MASSIVE BINARY WR 112 AND PROPERTIES OF WOLF-RAYET DUST

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ABSTRACT

Some hot, massive, Population I Wolf-Rayet (W-R) stars of the carbon subclass are known to be prolific dust producers. How dust can form in such a hostile environment remains a mystery. Here we report the discovery of a relatively cool, extended, multicrystalline dust envelope around the star WR 112, most likely formed by wind-wind collision in a long-period binary system. We derive the binary orbital parameters, the dust temperature, and the dust mass distributions in the envelope. We find that amorphous carbon is a main constituent of the dust, in agreement with earlier estimates and theoretical predictions. However, the characteristic size of the dust grains is estimated to be \(\sim 1 \mu m\), significantly larger than theoretical limits. The dust production rate is \(6.1 \times 10^{-3} \ M_\odot \ yr^{-1}\), and the total detectable dust mass is found to be about \(2.8 \times 10^{-5} \ M_\odot\) (for \(d = 4.15 \ kpc\)). We also show that, despite the hostile environment, at least \(\sim 20\%\) of the initially formed dust may reach the interstellar medium.

Subject headings: infrared: stars — stars: winds, outflows — stars: Wolf-Rayet

1. INTRODUCTION

Classes of objects known to produce significant quantities of dust include asymptotic giant branch stars, red giants, novae, supernovae (each of which contributes about equal rates, \(\sim 10^{-3} \ M_\odot \ yr^{-1}\), of dust in the whole Galaxy), along with planetary nebulae and protostars (each of which yields \(\sim 10\) times less; Dwek 1985). Surprisingly, some hot, massive, Population I Wolf-Rayet (W-R) stars also form dust (van der Hucht, Williams, & Thé 1987). W-R stars are the evolved descendants of massive O-type stars. They consist mainly of He-burning cores surrounded by hot envelopes that drive fast, dense winds with average mass-loss rates of \(\sim 10^{-5} \ M_\odot \ yr^{-1}\) and terminal velocities \(v_w \sim 1000–4000 \ km \ s^{-1}\). There are three successive W-R phases, WN, WC, and WO, characterized by the dominant emission lines of N, C, and O, respectively, in their optical spectra. All dust-making W-R stars belong to the carbon-rich, hydrogen-poor WC subclass (Williams 1995). The W-R dust makers are remarkable for two main reasons: (1) the absolute rate of formation is very high, up to \(10^{-4} \ M_\odot \ yr^{-1}\) in dust alone, and occurs in either a periodic (due to enhanced wind-wind compression at or near the periastron passage in long-period WC + O binaries with eccentric orbits) or sustained fashion (in single late-type WC stars or moderately short-period WC + O binaries with circular orbits); and (2) the dust is formed in a hot, extremely hostile environment, where the formation process is still unknown.

Here we report on near- and mid-infrared imaging observations of the dust envelope surrounding the star WR 112 (spectral class WC9). The morphology of this envelope provides clues to the nature of the stellar system, while the photometry allows us to estimate the properties of the dust and the total dust mass.

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2. OBSERVATIONS

WR 112 belongs to the group of five WC stars with the densest known dust envelopes (van der Hucht et al. 1996). We observed WR 112, along with WR 104 and WR 118, with the University of Florida mid-IR imager “OSCIR” (Observatory Spectrometer and Camera for the Infrared) at the Gemini North 8 m Telescope using the medium-band 7.9, 12.5, and 18.2 \(\mu m\) filters on 2001 May 7. For WR 112, we supplemented the mid-IR data with near-IR narrowband \(h\) and \(k\) images taken at the Canada-France-Hawaii Telescope (CFHT) on 1999 June 27 with the adaptive optics bonnette and KIR camera, and with broadband \(L^\prime\) images obtained at the Infrared Telescope Facility on 2000 May 28 in the “movie burst” (\(2 \times 8192 \ 0.01 \ s\) exposures) mode of the NSFCAM imager. We also acquired images of point sources (point-spread function [PSF] reference stars), usually immediately before and after the principal target, for image restoration. The original data cubes were split into individual frames, quickly checked and selected for image quality using basic image statistics for the OSCIR and CFHT data (initially compensated for atmospheric turbulence) or carefully selected using a specifically designed statistical procedure for the NSFCAM images (taken without compensation). The individual images were then appropriately shifted to form a final image for each wavelength/target/instrument. The final images were then restored using the images of the PSF reference stars and a maximum entropy algorithm (the “STSDAS:ANALYSIS.RESTORE.MEM” task of IRAF) for the CFHT data, enabling us to reach 0.5 pixels (0.01 arcsec) resolution, or the “STSDAS:ANALYSIS.RESTORE.LUCY” task of IRAF for the OSCIR and NSFCAM images, thus reaching a 1 pixel resolution of 0.008 and 0.005, respectively.

