THE INTERSTELLAR MEDIUM AROUND WOLF-RAYET STARS: CLUES TO EVOLUTION

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Abstract. Multi-wavelength investigations of the interstellar environment around WR stars using *IUE*, *IRAS*, and optical data have led to the discovery of extended shells of gas and dust 50-100 pc in diameter in the lines of sight to the WR stars HD 50896, HD 96548, and HD 192163. These three stars share several common characteristics: (1) associated N- and He-enriched ring nebula, (2) spectral class WN5-8, and (3) spectral and photometric variability. Surveys of *IUE* spectra and *IRAS* images reveal a few additional candidates for such extended shells. Although positional coincidences cannot be excluded, possible origins of these extended shells include interstellar bubbles formed by stellar winds, non-conservative mass loss from binary systems, and supernova remnants. Current data suggest these three stars may be in a post X-ray binary stage, representing the second WR phase of massive binary star evolution. The discovery of extended shells of gas and dust possibly related to WR stars is important because the search for stars in the second WR phase, after the supernova of the primary, has been quite elusive. However, the observational evidence and available theoretical models for post-supernova massive binary star evolution and subsequent non-conservative mass transfer are not yet sufficient to firmly identify the origins of these extended shells.

Key words: : stars: Wolf-Rayet – ring nebulae – evolution

1. Introduction

Massive stars will have a significant impact on their surrounding interstellar environment during the various phases of their lives. Evolving as either single or binary stars, these stars are expected to produce shells of swept-up interstellar material formed by their stellar winds, nebulae of ejected stellar material from either single or binary stars, and supernova remnants at the end of their lives. These interstellar structures will greatly influence the dynamics and chemical composition of the interstellar medium (ISM). The interstellar environment around WR stars can provide important information about their previous and current mass loss events.

Recent studies of the ISM around galactic WR stars have yielded important clues to the evolutionary status of these stars. H I shells have been detected around some WR stars (Cappa de Nicolau & Niemela 1984, Cappa de Nicolau *et al.* 1986, 1988, Niemela & Cappa de Nicolau 1991, Dubner *et al.* 1990, Arnal & Mirabel 1991, Arnal 1992), believed to be produced by the progenitors of the WR stars. It is considered probable that all WR stars are embedded in such H I shells, which are often barrel-shaped. This finding has led to new models of SNRs evolving in an interstellar bubble (Tenorio-Tagle *et al.* 1991, Różyczka *et al.* 1993). Other recent studies of the ISM around WR stars include searches for and abundances of ring nebulae (Grant & Chu

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1993, Esteban & Vílchez 1992, Esteban *et al.* 1992), and IR morphology and dust distribution of ring nebulae (Marston 1991, Mathis *et al.* 1992). The study of ring nebulae around LBVs is providing new information concerning the evolution of WR stars (Paresce & Nota 1989, Smith 1991, Smith *et al.* 1994).

This paper discusses surveys of *IRAS* and *IUE* data for all observed galactic WR stars, and observational evidence in the ultraviolet (UV) and infrared (IR) indicating the existence of huge extended shells of gas and dust associated with three WR stars. The origin of these shells is evaluated and possible evolutionary scenarios of these WR stars are presented.

2. Observations of extended shells in the lines of sight to Wolf-Rayet stars

Investigations of the interstellar environments around Wolf-Rayet (WR) stars using *IUE* UV absorption line data, optical narrow-band imagery, and infrared *IRAS* imagery have resulted in the identification of large interstellar structures in the lines of sight to HD 50896, HD 96548, and HD 192163. High-velocity components in the UV interstellar absorption lines were detected in the spectra of HD 50896, a WN6 star 10° below the Galactic plane and 11 neighboring field stars covering a region 5 × 6 degrees (Nichols-Bohlin & Fesen 1986, Howarth & Phillips 1986), indicating the existence of a large interstellar shell at a distance of ~1.0 kpc with a linear diameter of approximately 100 pc. The WR star and its associated ring nebula S308 appear centrally located in this expanding shell of gas.

High-velocity UV components were also detected in the direction to HD 96548, a WN8 star 5° out of the Galactic plane (Nichols-Bohlin & Fesen 1990). Supplemental analysis of *IRAS* AllSky Flux image data revealed an IR emission shell with linear dimensions 100 × 150 pc if at the same distance as the WR star. This emission shell is nearly centered on the WR star and its morphology indicates association with the high-velocity gas detected with the UV absorption line data.

