RADIO PROPERTIES OF PINWHEEL NEBULAE

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ABSTRACT

A small number of dusty Wolf-Rayet stars have been resolved into pinwheel nebulae, defined by their "rotating" spiral dust shells observed in the infrared. This morphology is naturally explained by dust formation associated with colliding winds in a binary system. In order to confirm and further explore this hypothesis, we have observed the known pinwheel nebulae (WR 104 and WR 98a) as well as the suspected binary WR 112 at multiple radio wavelengths with the Very Large Array to search for non-thermal radio emission from colliding winds. The spectrum of each target is nearly flat between 5 and 22 GHz, consistent with the presence of nonthermal emission that is reduced at low frequencies by free-free absorption. This emission must lie outside the radio "photosphere," leading us to estimate a lower limit to the physical size of the nonthermal emitting region that is larger than expected from current theory. Based on a radio and infrared comparison to WR 104 and WR 98a, we conclude that WR 112 is a likely candidate pinwheel nebula, but its temporal variability indicates an eccentric binary orbit or a pinwheel viewed nearly edge-on. A sensitive radio survey of IR-bright WRs would stringently test the hypothesis that colliding winds lie at the heart of all dusty WR systems. We also discuss the effects of dust obscuration in the ultraviolet and how radio-determined mass-loss rates of pinwheel nebulae (and dusty WR stars in general) may be underestimated due to shadowing effects.

Subject headings: binaries: close — circumsolar matter — radio continuum: stars — stars: winds, outflows — stars: Wolf-Rayet

1. INTRODUCTION

The vast majority of late-WC (carbon-rich) Wolf-Rayet (WR) stars are surrounded by dust shells (Williams, van der Hucht, & The 1987a) that absorb stellar flux and reemit the energy in the infrared (IR). Recently, the geometry of the IR-brightest dust shells have been resolved into spiral plumes that rotate with a ~1 yr period: the pinwheel nebulae (Tuthill, Monnier, & Danchi 1999; Monnier et al. 1999). This morphology has been explained as a consequence of colliding winds with unequal momenta, where dust forms at the interface or in the wake of the winds and is subsequently carried out in the flow (Uslov 1991). Because of orbital motion, the direction of the dust flow rotates, generating the observed spiral pattern although the dust motion itself is purely radial. By analyzing the time-dependent morphology, important orbital and wind parameters, such as the period, inclination angle, eccentricity, and even the distance (when combined with observed terminal wind speeds), can be determined with high precision (Monnier 1999; Tuthill et al. 2001).

These observations have led to a more unified picture of the dusty Wolf-Rayet stars in terms of interacting wind (binary) systems. Williams & van der Hucht (1992) have categorized dusty WC's as either "variable" or "persistent" dust-producers, based on the variability of IR flux. WR 140 and other variable sources consist of eccentric systems with >10 yr orbits catalyzing dust formation only near periastron (Moffat et al. 1987; Williams et al. 1987b; Williams et al. 1990), while WR 104 and WR 98a have more circular orbits (possibly circularized at an earlier epoch; Monnier et al. 1999) with periods ~1 yr, allowing continuous ("persistent") dust production. An important unanswered question is whether all dusty WR sources lie somewhere along a continuum of binary orbits (Williams & van der Hucht 1992) or whether some of them could be single stars (Zubko 1998).

Another potential observational signature of binaries in dusty WR systems is nonthermal emission from colliding winds. However, one must first establish that nonthermal radio emission from a WR star requires a massive companion (van der Hucht et al. 1992). Recently, Dougherty & Williams (2000) reexamined just this question, and they found that known WR binaries with periods longer than 1 yr do consistently show evidence for nonthermal radio emission, supporting the theory that colliding winds are responsible (Eichler & Uslov 1993; Jardine, Allen, & Pollock 1996). Further, Dougherty & Williams (2000) show that most binaries with periods less than 1 yr have radio spectra similar to that expected for pure thermal wind sources (spectral index $\gamma$ ~ 0.65), the intrinsic nonthermal emission presumably having been mostly absorbed by the ionized wind.

Having periods (~1 yr) lying between the short- and long-period systems studied previously, it is unclear whether pinwheel nebulae should have detectable nonthermal radio emission. We have observed the confirmed pinwheel nebulae around WR 104 and WR 98a and the enigmatic candidate pinwheel WR 112 with the Very Large Array (VLA) of the National Radio Astronomy Observatory (VLA) in order to characterize their radio properties. The goals of this study were to confirm the colliding wind origin of the pinwheel nebulae by definitive detection.

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of nonthermal radio emission, to determine if there exists a distinctive radio signature that can be used as a diagnostic for binarity in systems whose infrared structure is too small or too dim to resolve (Monnier et al. 2001a), and to elucidate the true nature of the WR 112 system whose IR and radio properties have been difficult to understand (Ragland & Richichi 1999; Monnier et al. 2002, in preparation).

