*A Massive Star Odyssey, from Main Sequence to Supernova*
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# Radio observations of interstellar bubbles surrounding massive stars

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**Abstract.** We show radio continuum observations of the WR ring nebulae around WR 101 and WR 113 obtained using the VLA and H I 21 cm line data of the interstellar bubble around the O type stars BD +24° 3866 and BD+25° 3952 obtained with the DRAO Synthesis Telescope. We review previous radio continuum and H I line results toward WR and O-type stars.

## 1. Introduction

With mass loss rates in the range $10^{-7}$-$10^{-5}\,M_{\odot}yr^{-1}$ and terminal velocities of 1000 - 3000 $km\,s^{-1}$, massive stars transfer vast amounts of mechanical energy to the interstellar medium (ISM), creating hot low density regions bounded by expanding shells, usually referred to as *interstellar bubbles* (ISBs).

From the theoretical point of view, analytical models for the evolution of ISBs were developped in several classical papers (*e.g.*, Weaver *et al.* 1977; Dyson 1989). Later on, models of ISBs took into account different interstellar environments as well as the evolution of the central star.

Observationally, ISBs were found as optical ring nebulae linked to WR and Of stars (*e.g.*, Lozinskaya 1982; Chu, Treffers, & Kwitter 1983; Marston *et al.* 1994a,b). They can also be identified in the infrared (*e.g.*, Mathis *et al.* 1992), in X-rays (*e.g.*, Wrigge 1999) and in the radio regime.

At radio wavelengths, ISBs can be detected in both the radio continuum and in spectral lines. Radio continuum studies provide information about the distribution of the H II gas in the nebulae, the electron density and the ionized mass. The H I 21 cm and molecular line observations give valuable information about the ISM where the bubbles evolve, allowing the detection of the associated atomic and molecular material, as well as the determination of its kinematics, densities and masses. Both radio continuum and line data contribute in the analysis of the energetics and origins of the nebulae.



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Table 1. Radio observations of optical ring nebulae.

| WR | nebula | HPBW | $M_i$ ($M_\odot$) | $n_e$ ($cm^{-3}$) | $f$ | Refs. |
|---|---|---|---|---|---|---|
| WR 7 | NGC 2359 | 30″ | 70[a] | 120[a] | 0.03[a] | 1 |
| WR 101 | G 357.5–1.4 | 38″ | 190-265 | 40-55 | 0.15-0.30 | 2 |
| WR 102 | G 2.4+1.4 | 19″ | 100 | 60 | 0.1 | 3 |
| WR 113 | G 18.9+1.8 | 30″ | 11-29[b] | 180-5 00[b] | 0.02-0.15[b] | 2 |
| | | | 90[c] | 40[c] | 1[c] | 2 |
| WR 124 | M1-67 | 46″ | 260 | 4.1 | | 4 |
| WR 130 | G 68.1+1.1 | 1.′5 | 3000 | 3 | 1 | 5 |
| WR 134 | Anon (WR 134) | 1.′5 | ≥3.3 | ≤100 | 1 | 6 |
| WR 136 | NGC 6888 | ≤1′ | 2.5-6.0 | 300-600 | 0.003-0.001 | 4,7 |

Notes: *a*: filamentary shell only; *b*: inner optical shell; *c*: outer optical shell.
References: 1. Cappa *et al.* 1999; 2. Cappa *et al.* 2002a; 3. Goss & Lozinskaya 1995; 4. Israel & Felli 1976; 5. Cichowolski *et al.* 2001; 6. Gervais & St-Louis 1999; 7. Wendker *et al.* 1975.

## 2. Radio continuum observations: the nebulae around WR 101 and WR 113

Ring nebulae were first observed at radio wavelengths by Johnson & Hogg (1965) and Smith & Batchelor (1970) who identified four typical nebulae and confirmed their thermal nature.