In contrast to HD 50896 and HD 96548, HD 192163 is located near the galactic plane and is a member of a rich OB association, Cyg OB1. *IRAS* images reveal a shell-like structure of IR emission whose projected center lies close to HD 192163 (Nichols-Bohlin & Fesen 1993). This extended shell is significantly larger than the 12′× 18′ ring nebula NGC 6888. If located at the 1.8 kpc distance of the HD 192163, the extended shell has dimensions of 47 × 56 pc with an IR estimated total mass of 3×10^4 $M_\odot$, energy of 10^{51} ergs, and an age of $\geq 10^5$ yr. Energy budget calculations, IR morphology, and bright optical [S II] filaments indicate the IR shell is not a stellar wind-blown bubble. Spectra of strong [S II] optical emission filaments coincident with the extended shell's northeast edge are consistent with a supernova remnant interpretation. The study of this region included analysis of *IUE* spectral data which shows the presence of high-velocity components in the UV absorption lines in 18 of 22 stars located in this direction (St-Louis & Smith 1991, Nichols-Bohlin & Fesen 1993). This pervasive expanding gas in Cygnus is not uniquely identifiable with NGC 6888, the IR shell centered on HD 192163, or the IR Cyg OB1 superbubble, but may instead be due to a larger, multi-association superbubble.

3. Survey of high-velocity UV absorption line components in Wolf-Rayet stars

To assess whether the high-velocity gas detected in the lines of sight to these WR stars is a phenomenon related to the stellar winds of WR stars in general, Nichols & Fesen (1994) have surveyed all high dispersion spectra of WR stars observed with *IUE*. Table 1 shows the results of this survey for stars not known to be embedded in OB association supershells, along with an indication of variability or associated ring nebula. The results of this survey indicate that high-velocity gas in the lines of sight to WR stars is quite rare outside of those known to be embedded in OB association superbubbles. Eighty-five percent of the non-association stars included in this survey show no evidence of high-velocity gas in their lines of sight at the resolution of *IUE*. Thus, stellar winds, even strong ones associated with WR stars, are apparently insufficient by themselves to always produce absorption effects from interstellar bubbles observable with *IUE*.

Two stars in Table 1 represent new detections of high-velocity gas in the line of sight to a WR star. Features at –60 km s^{-1} occur in S II, Si II, Si IV, C IV, and C II in the spectra of HD 143414. With the detection of a possible ring nebula (see below), a classification of WN6, reported variability, and a large z distance (-885 pc), this star may be another WR star in the class of objects with extended ISM shells. No ring nebula has been detected around HD 197406, although two H I shells have been reported associated with this star. Both of these stars are too distant to allow field star observations with *IUE* to detect an extended shell.

4. Survey of *IRAS* data in the direction to WR stars

To assess the frequency of detection of large IR shells associated with WR stars, a survey of the *IRAS* AllSky survey data in the regions around WR stars has been completed in collaboration with R. Fesen and J. Saken. Six-degree fields were searched for arcs or rings of IR emission, or cavities of absorption in the lines of sight to WR stars. Twenty-eight such structures were identified, although some are probably fortuitous. The WR star is sometimes offcenter in the structure and most emission features catalogued are

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Table 1
Survey of non-Association Wolf-Rayet star *IUE* spectra to detect high-velocity (H-V) components

target star	spectral type	variability	ring nebula	H-V gas?
HD 50896	WN5	(1)	W	Yes
HD 62910	WN6+WC4		IR	No
HD 68273	WC8+O9I			No
HD 76536	WC6			No
HD 86161	WN8	(2)	IR	No
HD 96548	WN8	(3)	E	Yes
HD 104994	WN3pec			No
HD 113904	WC6+O9.5I		R_s	No
HD 115473	WC5			No
HD 119078	WC7			No
HD 136488	WC9			No
HD 143414	WN6	(4)	IR	Yes
HD 156385	WC7			No
HD 157451	WC9			No
HD 164270	WC9	(5)		No
HD 165763	WC5			No
HD 187282	WN4	(6)	R_s	No
HD 193576	WN5+O6			No
HD 193793	WC7+abs			No
HD 197406	WN7	(7)		Yes
HD 211853	WN6+O			No
HD 214419	WN7+O			No

Notes: (1) Firmani *et al.* 1980, (2) Moffat & Niemela 1982, (3) Moffat & Isserstedt 1980, (4) Isserstedt *et al.* 1983, (5) Isserstedt & Moffat 1981, (6) Antokhin *et al.* 1982, (7) Drissen *et al.* 1986

arcs rather than complete rings. In a number of the fields, cirrus confusion must be considered. Large-scale *IRAS* structures were identified toward 10 WC and 18 WN stars. Six of the structures are absorption cavities, while the rest are characterized as emission rings or arcs. WC stars have more of a tendency to be offcenter in the structure than WN stars, similar to the findings of Arnal (1992) for the H I shells. However, these newly identified potential IR shells do not coincide morphologically with known H I shells. More detailed analysis of these data is in progress. However, none of the structures catalogued in this survey present as strong a case for association with a particular WR star as the structures around HD 192163 and HD 96548.