2. OBSERVATIONS AND RESULTS

We have 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 1.43, 4.86, 8.46, 14.9, and 22.5 GHz. Before beginning our study, we cross-ferenced the persistent and variable WR dust emitters from Williams & van der Hucht (1992) (which includes our target sample) with the southern hemisphere sample of Leitherer, Chapman, & Koribalski (1997) and Chapman et al. (1999). Of the 12 sources in common, only two have been detected in the radio (WR 65 and WR 112). In order to have good chance to detect our program sources at most of the target wavelengths, our program was designed to improve

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Table 1, including the adopted VLA calibrator positions and our new flux density measurements. In general we followed the guidelines of the VLA calibrator manual for amplitude calibration; however, for WR 104 and WR 98a, we used the compact component of Sgr A* as a high-frequency calibrator by considering only \((u, v)\) components beyond 50 k\(\lambda\) (100 k\(\lambda\)) at 8.46 and 14.9 GHz (22.5 GHz). Our 8.46 GHz flux estimates for Sgr A* are similar to contemporaneous measurements by G. C. Bower (2000, personal communication), but our fluxes at higher frequencies are ~15\% higher. This discrepancy may be due to slightly different cutoffs in \((u, v)\) coverage employed during calibration or variability of Sgr A* itself (Zhao, Bower, & Goss 2001), but is also nearly consistent with the expected level of systematic errors in the amplitude calibration; our final conclusions do not hinge upon this possible source of miscalibration.

Table 2 contains the calibrated fluxes and source positions for the target sample, including the first radio detections of WR 104 and WR 98a. The resolution of the VLA in A-array is sufficient to resolve the thermal emission from some WR stars (e.g., Contreras & Rodríguez 1999), and the data were inspected for evidence of structure. Gaussian fits to the deconvolved images did not reveal any significant deviations from point sources.

We note that the 8.46 GHz measurement of WR 112 in 1999 September was corrupted by poor atmospheric phase stability, and the bispectrum was vector-averaged in order to extract an estimate of the point-source flux (for further discussion see Cornwall 1987). This method is accurate only if no other sources are present in the field and if the target is unresolved, and the validity of these assumptions was checked using subsequent observations in 2000 February.

New positions and the associated uncertainties of the Wolf-Rayet stars were estimated by taking the mean and standard deviation of the right ascension and declination

\[1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}.\]

### Table 1

| SOURCE | R.A.    | Decl.     | DATE (U.T.) | 1.43 GHz | 4.86 GHz | 8.46 GHz | 14.9 GHz | 22.5 GHz | TARGET CALIBRATED |
|-------|---------|-----------|-------------|----------|----------|----------|----------|----------|------------------|
| 1733–130……. | 17 33 02.7058 | -13 04 49.548 | 1999 Sep 28 | … | 4.416 | … | 3.765 | 3.693 | WR 112 |
| Sgr A*…….. | 17 45 40.0409 | -29 00 28.118 | 1999 Sep 27 | … | 0.690 | 0.967 | 1.062 | 3.132 | WR 104, WR 98a |
| 1751–253……. | 17 51 51.2628 | -25 24 00.063 | 1999 Sep 28 | 1.236 | … | … | … | … | … |
| 1820–254……. | 18 20 57.8487 | -25 28 12.584 | 1999 Sep 27 | … | 1.094 | … | … | … | … |
| 1832–105……. | 18 32 20.8360 | -10 35 11.200 | 1999 Sep 27 | … | … | 1.328 | … | … | … |
| 1999 Sep 28 | … | 1.174 | … | … | … | … |
| 2000 Feb 15 | … | 1.321 | 1.359 | … | … | … |

**Note:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* Flux density scale was defined by the adopted strength of 3C 286 using NRAO values of 14.75, 7.486, 5.181, 3.428, and 2.498 Jy at 1.43, 4.86, 8.46, 14.9, and 22.5 GHz, respectively.

* Statistical uncertainties were ≤1%. From the apparent scatter, we estimate systematic calibration uncertainties were generally better than 5%, but occasionally as bad as 10%.

* Sgr A* J2000 positions taken from Reid et al. (1999) measured on 1996.25 not correcting for apparent proper motion; this should be accurate to ~20 mas for the epoch of measurements reported here.

* Positional accuracy <150 mas. All others here have less than 10 mas error.
values found in Table 2, excluding data with unusually large
errors (due to low elevation observations or calibrators with
poorly known positions). Our reported uncertainties are
conservative, being based on the dispersion of the measure-
ments rather than the uncertainty in the mean, since we lack
sufficient independent observations to properly average
over observing conditions. Table 3 contains these results
along with the previously determined positions. The posi-
tions for WR 104 and WR 98a are significantly improved by
this work, since the previous coordinates were based on
optical and infrared observations, suffering from \( \gtrsim 1'' \)
errors.