3. DUST PROPERTIES

While WR 104 and WR 118 show only modest extensions on scales of several 0.1, a combination of the original mid-IR images of WR 112 reveals three sets of regularly spaced arclike structures extending out 3” from the central star (Fig. 1, left). It is apparent that the dust temperature gradually falls off o...
WR 112 is the fourth case in which dust around a W-R star has been mapped in some detail, with all the previous examples occurring in WC + O binaries (Marchenko, Moffat, & Gooddier 1999; Monnier, Tuthill, & Danchi 1999; Tuthill, Monnier, & Danchi 1999). Note that six other W-R stars have been shown to possess an extended (presumably spherically symmetric) envelope (Yudin et al. 2001; Monnier et al. 2002). WR 112 is also known to be a variable nonthermal radio emission source (Chapman et al. 1999; Monnier et al. 2002), which might indicate binarity (Dougherty & Williams 2000). There are few viable scenarios for dust production in WR 112. For example, the primordial circumstellar envelope would not have survived in the hard UV radiation field of the W-R progenitor. Periodic outbursts driven by stellar oscillations cannot explain the observed dust envelope shape without invoking a factor of 2 azimuthal variation in the terminal-wind velocity along with an extreme latitudinal dependence of the mass loss. Therefore, we assume that the dust is formed in the wind-wind collision zone of a massive binary system (thus resembling a collimated but rotating “beam” for a distant observer) and expelled radially outward at a constant, terminal-wind velocity \( v_w = 1200 \) km s\(^{-1}\) (Rochowicz & Niedzielski 1995). We then calculate the resulting locus of maximum dust density and fit it to the observed dust distribution in the restored mid-IR images, taking the necessary orbital elements \( (P, e, i, \omega, \Omega) \) as free parameters. We find a family of minimum-\( \chi^2 \) solutions for counterclockwise loci, in which the coupling of \( e-i \) and \( \omega-\Omega \) leads to some degree of degeneracy. Instead of relying solely on the single formal best fit, we therefore construct a synthetic solution by averaging all the possible combinations of solutions for which the \( \chi^2 \) values lie within 5% of the absolute minimum. This average solution has a period \( P = 24.8 \pm 1.5 \) yr, an eccentricity \( e = 0.11 \pm 0.11 \), an orbital inclination \( i = 38.0 \pm 38.8 \) deg, a periastron angle \( \omega = 179.6 \pm 18.5 \) deg, and an orbital orientation \( \Omega = 123.5 \pm 7.9 \) deg (1 \( \sigma \) errors). In Figure 2, we plot the solution with the highest possible, but still plausible, eccentricity: \( e = 0.40 \). This particular model yields a dust locus that is actually very close to that derived from the synthetic
solution. In general, the model provides fairly good fits to the southwest arms, although it fails to explain the pronounced northeast excursions as well as the bright southwest protrusion. The latter extends in the direction toward a stellar visual companion \( \sim 1'' \) from WR 112 (Wallace, Moffat, & Shara 2002 and our Fig. 2), which is not seen at near-IR, and is therefore probably also invisible at mid-IR wavelengths. Clearly the dust-production rate depends on orbital phase, diminishing as expected around apastron but surprisingly also absent around periastron, contrary to the situation in the eccentric, long-period colliding-wind WR + O binaries WR 137 and WR 140 (van der Hucht, Williams, & Morris 2001; Marchenko et al. 1999). The average thickness, \( \delta r \), of the dust arcs in the deconvolved images relative to the separation between the successive arcs, \( \Delta r \) (measured at the same orbital phase), gives an estimate of the shock-cone opening angle: \( \Theta \sim 2 \pi \times \delta r/\Delta r \sim 60^\circ -110^\circ \), similar to that found in other colliding-wind W-R + O systems (Marchenko et al. 1997; Bartzakos, Moffat, & Niemela 2001).

