “edge-on” viewing angle of the underlying binary. We are currently monitoring the broadband radio spectrum of WR 112 every two months, and hope to constrain the period and geometry by combining this information with IR images (to be discussed in the next section) and possible VLBA images of the wind-collision shock. We note that, as of 2000 June, the radio flux of WR 112 is about a factor 2 (more at longer wavelengths) lower than seen in 2000 February.
3. Infrared Observations

Diffraction-limited imaging in the infrared (resolution $\lesssim 0.050$) was performed using aperture masking techniques on the Keck-I telescope. Observing details can be found elsewhere in this volume (Tuthill et al. 2001), and in the literature (Tuthill et al. 2000; Monnier 1999). After the initial discoveries of pinwheel nebulae around WR 104 (Tuthill et al. 1999) and WR 98a (Monnier et al. 1999), we enlarged our sample to include most WR stars with K-magnitude brighter than K=6. This sample consists mostly of late-type WC stars (WC8-10), categorized as persistent dust emitters by Williams & van der Hucht (1992).

All of the dusty sources are at least partially resolved with sizes between 20 and 80 mas, assuming Gaussian brightness distributions and azimuthal symmetry (see Figure 2). A few sources (WR 140 and WR 11) do not show evidence for dust in their spectrum and our observations confirm that these sources are not extended.
Four sources are extended enough to allow meaningful image reconstructions: WR 104, WR 98a, WR 112, and WR 48a. While WR 104 and WR 98a have already been subjects of recently published papers based on aperture masking, the structure of the dust shell of WR 112 was first resolved using lunar occultations (Ragland & Richichi 1999). In a future paper (Monnier et al. 2001), we will present our multi-epoch images of WR 112 showing a very disorganized and asymmetric dust shell changing significantly with time, rather unlike the pinwheel nebulae of WR 104 and WR 98a. WR 48a appears to be quite extended, but high resolution imaging is hampered by telescope vignetting and poor atmospheric stability when observing this low declination source (maximum elevation \(\sim 8^\circ\) at Keck!).

Since we have surveyed all known IR-bright Wolf-Rayet stars and because the emission at 2.2\(\mu\)m is dominated by thermal emission, we do not expect to discover any more Wolf-Rayets systems with large-scale dust emission that can be mapped using the Keck-I telescope at this wavelength. This is simply because the expected angular size is proportional to the received flux, for a given surface brightness (i.e., dust temperature). However, there are likely variable sources which produce dust periodically (e.g., WR 140 in 2001 April), and these could be observed at IR-maximum once identified.

4. Conclusions

- The reddest (most obscured) WR stars (WR 104, WR 98a, WR 112) are in binaries.
- Non-thermal (i.e., flat spectrum) radio emission from colliding winds in these systems is detectable, although weak, confirming the binary hypothesis, and offering another way to establish the binary nature of systems which are too distant to resolve with direct imaging.
- WR 112 shows time variable infrared and radio emission, indicating an eccentric orbit for the underlying binary. IR imaging does not reveal a pinwheel nebula, but rather an extended and dynamically changing asymmetric envelope.

5. Future Work

- Conduct coordinated VLA/VLBA monitoring and IR imaging at Keck to answer the questions: why is this dust shell so complex? what are the physical parameters of the underlying binary?
- Determine if other obscured WR systems are in binaries. Methods to detect binarity include: monitoring IR light curves, measuring radio broadband spectra, visible and IR spectroscopy, detection of X-ray signature of colliding winds (?), precise radial velocity work (?)
- Since the vast majority of WC8-10 stars produce dust (Williams et al. 1987), then establishing that “all” dusty WRs are in binaries would further imply that WC8-10 stars are not produced through single star evolution.
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How could binary evolution affect the WR precursors to produce the photospheric structure of the late WCs? Perhaps Roche lobe overflow during a previous red supergiant phase (e.g., Monnier et al. 1999) could play a role here.

- With improved measurements of wind and binary parameters, accurate modelling of the high quality imagery of spiral structure could yield new distance estimates and probe mass-loss and colliding wind physics.

- Pursue IR interferometric observations to significantly resolve and image dust shells around other WR stars (possible with CHARA, IOTA). A number of promising candidates have been identified herein.

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