High angular resolution observations were carried out using different interferometric instruments. NGC 2359 and M1-67 were observed with the Westerbork Synthesis Radio Telescope (WSRT) at 1.4 and 5 GHZ by Israel & Felli (1976) and Felli & Perinotto (1979). The same telescope was used to observe NGC 6888 at 0.6, 1.4 and 5 GHz (Wendker et al. 1975). G 2.4+1.4 (Goss & Lozinskaya 1995) and NGC 2359 (Cappa *et al.* 1999) were studied using the the Very Large Array (VLA) at 1.465 GHz. The nebulae around WR 134 and WR 130 were analyzed using the Synthesis Telescope of the Dominion Radio Astrophysical Observatory (DRAO) at 21 cm (Gervais & St-Louis 1999; Cichowolski *et al.* 2001). It is found that there is very good agreement between the radio and optical emissions for most of the nebulae.

The ring nebulae around WR 101 and WR 113 were observed using the VLA with angular resolutions of $\sim 38''$ and $30''$, respectively (Cappa *et al.* 2002a). The radio continuum images of both nebulae as well as the H$\alpha$ image of the nebula linked to WR 113 are displayed in Figure 1. As for the other nebulae, the correlation between the radio continuum and the optical nebular emission is excellent for the nebula around WR 101, while only the SW portion of the inner optical ring and the outer optical arc related to WR 113 are identified at radio wavelengths. Both nebulae are thermal sources.

Table 1 summarizes the main parameters of the nebulae around WR 101 and WR 113, along with the WR ring nebulae that have been studied in the radio continuum with high angular resolution data. The first three columns list the names of the WR star and the nebula and the half power beam width

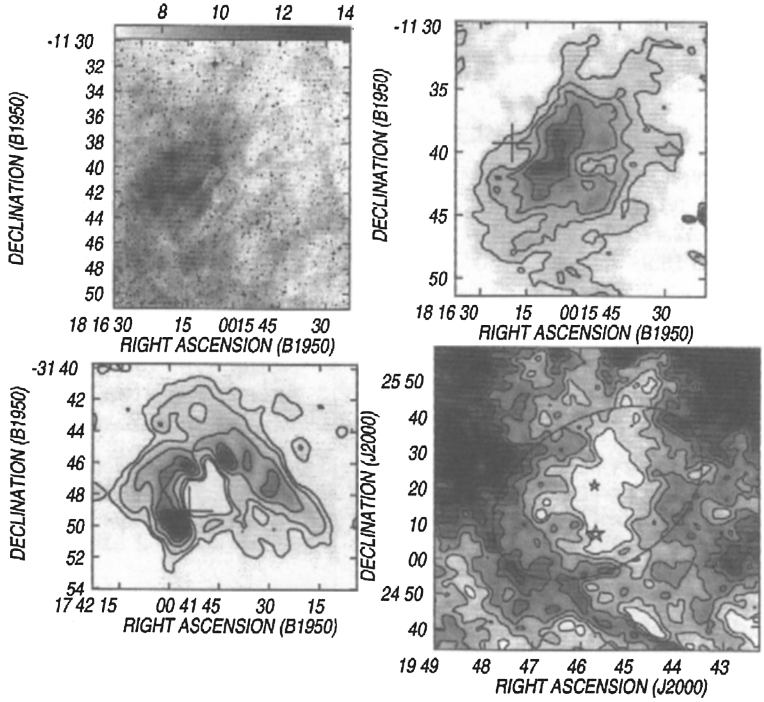


Figure 1. *Upper panel, left:* DSS image of the WR ring nebula around WR 113. *Right:* VLA image of the nebula around WR 113 at 1465 MHz. The contours are 5, 10, 15, 25, 35, 45 and 55 mJy beam$^{-1}$. The cross indicates the position of the star. *Lower panel, left:* VLA image of the ring nebula around WR 101. The contours are 2, 5, 15, 30 and 45 mJy beam$^{-1}$ . *Right:* H I emission distribution within the velocity range 23.7 to 30.3 km s$^{-1}$ showing the H I bubble around BD+24° 3866 and BD+25° 3952. The ellipse delineates the bubble. The large star symbol marks the position of BD+24° 3866 while the small star symbol indicates the position of BD+25° 3952.

(HPBW) of the observations. Ionized masses, electron densities and derived filling factors are indicated in columns 4 to 6. Clearly, there are a variety of masses and densities. Low filling factors are generally inferred from the optical images, indicating a clumpy structure.