In Table 1, we list the calculated orbital elements along with the main characteristics of the dust envelope and the assumed parameters.

To derive the basic dust properties, which fortunately do not depend sensitively on the adopted orbital parameters, we first deproject all apparent distances by applying the synthetic average orbit solution. We calibrate the restored images using all available IR-flux measurements of WR 112 (Williams, van der Hucht, & Thé 1987; van der Hucht et al. 1996), assuming that the system has not experienced any large-amplitude IR outbursts. In the mid-IR range, the relatively large apertures used in previous ground- and space-based observations will tend to smooth out the variability by averaging over the output of many dust-formation cycles. We deredden the near-IR data by applying a Galactic interstellar-extinction model (Arenou, Grenon, & Gomez 1992) and then calculate the net dust fluxes after subtracting the stellar component, approximated as \( F_\lambda \sim \lambda^{-\alpha} \), with \( \alpha = 2.97 \) (Morris et al. 1993). Then we use the relation (Hildebrand 1983)

\[
M_d(r) = \frac{4\rho F(\lambda, r) d^2 a}{3B(\lambda, T(r))Q_\lambda(\lambda, a)},
\]

where \( M_d \) is the dust mass, \( F(\lambda, r) \) is the measured flux at a given position \( r \), \( \rho \) is the grain density, \( d = 4.15 \) kpc is the distance to WR 112 (van der Hucht 2001), \( a \) is the grain size, \( B(\lambda, T(r)) \) is the blackbody emissivity, and \( Q_\lambda(\lambda, a) \) is the grain emission coefficient. We adopt the general relation \( Q_\lambda(\lambda, a)/a = k\lambda^{-\beta} \) along with a \( T = T_r r^{-\beta} \) temperature profile (Williams et al. 1987) and measure the fluxes \( F(\lambda, r) \) over regions of fixed \( 7 \times 7 \) pixel size (0.623 x 0.623), assigning 15%/30% errors to \( F(\lambda, r) \) in the inner/outermost arcs. Taking the ratios of fluxes at every given position in the envelope (except the very central part, where the spectral distribution cannot be represented by a single temperature) in order to reduce the number of free parameters and to be impervious to large positional fluctuations in \( F(\lambda, r) \), we obtain via \( \chi^2 \)-minimization the following estimates: \( s = 0.90^{+0.22}_{-0.05}, T_r = 320^{+70}_{-30} \) K, and \( \beta = 0.40^{+0.05}_{-0.05} (T_r at 1''; 95\% confidence intervals) \). The dust emissivity index \( s \), though loosely constrained, is close to the range expected for amorphous carbon in the near-to-mid-IR domain (Borghesi, Bussoletti, & Colangeli 1985; Suh 2000).

On the other hand, the absence of the telltale 9.7 \( \mu \)m silicate emission feature in the WR 112 spectrum (van der Hucht et al. 1996) rules out the presence of any silicate-based mixture. The derived temperature profile follows the \( \beta = 0.4 \) dependence expected in the case of thermal equilibrium. Adopting \( \rho = 2.0 \) g cm\(^{-3} \) for the amorphous carbon dust, we estimate the dust mass separately for each \( 7 \times 7 \) pixel\(^2 \) area of each of the three mid-IR images and then average the results (Fig. 3). We find a total \( M_d = 5.5 \times 10^{-2} \) g, integrated over the observed envelope. To compare our result with an earlier theoretical estimate of the mass, we (1) account for the difference in the adopted distances to WR 112 and (2) assume that the observed dust is created for 15 yr (see Fig. 2) during each 25 yr orbital cycle, with three complete cycles accounted for. A model (Zubko 1998) with the assumption of a spherically symmetric envelope gives \( M_d = 3.8 \times 10^{-7} M_{\odot} \) yr\(^{-1} \) (converted to \( d = 4.15 \) kpc), while our estimate is \( M_d = 6.1 \times 10^{-7} M_{\odot} \) yr\(^{-1} \). A calculation of the integrated mass ratios, \( M(\text{innermost region + arcs}) : M(\text{middle arcs}) : M(\text{outermost arcs}) = 1.0 : 0.6 : 0.2 \), shows that the dust is gradually destroyed while leaving the system. Both the intense UV radiation field and the sputtering caused by the high drift velocities of the dust grains (Zubko 1998) may be responsible for the dust destruction. Nevertheless, the flattening of the trend at large