3. MODELING

3.1. Methodology

The radio data for each source were fitted with a com-
posite spectral model, consisting of a thermal wind source
\( F(T) \) with nonthermal emission \( F(NT) \) absorbed by a variable
amount of free-free opacity \( \tau_c \) from the overlying ionized

| TARGET STAR | DATE (U.T.) | FREQUENCY BAND (GHz) | MEASURED FLUX DENSITY (mJy) | R.A. | DECL. | COMMENTS |
|-------------|------------|---------------------|-----------------------------|-----|------|----------|
| WR 104 ...... | 1999 Sep 28 | L (1.425) | <0.30 | ... | ... | ... |
| 2000 Feb 24 | X (8.460) | 0.87 ± 0.06 | 18 02 04.128 ± 0.006 | -23 37 42.14 ± 0.05 | Unresolved |
| 2000 Feb 24 | U (14.94) | 1.02 ± 0.12 | 18 02 04.110 ± 0.005 | -23 37 42.40 ± 0.07 | Unresolved |
| 1999 Sep 28 | K (22.46) | 0.90 ± 0.15 | 18 02 04.127 ± 0.001 | -23 37 42.18 ± 0.01 | Unresolved |
| 2000 Feb 25 | K (22.46) | 0.97 ± 0.12 | 18 02 04.126 ± 0.005 | -23 37 42.25 ± 0.08 | Unresolved |
| WR 98A ...... | 1999 Sep 28 | L (1.425) | <0.36 | ... | ... | ... |
| 1999 Sep 28 | C (4.860) | 0.37 ± 0.07 | 17 41 13.044 | -30 32 30.25 | Weak detection |
| 1999 Sep 28 | X (8.460) | 0.55 ± 0.15 | 17 41 13.044 ± 0.005 | -30 32 30.35 ± 0.10 | Weak detection |
| 2000 Feb 24 | X (8.460) | 0.62 ± 0.05 | 17 41 13.057 ± 0.006 | -30 32 30.39 ± 0.06 | Unresolved |
| 2000 Feb 24 | U (14.94) | 0.64 ± 0.11 | 17 41 13.047 ± 0.008 | -30 32 30.23 ± 0.18 | Unresolved |
| 2000 Feb 25 | K (22.46) | 0.57 ± 0.10 | 17 41 13.054 ± 0.008 | -30 32 30.38 ± 0.10 | Unresolved |
| WR 112 ...... | 1999 Sep 29 | L (1.425) | 2.71 ± 0.17 | 18 16 33.484 ± 0.002 | -18 58 42.79 ± 0.03 | Unresolved |
| 2000 Feb 15 | L (1.425) | 2.30 ± 0.30 | 18 16 33.484 ± 0.006 | -18 58 42.36 ± 0.13 | Unresolved |
| 1999 Sep 28 | C (4.860) | 4.12 ± 0.10 | 18 16 33.488 ± 0.030 | -18 58 42.47 ± 0.30 | Unresolved |
| 2000 Feb 15 | C (4.860) | 3.75 ± 0.08 | 18 16 33.490 ± 0.001 | -18 58 42.33 ± 0.02 | Unresolved |
| 1999 Sep 27 | X (8.460) | 4.40 ± 0.3 | ... | ... | ... | ... |
| 2000 Feb 15 | X (8.460) | 4.07 ± 0.06 | 18 16 33.4879 ± 0.0003 | -18 58 42.289 ± 0.006 | Unresolved |
| 1999 Sep 29 | U (14.94) | 4.20 ± 0.3 | 18 16 33.490 ± 0.0001 | -18 58 42.50 ± 0.01 | Unresolved |
| 2000 Feb 15 | U (14.94) | 4.39 ± 0.17 | 18 16 33.4902 ± 0.0004 | -18 58 42.347 ± 0.010 | Unresolved |
| 1999 Sep 28 | K (22.46) | 4.05 ± 0.25 | 18 16 33.4912 ± 0.0001 | -18 58 42.353 ± 0.002 | Unresolved |
| 2000 Feb 15 | K (22.46) | 3.97 ± 0.12 | 18 16 33.4901 ± 0.0003 | -18 58 42.374 ± 0.007 | Unresolved |

| NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
| a Position estimates and errors derived from fits to a single Gaussian.
| b Flux density determined using AIPS tasks jmfj and maxfit.
| c When not detected, we report 3σ upper limits.
| d Flux uncertainties here include only measurement error, not systematic calibration uncertainties which are generally \( \lesssim 5\% \).
| e "Unresolved": Gaussian fit to image consistent with point-source response (FWHM less than one-third of beam). No comment indicates too little flux density to adequately constrain a Gaussian fit, and the flux density reported assumes the source is unresolved.
| f Low elevation observations (\( \sim 13\)°) had poor phase calibration, resulting in degraded astrometry; self-calibration was possible to retain precise photometry.
| g Phase stability was too poor to successfully phase reference. However, the flux for WR 112 was estimated by vector-averaging the bispectrum. See §2 for more details.

## TABLE 3

| SOURCE | NEW RADIO POSITION* (J2000) | PREVIOUS RADIO POSITION* (J2000) |
|--------|-------------------------------|---------------------------------|
| R.A.   | R.A.                          | R.A.                           |
|        |                               |                                |
| WR 104 ...... | 18 02 04.123 ± 0.009 | -23 37 42.24 ± 0.11 | 18 02 04.07 | -23 37 41.2 |
| WR 98a ...... | 17 41 13.051 ± 0.006 | -30 32 30.34 ± 0.07 | 17 41 12.9 | -30 32 29 |
| WR 112 ...... | 18 16 33.489 ± 0.003 | -18 58 42.47 ± 0.19 | 18 16 33.49 | -18 58 42.5 |

| NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
| a This work.
| b From the V11th Catalogue of Wolf-Rayet Stars by van der Hucht (2001). WR 104 and WR 98a positions were from optical observations while the position of WR 112 was derived from radio work.
wind. We note that $F^T_v$ is directly related to the total optical depth of the wind but that in this model $\tau_v$ represents only the optical depth along the line of sight to the nonthermal emission region $F^{NT}_v$, which clearly must be less than or equal to the total opacity of the wind. This basic model has been used recently by several workers (Chapman et al. 1999; Skinner et al. 1999) and can be expressed in the following form (following Chapman):

$$F_v = F^T_{v,4.8\,\text{GHz}} \left(\frac{v}{4.8\,\text{GHz}}\right)^{x_T} + F^{NT}_{v,4.8\,\text{GHz}} \left(\frac{v}{4.8\,\text{GHz}}\right)^{x^{NT}} e^{-\tau_v},$$

(1)

where $F^T_{v,4.8\,\text{GHz}}$ refers to the flux density at 4.8 GHz.

For low signal-to-noise ratio (S/N) data of the weak sources (WR 104 and WR 98a), the free parameters of this model cannot all be independently well-constrained. Fortunately, the spectral indices for thermal and nonthermal emission have been measured for other Wolf-Rayet systems. Fortunately, the spectral indices for thermal and nonthermal emission have been measured for other Wolf-Rayet systems. We fix the spectral index of thermal emission ($x^T$) to be 0.65, which is the representative of the range observed and predicted by theory (Leitherer & Roberts 1991; Williams et al. 1990; Panagia & Felli 1975; Wright & Barlow 1975; Olnon 1975). We also fix the spectral index of the nonthermal ($x^{NT}$) emission to $-0.7$, based on the range of values ($-0.5$ to $-1.0$) observed around other colliding wind sources (Skinner et al. 1999; Chapman et al. 1999; Dougherty et al. 1996; Setia Gunawan et al. 2000, 2001). The value of $-0.5$ can be physically motivated by considering Fermi acceleration of energetic electrons in the colliding wind shocks (Bell 1978) and subsequent synchrotron emission (for more detailed discussion see Eichler & Usov 1993). Last, we fix the free-free opacity law to be $\tau_v = \tau_{4.8\,\text{GHz}}(v/4.8\,\text{GHz})^{-2.1}$, which is appropriate for an electron temperature of $\sim 10^6$ K (see eq. [3-57] in Spitzer 1978).

Table 4 contains the modeling results for our target stars, including 5% amplitude calibration errors (important only for WR 112). Because of the low S/N for WR 104 and WR 98a, the best-fitting parameters are not very meaningful, so we also report the full range of parameters values consistent with the data (i.e., the parameter range satisfying the condition that the reduced $\chi^2 < 1$).

### 3.2. WR 104

Figure 1 contains the modeling results for WR 104. A pure thermal model ($x^T = 0.65$) is not a good fit (reduced $\chi^2 = 3.5$); there must be some nonthermal emission. This result is robust to the potential miscalibration at high frequencies using Sgr A* (discussed in § 2), since potential overestimate of the calibrator flux density would cause our estimate of the spectral index to be too high (i.e., more similar to thermal emission).

The maximum possible thermal emission component that can be supported by these new data is 0.36 mJy at 4.8 GHz. Interestingly, the data are consistent with no detectable thermal emission for models with large free-free optical depth. Unfortunately, the optical depth is not very well-constrained for WR 104 because the spectrum lacks reliable low-frequency detections. Quantitatively, the optical depth to the nonthermal emitting region at 4.8 GHz can range between 0.18 and 3.85 (best-fitting value of 2.47) and still be consistent with the data. The resulting spectra from these scenarios, along with the best-fitting spectrum, are included in Figure 1.

We note that WR 104 was searched for radio emission by Leitherer et al. (1997) and Chapman et al. (1999), who reported 3 $\sigma$ upper limits of 1.59, 0.99, 2.01, and 0.39 mJy at 1.38, 2.38, 4.86, and 8.64 GHz, respectively. Except for the 8.64 GHz observations, these results are consistent with the weak detections reported here.

### TABLE 4

**RESULTS FROM TWO-COMPONENT MODEL FITTING**

| WR 104 | WR 98a | 1999 Sep | 2000 Feb |
|--------|--------|----------|----------|
| $F^T_{v,4.8\,\text{GHz}}$ (mJy) | 0.072 [0-0.36] | 0.078 [0-0.24] | 1.14 [0.97–1.32] | 1.18 |
| $\tau_v$ | 0.65 [fixed] | 0.65 [fixed] | 0.65 [fixed] | 0.65 [fixed] |
| $F^{NT}_{v,4.8\,\text{GHz}}$ (mJy) | 2.42 [0.78–3.70] | 1.14 [0.33–1.96] | 3.47 [3.01–3.94] | 3.16 |
| $\tau^{NT}_v$ | $-0.70$ [fixed] | $-0.70$ [fixed] | $-0.70$ [fixed] | $-0.70$ [fixed] |
| $\tau_{4.8\,\text{GHz}}$ | 2.47 [0.18–3.85] | 1.40 [0.38–2.43] | 0.10 [0.088–0.11] | 0.11 |
| Reduced $\chi^2$ | 0.024 | 0.040 | 0.63 | 1.75 |

**NOTE.**—The best-fitting parameters are given, with the range of acceptable values (as judged by a final reduced $\chi^2 < 1$) following in brackets.