The ionized masses suggest that the ring nebula related to WR 101 and the outer arc associated with WR 113 mainly consist of swept-up interstellar matter, while the inner shell of the nebula around WR 113 may contain a non-negligible contribution of expelled ejecta material.

The dust temperature derived from *IRAS*-HIRES data for the ring nebula around WR 101 is 40 - 44 K. Similar dust temperatures were obtained for bow shocks. The dust mass is $\sim$0.3 - 1.0 $M_\odot$.

The dynamical ages of the nebulae around WR 101 and WR 113 derived using Weaver *et al.* 's (1977) model are $t_d = 6 \times 10^4$ yr and $(1.3 - 2.5) \times 10^5$ yr, respectively, suggesting that both nebulae were created during the current WR phase of the star. These are, of course, lower limits. Upper limits for the expansion velocities of the nebulae around WR 101 and WR 113 are 40 and 5 - 10 km $s^{-1}$, respectively.

## 3. The H I bubble surrounding BD+24°3866 and BD+25°3952

Weaver *et al.* (1977) and Van Buren (1986) proposed that ISBs around massive stars may have an outer neutral counterpart which originates in gas recombination in the dense shell. Indeed, H I interstellar bubbles have been found surrounding a relatively large number of galactic WR and O-type stars. They appear as cavities and shells in the H I 21 cm line emission distribution.

Three main conditions should be fulfilled to link a massive star to an H I cavity or shell: (*i*) the star must be projected onto the cavity or close to its borders; (*ii*) the kinematic distance of the H I structure should agree with the stellar distance; and (*iii*) the stellar wind must be powerful enough to create the bubble.

Figure 1 displays the H I bubble around the stars BD+24°3866 (O8.5II[f]) and BD+25°3952 (O8). The atomic gas data were obtained using the Synthesis Telescope of the DRAO (Canada) with a synthesized beam of 1.0×2.3 arcmin. The H I bubble, which is delineated by the ellipse, has a systemic velocity of 27 km $s^{-1}$ and a radius of 23×15 pc. The kinematic distance of the H I structure (2.4 kpc) is compatible with the optical distance of both stars. This fact, along with the location of the stars within the cavity, favor the association of the H I ring and the stars. The proper motion of both stars, pointing toward the S-SW, gives additional support to this association.

BD+25°3952 is the exciting star of the H II region Sh2-88, which is projected onto the center of the cavity. The H II region itself appears to be interacting with neutral material at a systemic velocity of 23 km $s^{-1}$. Based on the slightly different systemic velocities of the H I bubble and the atomic gas related to Sh2-88, and on the relative locations of both features, we propose that Sh2-88 is placed in the approaching part of the H I bubble. Consequently, both stars are placed inside the bubble and have contributed to its formation. The ionized and neutral mass of the bubble amounts to 1 300 $M_{\odot}$.

The dynamical age derived for the H I bubble ($\sim 1.5\times10^6$ yr) indicates that the stellar winds from the main sequence phase of BD+24°3866 have played a role in shaping the bubble.

The energy conversion efficiency (equal to the ratio between the kinetic energy of the bubble and the mechanical energy provided by the massive star) is 0.03, indicating that BD+24°3866 alone is capable of creating the observed structure via stellar winds.

## 4. H I bubbles around massive stars: a brief review

Table 2 summarizes the main parameters of the H I interstellar bubbles found around WR and O-type stars. Only the H I bubbles observed with instruments providing an angular resolution less than 10′ are included. The table lists: column 1: the central star; column 2: the approximate HPBW of the observation; column 3: the radius of the size of the bubble; columns 4,5: the associated atomic and ionized masses; column 6: the original ambient density; column 7: the expansion velocity; and column 8: the dynamical age. The upper part of the table

Table 2. Neutral gas bubbles around Wolf-Rayet, O and Of stars.