Although motivated by a search for large scale extended structures around

WR stars, such as those found toward HD 96548 and HD 192163, the survey also revealed several potential new ring nebulae associated with WR stars, including three stars in the UV absorption line survey (designated "IR" in Table 1). In these cases, extended dust emission, as seen toward all WR stars with known ring nebulae, indicates the presence of a nebula ~ 10–15 pc in diameter.

5. Origin of the extended shells

5.1 Line-of-sight coincidences

Certainly it is possible that one or more of these shells are line-of-sight coincidences. None of the cases, considered alone, provides conclusive evidence that the shells are at the same distance as the WR star. However, the presence of only shortward-shifted components in the UV interstellar lines and the projected positions of the WR stars near the centers of the extended shells suggest a physical association, as does the absence of other hot stars within the perimeters of the shells. Most importantly, these three WR stars share several common characteristics, implying they represent a unique class of objects. Each of these stars has an associated, nitrogen- and helium-enriched ring nebula of much smaller dimensions than the extended shell, a spectral classification of WN5-8, and spectral and photometric variability. In addition, two of the three stars have relatively large z distances compared to WR stars in general.

5.2 Stellar wind

Assuming the extended shells are actually associated with the WR stars, they might be due solely to the massive stellar winds of WR stars or their precursors. The existence of such shells is expected around stars with such massive winds, both single and binary. However, the low frequency of detection of both high-velocity UV interstellar components and IR shell structures of large dimensions argues against this interpretation, as do the energy budgets for the interstellar structures detected. The mass loss rates for the three WR stars with extended shells are not greater than those determined for most WR stars (Abbott *et al.* 1986). It is difficult to understand why HD 50896, located some 300 pc out of the galactic plane, would have produced an interstellar wind-blown bubble of these dimensions when there is no evidence for similar structures around the majority of WR stars located in more dense interstellar environments. On the other hand, the shells may be relatively short lived, which would account for their scarcity and their detection only around WN5-8 stars (Lozinskaya 1992).

5.3 RLOF NEBULA: MODEL 1

The extended shells could be the result of non-conservative mass transfer in binary systems during previous Roche Lobe Overflow (RLOF) phases. In this case, the supernova of the primary would have occurred a few $\times\ 10^6$ years ago, probably near the galactic plane, producing a runaway O + compact companion (c) system (van den Heuvel & Heise 1972; Hellings & de Loore 1986). When the O star evolved off the main sequence in $\sim 10^6$ yr, it would have expanded, filling its Roche Lobe. With a kick velocity of about 100 km s^{-1}, the supernova remnant would be left behind in the galactic plane and the binary would have a large z distance. In this model, highly super-Eddington mass transfer from the O star to the compact companion would have resulted in the ejection of the O star envelope, perhaps in the form of beams as in the case of SS433, creating an expanding nebula (van den Heuvel *et al.* 1980; Hut & van den Heuvel 1981; Margon 1984). These three WR stars may then represent a later evolutionary phase of a massive X-ray binary, having already passed through an SS433-like phase. The dramatic mass loss during RLOF removes a significant part of the secondary envelope and can produce a WR star. After the loss of its hydrogen-rich envelope, the secondary star would have contracted to a radius less than the Roche Lobe radius and continued its evolution as a WR star.

During the helium shell burning phase a WR star might, in some cases, be expected to experience a second RLOF (Delgado & Thomas 1980; Habets 1986), which could produce a smaller optical ring nebula.

5.4 SUPERNOVA REMNANT: MODEL 2

The extended shells may be supernova remnants (SNRs) resulting from the explosions of the primaries in massive binary systems. The energy budgets for these extended shells are consistent with the SNR interpretation. In this case, the supernovae occurred only about 10^5 years ago based on energy considerations and detection limits for supernovae. Thus, the original mass ratio of the binary systems is constrained to be near one, because the secondaries would not have had time to evolve from O stars to WR stars in 10^5 years; they must have been evolved O or WR stars at the time of the supernova explosions. There are several problems with the identification of these extended shells as SNRs. Because these stars are well centered in the extended shells, the stars must be near their birthplaces, which is inconsistent with two of these stars (HD 50896 and HD 96548) being located about 300 pc out of the Galactic plane. Table 2 compares the observed characteristics of the extended shells to Models 1 and 2.