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**TABLE 1**  
**ORBITAL PARAMETERS ("SYNTHETIC SOLUTION"), BASIC DUST CHARACTERISTICS, AND ASSUMED VALUES**

| Parameter | Value | Errors\( ^a \) |
|-----------|-------|----------------|
| \( P \) (yr) | 24.8 | \( \pm 1.5 \) |
| \( e \) | 0.11 | \( \pm 0.11 \) |
| \( i \) (deg) | 38.0 | \( \pm 3.8 \) |
| \( \omega \) (deg) | 179.6 | \( \pm 18.5 \) |
| \( \Omega \) (deg) | 123.5 | \( \pm 7.9 \) |
| \( s \) | 0.90 | \( \pm 0.21, +0.22 \) |
| \( T_r \) (K) | 320 | \( -13, +12 \) |
| \( \beta \) | 0.40 | \( \pm 0.05, +0.05 \) |
| \( M_d (g) \) | 5.5 x 10^{28} | ... |
| \( M_d (M_{\odot} \text{ yr}^{-1}) \) | 6.2 x 10^{-7} | ... |
| \( a (\mu m) \) | 0.49 | \( \pm 0.11, +0.11 \) |
| \( v_{\text{los}} (\text{km s}^{-1}) \) | 1200 | Assumed |
| \( \rho_{\text{gas}} (\text{g cm}^{-2}) \) | 2.0 | Assumed |
| \( d (\text{kpc}) \) | 4.15 | Assumed |

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\( ^a \) Either 1 \( \sigma \) or a 95\% confidence interval.

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**Fig. 3.**—Integrated (within \( 7 \times 7 \) pixel areas) dust mass in grams. The filled triangles mark the central part of the image along with the two innermost arcs. The filled (open) squares/circles correspond to the southwest (northeast) mid-/outermost arc. The dotted line shows the trend expected in the case of mass conservation.
radii in Figure 3 suggests that some dust does reach the interstellar medium.

Finally, we use equation (1) to evaluate the characteristic size of the dust grains by comparing via least-square minimization the observed fluxes with the prediction of a simple model assuming that the envelope is populated by similar-sized spherical particles. We calculate the Mie absorption coefficients (Bohren & Huffman 1998), \( Q_{\text{abs}}(\lambda, a) = Q_{\text{abs}}(\lambda, a) \), using the optical constants for amorphous carbon (Zubko et al. 1996).

As a second free parameter, we take the integrated (innermost region + arcs) dust mass, allowing it to follow the general trend seen in Figure 3. This gives an estimate of \( M_d \) within 25% of the previously calculated value, thus providing a good consistency check. We find a characteristic grain size \( a = 0.49^{+0.11}_{-0.09} \) \( \mu m \) (95% confidence interval), in line with the estimates obtained for WR 112 from the Infrared Space Observatory spectroscopy, \( a \sim 1 \) \( \mu m \) (Chair & Tielens 2001). The large grain size poses a serious problem for the theory of grain growth, which calls for \( a \sim 0.01 \) \( \mu m \) (Zubko 1998).

4. CONCLUSIONS

The recently acquired high-resolution, high signal-to-noise ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio, near–to–mid-IR images of the W-R star WR 112 have enabled us to resolve and, for the first time, study in detail the ratio. We thank V. Zubko, P. Williams, and J. Monnier for helpful discussions and J.-R. Roy and D. Toomey for assistance in observations. S. V. M., A. F. J. M., and R. D. gratefully acknowledge financial support from NSERC (Canada) and FCAR (Québec). This Letter is based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: NSF (US), PPARC (UK), NRC (Canada), CONICYT (Chile), ARC (Australia), CNPq (Brazil), and CONICET (Argentina). The observations were made with the mid-infrared camera OSCIR, developed by the University of Florida with support from NASA and operated jointly by the Gemini Observatory and the University of Florida Infrared Astrophysics Group.

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