| star | HPBW (′) | $R_{ISB}$ (pc) | $M_{at}$ ($M_\odot$) | $M_{ion}$ ($M_\odot$) | $n_{ISM}$ ($cm^{-3}$) | $v_{exp}$ ($km\,s^{-1}$) | $t_d$ ($10^6$ yr) | Ref. |
|---|---|---|---|---|---|---|---|---|
| WR 2 | 9 | 16×11 | 270 | | 1.4 | 7 | 1.0 | 1 |
| WR 3 | 9 | 11×6 | 30 | | 0.8 | (8) | 0.6 | 2 |
| | 2.2 | 14×6 | 60 | | 1.2 | (8) | 0.6 | 3 |
| WR 4 | 9 | 34×11 | 990 | | 2.4 | (8) | 1.2 | 2 |
| WR 5 | 9 | 13×6 | 170 | | 3.6 | (8) | 0.6 | 2 |
| WR 6 * | 9+30 | 14×7 | 60 | | 1 | 9 | 0.6 | 4 |
| WR 7 * | 0.75 | 8 | 300 | 1400 | 20 | 6 | 0.7 | 5 |
| WR 123 | 9 | 48×23 | 780 | | 0.7 | (8) | 2.3 | 2 |
| WR 125 | 3.3 | ≃3 | 60 | 50 | 40 | (8) | 0.2 | 6 |
| WR 128 * | 9 | 15×8 | 130 | | 1.3 | 8 | 0.7 | 1 |
| WR 130 * | 1.5 | 14 | 670 | 3000 | 13 | (10) | 0.8 | 7 |
| WR 132 * | 9 | 30×11 | 1300 | | 2.2 | (8) | 1.2 | 2 |
| WR 134 * | 1.5 | 30×15 | 2500 | ≥ 3.3 | 2.6 | 10 | 1.3 | 8 |
| WR 136 * | 1.5 | 5.9×3.2 | 200 | 4 | | 10 | 0.3 | 9 |
| | 1.5 | 14 | 1000 | | 4 | 7 | 1 | 9 |
| WR 140 | 2.5 | 5.5×4.2 | 70 | | 1 | (8) | 0.3 | 10 |
| WR 143 | 1.5 | 15.4 | 580 | | 1.6 | 8 | 0.8 | 11 |
| WR 144 | 2 | 7 | 27 | | 0.8 | 7 | 0.6 | 12 |
| WR 146 | 2 | 7 | 23 | | 0.7 | | | 12 |
| WR 148 | 1.0 | 18, 3.8 | 600 | | 1.0 | ≤6 | 3, 0.62 | 13 |
| WR 149 | 9 | 57 | 9800 | 1900 | 2 | 9 | 3.5 | 14 |
| WR 151 | 9 | 15×19 | 640 | | 1.4 | 10 | 0.6 | 1 |
| HD 10125 | 1.1 | 9 | 190 | 110 | 4.1 | 9 | 0.5 | 15 |
| HD 13022 | 9 | 22×29 | 1100 | | 1.4 | 14 | 1.0 | 16 |
| HD 13338 | 9 | 18 | 470 | | 0.8 | 7 | 1.4 | 16 |
| HD 14442 | 9 | 35×30 | 2500 | | 0.8 | 9 | 2.0 | 16 |
| HD 14947 | 9 | 24×14 | 1040 | | 1.8 | 10 | 1.0 | 16 |
| HD 16691 | 9 | 31×20 | 1140 | | 1.0 | 8 | 1.8 | 16 |
| HD 192281 | 1.5 | 12×10 | 330 | | 0.5 | 8 | 0.8 | 17 |
| BD+24° 3866 | 1.2 | 19 | 900 | 400 | 1.9 | 10 | 1.5 | 18 |

Note: *: optical ring nebula detected.
References: 1. Arnal *et al.* 1999; 2. Arnal 1992; 3. Arnal & Roger 1997; 4. Arnal & Cappa 1996; 5. Cappa *et al.* 1999; 6. Arnal & Mirabel 1991; 7. Cichowolski *et al.* 2001; 8. Gervais & St-Louis 1999; 9. Cappa *et al.* 1996a; 10. Arnal 2001; 11. Cazzolato & Pineault 2000; 12. St-Louis 2002; 13. Dubner, Niemela, & Purton 1990; 14. Cappa *et al.* 1996b; 15. Cichowolski *et al.* in preparation; 16. Cappa & Herbstmeier 2000; 17. Arnal *et al.* in preparation; 18. Cappa *et al.* 2002b.

lists the H I bubbles related to WR stars, while the lower part summarizes those associated with O and Of stars. Taking into account the H I bubbles analyzed using low angular resolution data (see Niemela & Cappa de Nicolau 1991; Cappa & Herbstmeier 2000 for a summary; Dubner *et al.* 1992), 30 H I bubbles have been found around WR stars and 17 around O and Of type stars.