* The best-fitting model had a reduced $\chi^2 > 1$. 

![Figure 1](image-url)
3.3. WR 98a

Figure 2 contains the modeling results for WR 98a. WR 98a and WR 104 have qualitatively similar spectra, although a weak 4.86 GHz detection of WR 98a allows composite spectra models to be better constrained.

As for WR 104, a pure thermal model ($\alpha^T = 0.65$) is not consistent with these data (reduced $\chi^2 = 2.8$), and the maximum thermal emission at 4.8 GHz supported by the data is 0.24 mJy. The data are consistent with no detectable thermal emission for large free-free optical depths to the nonthermal emission region. These data constrain the optical depth to the nonthermal emitting region (at 4.8 GHz) to lie between 0.38 and 2.43 (best fit at 1.40), based largely on the 4.86 GHz detection.

3.4. WR 112

WR 112 was definitively detected by both Leitherer et al. (1997) and Chapman et al. (1999), and marked variability was observed between 1995 and 1997, probably caused by varying nonthermal radio emission. Our observations support this interpretation and reveal that WR 112 was in a radio-bright state between 1999 September and 2000 February. However, at these recent epochs, we do not see evidence for the sharp drop (more than factor of 3) in flux density between 2.38 and 1.38 GHz reported by Chapman et al. (1999).

Figure 3 contains our modeling results for WR 112. At high frequencies, WR 112 shows a flat spectrum similar to WR 104 and WR 98a. However, there appears to be significantly less wind optical depth to the nonthermal emitting region ($\tau_{4.8 \text{ GHz}} = 0.10$) here than for WR 104 and WR 98a. This supports the hypothesis that WR 112 is a longer period system than WR 104 and WR 98a, already suspected based on IR and radio variability considerations. There is some evidence for a decrease in the low-frequency flux density between 1999 September and 2000 February, corresponding to a $\sim 10\%$ decrease in the nonthermal emission component. We note that subsequent and ongoing monitoring of WR 112 by our group confirms the trend of decreasing nonthermal emission with time, and full analysis of these variations will be considered in a future paper.

The high S/N data from 2000 February cannot be fitted by our simple model within the expected uncertainties (minimum reduced $\chi^2 = 1.75$), where the 5% amplitude calibration error generally dominates over the statistical measurement error. If we allow the spectral indices of the nonthermal and thermal components to deviate from their fixed values, the fit improves but is still not satisfactory. Specifically, if we insist that $\alpha^T$ lie between 0.6 and 0.7 and that $\alpha^{NT}$ stay between $-0.5$ and $-1.0$, the best-fit model has a reduced $\chi^2 = 1.20$ (for $\alpha^T = 0.6$ and $\alpha^{NT} = -0.5$).

Skinner et al. (1999; see also Setia Gunawan et al. 2001) fitted the radio spectrum of long-period, colliding-wind binary WR 147 over a similar frequency range and found that an absorbed monoenergetic synchrotron spectrum fitted the data better than the absorbed power-law model considered here. This better fit was largely due to a steep high-frequency cutoff observed in the nonthermal spectrum around 22 GHz, which is more naturally accommodated by the synchrotron spectrum. A high-frequency cutoff is intimated in our WR 112 data but is uncertain owing to difficulty in estimating the strength of the thermal emission. Skinner et al. (1999) were able to more reliably estimate the thermal emission component using 43 GHz observations and the fact that the thermal and nonthermal components were spatially resolved from each other at both 15 GHz and 22 GHz.

4. DISCUSSION

4.1. Thermal Emission and Mass-Loss Rates

The thermal emission from Wolf-Rayet stars is understood to arise from free-free emission in an expanding, ionized wind (Wright & Barlow 1975; Panagia & Felli 1975; Olnon 1975). Following Wright & Barlow (1975), the observed flux density can be related to stellar and wind parameters as follows:

$$F^T_v = 2.32 \times 10^6 \left(\frac{MZ}{v_\infty \mu}\right)^{4/3} \left(\frac{gy_c}{d^3}\right)^{2/3},$$

(2)
where $F_T^r$ is the observed flux density in mJy, $\dot{M}$ is the mass-loss rate in $M_\odot$ yr$^{-1}$, $Z$ is the mean ionic charge, $v_w$ is the wind velocity in km s$^{-1}$, $\mu$ is the mean molecular weight, $\gamma$ is the mean number of electrons per ion, $g_{\text{eff}}$ is the free-free Gaunt factor, $v$ is the observing frequency in Hz, and $d$ is the distance in kpc.

Leitherer et al. (1997) discuss the best values to use for late-WC stars, and we have followed these authors in adopting $Z = 1.1$, $\gamma = 1.1$, $\mu = 4.7$, and $g_{4.8 \text{ GHz}} = 5.03$ in the calculations that follow. Table 5 contains the estimated distances and wind velocities of our targets derived from the literature and fluxes from thermal emission at 4.8 GHz (from Table 4) based on the spectral decompositions of § 3. With these data, equation (2) can be inverted to solve for the mass-loss rate, and these results are also contained in Table 5, corresponding to both the best-fitting values for the thermal emission component and the maximum allowed value.