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Table 2
Observed characteristics of the WR stars with ring nebulae and extended shells compared with predictions of the two binary models

observed phenomena	post SS433 system (model 1)	system $\sim 10^5$ yrs after first SN (model 2)
1. extended shell produced $\sim 10^5$ yrs ago	yes	yes (if $q \simeq 1$)
2. ring nebula produced $\sim 10^4 - 10^5$ yrs ago	yes	yes
3. size and energy content of extended shell	yes (SS433-like jets)	yes (SNR)
4. large z-value (runaway character)	yes	no
5. WR star centered in extended shell and ring nebula	yes	yes

6. Conclusions

Based on the currently available data, the two models of the origin of these extended shells that assume the WR stars are binary systems in the second WR phase are the most plausible. The interpretation that the extended shells are the result of non-conservative mass transfer during RLOF (Model 1) appears more consistent with the observed properties of HD 50896 and HD 96548 than the interpretation that these extended shells are SNRs. On the other hand, the extended shell in the line of sight to HD 192163 is more consistent with a supernova remnant interpretation (Model 2). The smaller ring nebulae associated with these WR stars could perhaps be the result of a more current RLOF phase which began some 10^4 years ago, when the WR star was in the shell helium burning stage, although other interpretations are possible. The existence of compact companions for these three stars is a matter of some debate, but the compact companions may have spiraled into the dense wind of the WR star, evading detection. If either of these models for the extended shells can be verified by future observational and theoretical work, these objects may constitute a new and direct observational confirmation for massive binary star evolutionary theory.

References

Abbott, D.C., Bieging, J.H., Churchwell, E., Torres, A.V. 1986 *ApJ* **303**,239
Antokhin, I.I., Aslanov, A.A., Cherepashchuk, A.M. 1982, *Sov. Astron. (Letters)* **8**, 395

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Arnal, E.M., Mirabel, I.F. 1991, *A&A* **250**, 171
Arnal, E.M. 1992, *A&A* **254**, 305
Cappa de Nicolau, C.E., Niemela, V.S. 1984, *AJ* **89**, 1398
Cappa de Nicolau, C.E., Niemela, V.S., Arnal, E.M. 1986, *AJ* **92**1414
Cappa de Nicolau, C.E., Niemela, V.S., Dubner, G.M., Arnal, E.M. 1988, *AJ* **96** 1671
Delgado, A.J., Thomas, H.-C. 1981, *A&A* **96**, 142
Drissen, L., Lamontagne, R., Moffat, A.F.J., Bastein, P., Seguin, M. 1986, *ApJ* **304**, 188
Dubner, G.M., Niemela, V.S., Purton, C.R. 1990, *AJ* **99**, 857
Esteban, C., Vílchez, J.M. 1992, *ApJ* **390**, 536
Esteban, C., Vílchez, J.M., Smith, L.J., Clegg, R.E.S. 1992 *A&A* **259**, 629
Firmani, C., Koeigsberger, G., Bisiacchi, G.F., Moffat, A.F.J., Habets, G.M.H.J. 1986, *A&A* **165**, 95
Grant, G.J., Chu, Y.-H. 1993, *ApJ Suppl.* **85**, 137
Hellings, P., de Loore, C. 1986, *A&A* **161**, 75
Howarth, I.D., Phillips, A.P. 1986, *MNRAS* **222**, 809
Hut, P., van den Heuvel, E.P.J. 1981, *A&A* **94**, 327
Isserstedt, J. 1980, *ApJ* **239**, 607
Isserstedt, J., Moffat, A.F.J. 1981, *A&A* 96, 133
Isserstedt, J., Moffat, A.F.J., Niemela, V.S. 1983, *A&A* **126**, 183
Lozinskaya, T.A. 1992, in: Supernovae and Stellar Wind in the Interstellar Medium (New York: American Inst. of Phys.), p.337
Margon, B. 1984, *Ann. Rev. A&A* **22**, 507
Marston, A.P. 1991, *ApJ* **366**, 181
Mathis, J.S., Cassinelli, J.P., van der Hucht, K.A., Prusti, T., Wesselius, P.R., Williams, P.M. 1992, *ApJ* **384**, 197
Moffat, A.F.J., Isserstedt, J. 1980, *A&A* **91**, 147
Moffat, A.F.J., Niemela, V.S. 1982, *A&A* **108**, 326
Nichols-Bohlin, J., Fesen, R.A. 1986, *AJ* **92**, 642
Nichols-Bohlin, J., Fesen, R.A. 1990, *ApJ* **353**, 281
Nichols-Bohlin, J., Fesen, R.A. 1993, *AJ* **105**, 672
Nichols, J. S., Fesen, R.A. 1994, *A&A* in press
Niemela, V. S., Cappa de Nicolau, C.E. 1991, *AJ* **101**, 572
Paresce, F., Nota, A. 1989, *ApJ (Letters)* **341**, L83
Różyczka, M., Tenorio-Tagle, G., Franco, J., Bodenheimer, P. 1993, *MNRAS* **261**, 674
Smith, L.J. 1991, in: K.A. van der Hucht & B. Hidayat (eds.), Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, *Proc. IAU Symp. No. 163* (Dordrecht: Kluwer), p. 385
Smith, L.J., Crowther, P.A., Prinja, R.K. 1994, *A&A* **281**, 833
St-Louis, N., Smith, L.J. 1991, *A&A* **252**, 781
Tenorio-Tagle, G., Różyczka, M., Franco, J., Bodenheimer, P. 1991, *MNRAS* **251**, 318
van den Heuvel, E.P.J., Heise, J. 1972 ,*Nature* **239**, 67
van den Heuvel, E.P.J., Ostriker, J.P., Petterson, J.A. 1980, *A&A (Letters)* **81**, L7