Some conclusions can be drawn from the table: (*i*) most of the H I bubbles have radii $R_{ISB} \simeq 3$ - 35 pc and expansion velocities in the range 5 - 10 $km\,s^{-1}$; (*ii*) in many cases, the dynamical ages of the ISBs related to WR stars are larger than the lifetime of the WR phase of a massive star. Thus, the progenitors of

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the current WR stars may have contributed in shaping the bubbles; and (*iii*) the H I bubbles around Of stars are similar in radius, expansion velocities and dynamical ages to those around WR stars.

WR 136 and WR 148 are the only cases where several H I structures with a hierarchical organization have been detected. They could originate in the different evolutionary phases of the current WR star as has been proposed for some optical ring nebulae. Some H I bubbles, like the ones around WR 3, WR 6 and WR 140 display a double H I cavity, which has been explained as caused by an asymmetric stellar wind (*e.g.*, Arnal 2001).

In many cases, H I bubbles display neither an optical ring nebula nor radio continuum emission. As was shown by Nazé *et al.* (2001) for the optical ISB in the LMC, galactic optical ring nebulae and/or thermal radio emission seems to be detected in regions of relatively high ambient density.

The energy conversion efficiency for H I interstellar bubbles is $\epsilon \leq 0.03$, indicating that large energetic losses occur. Similar results were obtained for ISB in the LMC (Oey 1996). The energy conversion efficiency $\epsilon$ depends on the mass loss rate and the terminal velocity of the wind, on the expansion velocity of the ISB and on the amount of material that participates in the expansion. This efficiency has large uncertainties. An additional source of error originates in the probable leakage of energy through breakout regions in the shells.

In particular, the amount of material in the expanding bubble may be underestimated since, in most of the cases, only atomic gas was taken into account. At present, NGC 2359 is the only WR ring nebula for which the ionized, atomic and molecular material have been taken into account (Cappa *et al.* 1999, 2001). We note that in this case, the energy conversion efficiency is also $\leq 0.03$.

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## Discussion

OWOCKI: The bubbles you show all look pretty spherical, while the nebulae from LBVs sometimes have a bipolar form, as in, *e.g.*, $\eta$ Car. Do you ever see WR bubbles that are perhaps younger and smaller and also brighter?

CAPPA: There is at least one case in which two H I cavities with the star in between is seen. However, this structure is larger (and older) than bi-polar nebulae around LBVs.

LANGER: You explained that the H I bubbles around WR stars fall into two categories, those formed by the WR stars themselves, and those formed by the O-type star progenitor of the WR star. How can this be understood regarding that *all* WR stars have

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an O-type star progenitor phase?

CAPPA: This is not so clear, but the ISM is so complex. I do not have a final answer for that. If the star is close to the caps of the main sequence shell and/or if it has moved from it's original position it is possible to find a new H I shell. Probably there are other ways.

OEY: When we studied super bubbles around associations with many massive stars, we found that energetically the shells seemed too small. So it is extremely interesting that you do not find this discrepancy. Also do you have any estimate for the relative importance of molecular gas in the ambient ISM relative to H I or ionized gas?

CAPPA: Indeed, we do find the same discrepancy, since the energy needed to create the H I galactic bubbles is far lower than provided by the central star. For the case of NGC 2359, the amount of molecular gas is a large fraction of the total associated mass, while it seems to be a small portion of the total material in the case of NGC 3199 (the ionized mass is $\sim 250\,M_{\odot}$ in the nebula). For the nebula around WR 16, the amount of molecular gas is comparable to the amount of ionized material.

Rotation, rotation, rotation

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