Also included in this table is an estimate of the major axis of the binary system based on the period and assumption of 15 $M_\odot$ components.

The estimated mass-loss rates span 0.5 to $2.8 \times 10^{-5} M_\odot$ yr$^{-1}$, similar to results from previous studies of late-WC WR stars. (e.g., Nugis, Crowther, & Willis 1998; Leitherer et al. 1997; Abbott et al. 1986). Because of the presence of nonthermal emission in all our sources, our determinations of mass-loss rate are very uncertain and we have neglected secondary effects such as clumping corrections (Moffat & Robert 1994; Morris et al. 2000). Interestingly, WR 112 seems to show a markedly higher (2.5 times) mass-loss rate than observed in 1995 (Leitherer et al. 1997)—that is, the high-frequency radio emission (most likely dominated by thermal emission) was significantly higher in the more recent epochs. Although the orbital properties of the WR 112 binary are unknown, it is not expected that the thermal emission, which is dominated by free-free emission in the Wolf-Rayet wind, should be a strong function of the binary separation or other parameter. Higher frequency observations at multiple epochs can better isolate the thermal emission from nonthermal emission, critical for accurately estimating the mass-loss rates for individual colliding wind sources.

### 4.2. Nonthermal Emission

As previously discussed in § 3.4, the physical mechanism producing the nonthermal radio emission is not well known, and predictions from many models can be compared to the observed spectra (e.g., Skinner et al. 1999; Setia Gunawan et al. 2000, 2001). Despite these uncertainties, one component that all nonthermal emission models contain is free-free absorption by the overlying ionized wind. The free-free optical depth to the nonthermal emission implied by power-law models (as considered here) is generally larger than that obtained by fitting to alternative model spectra whose nonthermal source contains an intrinsic low-frequency turnover. Hence we can interpret the optical depth parameters derived in the last section to be reasonable upper limits. We can therefore estimate a lower limit on wind depth where the emission arises, assuming only that the intrinsic nonthermal spectrum has low-frequency behavior flatter than the $-0.7$ spectral index used here for fitting (this includes the absorbed monoenergetic synchrotron spectrum preferred by Skinner et al. 1999).

In order to calculate the optical depth of the overlying wind for variously sized nonthermal emitting regions, we must first discuss how a binary system alters the wind density around the WR star. Let us consider a colliding wind system viewed nearly face-on, as is appropriate for the pinwheel nebulae WR 104 and WR 98a. The nonthermal radio emission originates at the interface of the colliding winds, which has a nearly conical geometry outside the interaction region (see Fig. 4) with an opening angle, $\theta$, dependent on the relative WR and O-star wind momenta. For wind momenta ratio between 0.01 and 0.1 (expected for these systems), the opening angle $\theta$ lies between 50° and 90° (Eichler & Usov 1993), consistent with the thickness of the dust plume seen around WR 104. In order to estimate the minimum intrinsic size of the nonthermal emission, we must calculate the impact parameter, $q$, which would intersect this cone with $\tau_{4.8 \text{ GHz}} \sim 1$. Because the integrated line-of-sight optical depth of the wind falls off steeply, $\tau \propto \xi^{-3}$ (Wright & Barlow 1975; Panagia & Felli 1975), this estimate is relatively insensitive to wind parameters. See Figure 4 for a sketch of the wind and orbital geometry.

For a generic late-WC wind with $\dot{M} = 1 \times 10^{-5} M_\odot$ yr$^{-1}$ and wind speed of 1000 km s$^{-1}$, the $\tau_{4.8 \text{ GHz}} \sim 1$ condition is reached for $\xi \sim 18, 15, 13$ AU for opening angles $\theta \sim 0^\circ, 60^\circ$, and $90^\circ$, respectively. For larger opening angles, the nonthermal emission extends more toward the observer and is visible at smaller impact parameters. Hence to be observed at all, the intrinsic nonthermal emission region must extend along the interface cone to this distance $\xi$. This size is significantly larger than the estimated nonthermal emission region size estimated by Eichler & Usov (1993), which was largely based on what scale the wind collision

**TABLE 5**

| Source       | Distance (kpc) | $v_w$ (km s$^{-1}$) | $a^*$ (AU) | $F_T^r$ $4.8$ GHz (mJy) | Maximum $\tau_{4.8 \text{ GHz}}$ | Reference | $M$ ($10^{-5} M_\odot$ yr$^{-1}$) | $R_{\text{NTD}}^*$ (AU) |
|--------------|---------------|-------------------|------------|-------------------------|---------------------------------|-----------|---------------------------------|-----------------------------|
| WR 104 (WC9) | 2.3           | 1220              | 2.4        | 0.072 ($<0.36^a$)       | 3.9                             | 1, 4      | 0.8 ($<2.8$)                    | >5                          |
| WR 98a (WC8-9) | 1.9         | 900 1100          | 6.1$^d$    | 1.16 ± 0.17             | 0.11                            | 3, 4      | 2.5 ± 0.3$^c$                   | ~46$^b$                     |

$^a$ Binary separation based on the orbital period and the assumption that both components are 15 $M_\odot$.