DISCUSSION:

Niemela: The large z distances involve assuming that the absolute magnitude of the field WR stars are equal to those observed in clusters and associations. This could not be true. For the WR stars in the galactic plane, would the confusion effects hinder the detection of the rings?

Nichols: I agree the distance determinations for WR stars are uncertain and that is a major difficulty in verifying physical associations with the extended shells. Some of the detected IR rings may turn out to be invalid. A number of the IRAS images have multiple structures or cirrus confusion; thus we could have missed some detections because no distinct ring structure could be identified. However, the shells we have identified as possibly associated with WR stars are fairly convincing as distinct structures.

Manchado: I think that because you do not see those big shells around WR stars you cannot say that they do not exist. It may be a detection problem. Therefore I think that we should wait to ISO to really confirm that.

Nichols: Yes, you are right.

Maeder: Would you please comment about the amount of mass in these shells ejected by WR stars.

Nichols: We have a mass estimate only for the shell around HD192163, estimated from the IR fluxes as 2-3 x $10^4 M_\odot$. This estimate is primarily swept-up interstellar medium. I would expect the amount of stellar ejecta in these shells to be 2-3 $M_\odot$.

Owocki: Why do you always emphasize SNR and Roche Flow overflow ejecta as source of nebula material, and not material lost in the wind itself? Is the wind mass just too extended to be easily observed as a nebula?

Nichols: The energy budget calculations for each of the shells I have discussed are less consistent with a wind-blown bubble than with a supernova remnant. In addition optical, spectrophotometry of filaments coincident with the shell around HD192163 indicates $H\alpha$/[SII] $\sim$ 1.1, as expected in an evolved supernova remnant.

Lindsey Smith: But I think the important point here is that these shells are only found around 3 stars which would be hard to explain if they were solely the result of stellar winds.

van Kerkwijk: Would you not expect to see systems in the second WR phase as X-ray sources, like Cygnus X-3?

Nichols: Not necessarily. The compact companion may have been spun-up sufficiently to preclude accretion. Also, the X-rays may be smothered by a thick accretion disk.

Cherepashchuk: I have some comments about SS433. It is very surprising but this unique object does not show any period change. So there is some compensation between angular momentum loss through the inner lagrangian point and that through the supercritical accretion disk. In this case it seems to me that the formation of a common envelope has a low probability. It can be suggested that the formation of a WR star in SS433 system is going directly through the supercritical accretion disk stage but not through the common envelope state.

Miller: You mentioned 27 WR stars with IR "structures" around them. Have you found a correlation between these structures and either the presence or absence of optical ring nebula?

Nichols: No, we have looked and found no correlation. I have the data if you'd like to see it.

Williams: What are your criteria for determining whether arc and ring structures are associated with the WR stars?

Nichols: The criteria are central position or near-central position of the WR stars in the detected structure, the presence of only shortward-shifted interstellar line components and the absence of other hot stars within the perimeter of the shell. In addition, the differing morphology between the eastern and western hemispheres of the shell around HD 192163 indicates an interaction with the Cyg OB1 superbubble, HD 192163 being a member of that association.