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RADIO OBSERVATIONS OF WOLF-RAYET RING NEBULAE

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RESUMEN

Se detallan en este trabajo las principales características físicas de las nebulosas anillo ópticas detectadas alrededor de estrellas WR, obtenidas utilizando observaciones en el continuo de radio, en la línea de 21 cm del Hi, y en líneas moleculares. Se analizan la energética de estas estructuras a la luz de los modelos evolutivos de burbujas interestelares y los problemas no resueltos.

ABSTRACT

The main physical characteristics of the optical ring nebulae around WR stars based on radio continuum, Hi 21 cm line and molecular observations are summarized. The energetics of these structures is analyzed taking into account predictions from evolutionary models of interstellar bubbles. The main open questions are also discussed.

Key Words: **ISM: BUBBLES — STARS: WOLF-RAYET**

1. INTRODUCTION

With mass loss rates of about 10^{-6} – 10^{-5} $M_{\odot}$ yr^{-1} (Cappa, Goss & van der Hucht 2004) and terminal velocities of 1000-3000 km s^{-1} (Niedzielski & Skorzynski 2002), Wolf-Rayet stars inject to the interstellar medium about 50% of the total wind energy suplied by all stellar types, at least in the solar vicinity (Abbot & Conti 1987) and provide a large amount of enriched gas. The mass lost by these stars, along with the interstellar matter swept-up by the stellar wind, are expected to appear as circumstellar *ring nebulae* detected in the Hα and [OIII] lines (e.g. Marston et al. 1994 and references therein).

A quarter of the about 220 galactic WR stars appear surrounded by optical ring nebulae (van der Hucht 2001). These interstellar bubbles are small in size ($< 30'$) and generally filamentary in appearance, with expansion velocities in the range 15 to 80 km s^{-1}, and dynamical ages of a few times 10^5 yr (Chu, Treffers, & Kwitter 1983).

Optical ring nebulae are also detected in the infrared, in X-rays, and in the radio wavelengths. In this paper, the main radio characteristics of interstellar bubbles around galactic WR stars are summarized.

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2. RADIO CONTINUUM OBSERVATIONS

Ring nebulae are detected as shell-shaped thermal radio sources (spectral index $\alpha \simeq -0.1$, $S_\nu \, \alpha \, \nu^\alpha$). Thus, radio continuum studies provide information about the distribution of the ionized gas, the electron density and the ionized mass.

Up to present, radio continuum studies performed with appropriate angular resolution were carried out towards a few ring nebulae. In all cases, the correlation between the optical and the radio images is excellent. Table 1 lists the main parameters of the ring nebulae having high angular resolution radio continuum studies. The table lists the WR star number, the name of the nebula, the half power beam width of the data, the ionized mass, the electron density and the volume filling factor. Clearly, there is a variety of masses and densities. Small filling factors indicate a clumpy structure.

The top panel of Fig. 1 displays the Hα image and the radio continuum image at 1.465 GHz, obtained using the Very Large Array, of the ring nebula NGC 2359 around WR 7 (Cappa et al. 1999). Note the excellent correspondence between the optical and the radio emissions.

The ionized masses suggest that some of the nebulae mainly consist of processed stellar material (like the ones linked to WR 113 [inner arc], WR 124, WR 134 and WR 136 [inner shell]), as is also indicated from studies of chemical abundances (Esteban et al. 1992).

The interstellar dust mixed with the ionized gas in the ring nebulae is responsible for the emission at 60 and 100μm. This IR emission coincides with

TABLE 1

RING NEBULAE WITH HIGH RESOLUTION RADIO CONTINUUM OBSERVATIONS

WR#	Nebula	HPBW	M_{HII} ($M_\odot$)	n_e (cm^{-3})	f	Refs.
7	NGC2359	30″	70[a]	120[a]	0.03[a]	1
101	G357.5-1.4	30″	190-265	40-55	0.15-0.30	2
102	G2.4-1.2	19″	100	60	0.1	3
113	G18.8+1.8	30″	11-29[b]	180-500[b]	0.02-0.15[b]	2
			90[c]	40[c]	1[c]	2
124	M1-67	8″	4.1	260		4
130	G68.1+1.1	1.′5	3000	3	1	5
134		1.′5	≥3.3	≤100	1	6
136	NGC6888	≤1′	2.5-6.0	300-600	0.003-0.001	7,8
157	Sh2-157	1.′0	3000	15	0.3	9

[a]Filamentary shell only.

[b]Inner optical shell.

[c]Outer optical shell.

1 – Cappa et al. 1999; 2 – Cappa, Goss, & Pineault 2002; 3 – Goss & Lozinskaya 1995; 4 – Cichowolski et al. 2005; 5 – Cichowolski et al. 2001; 6 – Gervais & St-Louis 1999; 7 –Wendker et al. 1975; 8 – Israel & Felli 1976; 9 – Vásquez et al. 2006.

the radio continuum emission. In some cases, the derived dust color temperatures are typical for bow shocks.

3. HI 21 CM LINE EMISSION OBSERVATIONS

Weaver et al. (1977) and Van Buren (1986) proposed that interstellar bubbles around massive stars may have an outer neutral counterpart which originates in gas recombination in the dense shell. Indeed, the analysis of the HI 21 cm line emission distribution in the environs of WR stars allowed to disclose cavities and expanding shells associated with the central stars. These HI structures are the neutral gas counterparts of the optical ring nebulae.

Figure 1 (bottom panel, left) shows the optical and HI interstellar bubbles around WR 23 (Cappa et al. 2005).