$^b$ Transverse distance from shock stagnation point to location corresponding to wind opacity estimate of the intrinsic size of the nonthermal emission (see discussion in § 4.2).

$^c$ Quantities in parentheses represent upper limits based on fits to radio spectra.

$^d$ Period of WR 112 binary is unknown, but estimated to be ~1000 days based on unpublished radio and IR data.

$^e$ This error bar only reflects errors in determining $F_T^r$ $4.8$ GHz, and not the much larger uncertainties in the distance and wind velocity.

$^f$ This assumes line of sight does not traverse the OB-star wind, but only the WR wind.

**REFERENCES**—(1) Thubill et al. (1999); (2) Monnier et al. (1999); (3) Nugis et al. (1998); (4) this work.
can efficiently put energy into the shocks (1–3 AU for our target stars).

It has been pointed out by previous investigators that the estimated optical depth to the shock collision zone is so large that all nonthermal radio emission should be completely obscured for periods ≲ 2 yr (Dougherty & Williams 2000; Chapman et al. 1999; White & Becker 1995; Williams et al. 1990; Williams, van der Hucht, & Spoelstra 1994). Most recently, Dougherty & Williams (2000) discuss a number of explanations for why nonthermal emission is visible for WR 11 (σ² Vel, period 78.53 days). At radio wavelengths, one can see deeper into the wind if it is clumpy (e.g., Nugis et al. 1998) or nonspherical (Williams et al. 1997). In addition for nearly edge-on systems, lines of sight can pass through the relatively less-dense O-star wind during some parts of the orbit, causing the observed radio spectrum to vary.

Since the WR 104 and WR 98a binaries are viewed within ≈ 35° from face-on (Monnier et al. 1999), we can eliminate possible explanations invoking novel observing geometries, such as viewing the collision zone through the O-star wind. Further, the wind would need to be very clumpy and/or nonspherical to allow emission at ξ ≈ 1–3 AU to be visible, considering that τ₄₉ GHz ∝ ξ⁻²; the 4.8 GHz optical depth in the smooth wind to the collision zone is ≈ 50 for typical late-WC stars. Such radical departures from smooth flow would likely be seen as significant changes to the thermal emission, which arises from the same ionized wind material.

Here we develop another possibility, that the nonthermal emission region may be intrinsically larger than expected (also suggested in part by Dougherty & Williams 2000). The plasma could continue to radiate beyond the initial collision region for at least the synchrotron cooling timescale. In order for the plasma to travel out of the collision region and reach the τ₄₉ GHz ~ 1 surface, this time would need to be ≳ 10 days, a reasonable time span considering the analysis of Eichler & Usov (1993; see § 3), assuming magnetic fields of a few Gauss. The size and strength of the radio emission “tail” also depends greatly on the magnetic field geometry; for uniform magnetic fields the energetic electrons can escape to greater distances from the collision region than for nonuniform magnetic fields and could produce observable radio emission (Usov 2001, private communication); thus these observations might be revealing important new information regarding the magnetic fields of WR + OB binaries. Interestingly, Corcoran et al. (1996) found evidence that the X-ray-emitting region of the colliding wind system V444 Cyg (WR 139), presumed to trace hot shocked gas, was also unexpectedly large (10 times the binary separation). Last, it might be possible that even compact nonthermal radio emission may appear larger because of electron scattering in the dense ionized wind.

We have calculated the minimum impact parameter ξ for each of our target stars based on the (best-fit) estimated mass-loss rates, the orbital and wind parameters, the upper-limit of τ₄₉ GHz derived from our spectral fits, and a cone.
angle of 60°. From this minimum ξ, we can estimate the minimum extent of the nonthermal emission, \( R^{NT} \), by subtracting the binary separation from the minimum ξ (since the dense WR wind is centered on the WR star while the collision region occurs close to the OB-star). These values have been placed in Table 5 and should be taken as lower limits to the intrinsic size of the nonthermal emission region; the nonthermal emission region could be much larger since we are adopting conservative upper-limits for the optical depth.

This model can be tested by high-resolution imaging of the nonthermal radiation, but VLBA observations of WR 104 and WR 98a are currently not practical because of their weak flux. While WR 112 is bright enough to detect (in its radio-bright state), the closest phase reference calibrator is \( \sim 5° \) away. Initial attempts to image the nonthermal radio emission (by our group) have failed either because the source was overresolved or due to spatial incoherence effects attributed to low elevation and the large angular distance between the WR 112 and the phase reference. VLBA observations of closer colliding wind sources, such as WR 140 near periastron or WR 11, should be able to resolve these structures and determine precisely the physical geometry of the nonthermal emitting regions.

4.3. Effects of Dust on the Radio Emission

If the dust formed at the colliding wind interface is optically thick to UV-photons, a significant fraction of the circumstellar gas will be shielded from the ionizing flux of the central sources. Figure 5 shows an idealized model of colliding wind interface geometry for WR 104 (for opening angle \( \theta = 90° \)). The radius of the radio photosphere is \( \sim 15 \) AU at 4.8 GHz \(( \propto v^{-0.66}, \) Wright & Barlow 1975), which is similar to the length scale of the spiral wind interface in Figure 5. Hence, dust in the interface region can absorb the UV flux and shadow a significant volume of the wind (especially in the mid-plane). Initial calculations indicate that the thermal emission will be smaller by \( \sim 30\% \) for the same mass-loss rate, and the spectral slope might be slightly larger than the canonical \( z^{\prime} \sim 0.65 \). We note that these effects may even be important for spherical distributions of grains, since the inner radius of the dust shell in such models is also \( \sim 25 \) AU (Zubko 1998) and could change the ionization fraction in the outer envelope from standardly used values.

The brightness of the nonthermal radio emission could also be affected. For binary systems viewed nearly edge-on, the dust shadow would also significantly reduce the line-of-sight opacity to the collision zone (since the gas will not be ionized in the shadow) at certain orbital phases than currently expected. More work is needed to quantitatively understand these effects and will need to include a detailed treatment of the dust opacity as well as recombination timescale for "shadowed" gas.

Such effects could be detected with high-resolution images of the thermal emission region, since the shadowing would cause the emission to be very asymmetrical. By observing at millimeter-wave wavelengths, it would be possible to probe deeper layers on the wind, revealing the structure of the wind-wind interface on \( \sim 10 \) AU scales (e.g., using EVLA and Atacama Large Millimeter Array). In addition, signs of shadowing might also be seen on larger
scales in nebular emission lines or as linear polarization at visible wavelengths.

4.4. Time Variability

Unfortunately, our observations of individual sources at different frequencies were not taken at the same epoch, which is potentially troubling since WR 104 and WR 98a are known to have binary periods of 243.5 and 565 days, respectively (Monnier et al. 1999). Fortunately, there is some wavelength overlap between the epochs for both sources and these flux measurements are consistent to within errors. This is not surprising for WR 104 since analysis of the spiral morphology indicates a nearly face-on viewing angle (11° ± 7°, Monnier 1999). There is some IR flux variation observed for WR 98a (Williams et al. 1995), either due to optical depth effects (viewing angle is ~35° for WR 98a) or orbital eccentricity, but we do not detect a similar radio variation in our limited data set. In both cases, the colliding wind interface should not cross our line of sight, and hence we do not expect large variations of the kind seen in other systems, such as WR 140 (White & Becker 1995).

WR 112 showed evidence for slight variation between 1999 September and 2000 February at low frequencies. We are monitoring this source with the VLA in order to understand the large variation originally observed by Leitherer et al. (1997) and Chapman et al. (1999). This variation can be either due to changes in line of sight opacity or intrinsic radio emission, caused by either a large inclination angle or binary separation (or both). Coordinated infrared imaging and broadband radio spectra will go a long way toward supporting the creation of a self-consistent model and clarifying the likely cause(s) of the observed variability.

5. Conclusions

We detected nonthermal radio emission from both known pinwheel nebulae (WR 104 and WR 98a) and the suspected binary system WR 112. Pure thermal emission from a spherically symmetric ionized wind was not consistent with the spectra from any of the sources, and some nonthermal emission was always required to explain the observations. Simple composite spectral models were fitted to the broadband measurements, allowing emission strengths of the thermal and nonthermal components to be estimated along with the line-of-sight opacity toward the nonthermal emission region. From the inferred thermal emission strengths and known wind properties, we estimated the mass-loss rates and found them to be similar to those for other late-WC WR stars, validating the basic spectral decomposition employed here.

Using these results, the upper bound line-of-sight opacities to the nonthermal emission were inverted to estimate lower limit sizes of the nonthermal emission regions, which were many times larger than expected from current theory (Eichler & Usov 1993). We suggest that synchrotron cooling times of a few weeks would allow the radio-emitting plasma to travel into an optically thin portion of the thermal WR wind and to be observed, or that uniform magnetic fields could allow energetic electrons to escape out of the radio “photosphere.”

We also discussed implications of dust obscuration on the radio properties of dusty WRs. If the dust in the outflow is optically thick to ultraviolet photons, a significant fraction of the wind will be shadowed from the major sources of ionization. This will affect mass-loss rates determined from high-frequency radio observations for all binary (i.e., nonthermal) systems and could cause dramatic differences in the line-of-sight free-free opacity for binary systems viewed edge-on.

A lack of high-frequency (e.g., 43 GHz) observations hampered our analysis since even 22 GHz observations were significantly contaminated by nonthermal radio emission, making the decomposition of spectra reliant on a priori estimates for the model spectral indices. For WR 112, high S/N measurements suggest that simple two-component power-law models commonly used are inadequate, hinting at a high-frequency turnover to the nonthermal radio emission. We emphasize that further progress in this field will require multiwavelength simultaneous observations from 1 to 43 GHz in order to untangle the contributions from the thermal and nonthermal components.

The hypothesis that colliding winds lie at the heart of all Wolf-Rayet dust shells has passed another observational test, detection of nonthermal radio emissions from WR 104, WR 98a, and WR 112. A sensitive radio survey (σ ≤ 0.1 mJy) between 1 and 43 GHz of all known dusty Wolf-Rayets would put this hypothesis to a final challenge.

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