HI interstellar bubbles have been found around about 35 galactic WR stars. Their main characteristics are:

1. Most of the HI bubbles have radii in the range 3-40 pc, and low expansion velocities of 5-15 km s^{-1}.

2. HI bubbles are larger than their optical counterparts, with the ionized nebulae projected inside the HI shells.

3. In many cases, the dynamical age of the HI bubbles is larger than the lifetime of the WR phase of a massive star, indicating that the O-type star progenitor of the current WR star has also contributed in the formation of the structures.

4. HI bubbles have also been found around stars which do not display either optical ring nebulae or radio continuum emission. Very probably, optical ring nebulae and/or thermal radio emission are detected towards regions of relatively high ambient density, as was shown by Nazé et al. (2001) for ring nebulae in the LMC.

5. As for the optical ring nebulae, the WR stars are located at an eccentric position within the HI bubbles.

Some interstellar bubbles related to WR stars exhibit characteristics which are far from predictions from evolutionary models, as is the presence of double HI cavities and aspherical bubbles.

Double HI cavities are present around, for example, WR 6 and WR 140 (Arnal & Cappa 1996; Arnal 2001). This characteristic can be explained as caused by an asymmetric stellar wind.

Aspherical structures can originate in an inhomogeneous ISM, in the high stellar velocity, in an isotropic stellar wind, or in the presence of magnetic fields (e.g. Arnal & Cappa 1996).

The analysis of the interstellar medium around WR 136 and WR 148 showed the presence of concentric HI interstellar bubbles related to the stars (Dubner, Niemela, & Purton 1990; Cappa et al. 1996). These HI structures can originate in different evolutionary phases of the current WR star as has been proposed for optical ring nebulae (Marston 1995).

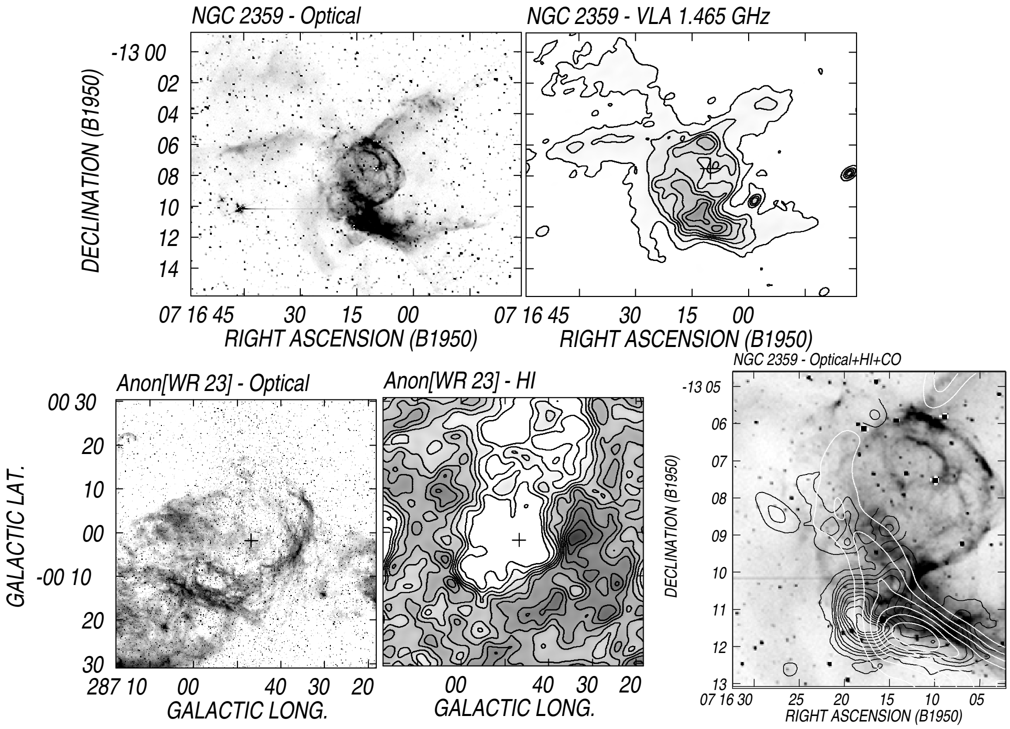

Fig. 1. *Top panel:* Hα and radio continuum images of the ring nebula NGC 2359 around WR 7. The radio continuum image was obtained with the VLA at 1.465 GHz. Contour lines are 2, 5, 8, 11, 15, 20, 25, 35 and 45 mJy beam^{-1}. The grayscale corresponds to 1.5 to 70.0 mJy beam^{-1}. *Bottom panel. Left:* Optical and HI interstellar bubbles around WR 23. Contour lines are from 12.4×10^{20} to 19.6×10^{20} cm^{-2}, in steps of 0.8×10^{20} cm^{-2}. The grayscale is 13.0×10^{20} to 21.0×10^{20} cm^{-2}. *Right:* Overlay of the Hα (grayscale), integrated HI emission within the velocity interval 51.4 to 57.9 km s^{-1} *(white contour lines)*, and integrated CO(2-1) line emission for the molecular component at 54 km s^{-1} (*black contours*). HI contour lines correspond to 5, 15, 25, 35, 45 and 55 mJy beam^{-1}. CO contours are 2.4, 4.8, 7.2, 9.6, 14.4, 19.2, 24.0, 28.8, 33.6 and 38.4 K km s^{-1}.

The HI interstellar bubbles linked to massive O-type stars are similar in radius, expansion velocity and dynamical age to those around WR stars (e.g. Cappa & Herbstmeier 2000).

4. MOLECULAR LINE OBSERVATIONS

Only a few ring nebulae have detailed molecular line studies.

Schneps et al (1981), based on CO(1-0) observations, revealed the presence of molecular emission related to NGC 2359. Cappa, Rubio & Goss (2001) performed CO(1-0) and CO(2-1) observations of the same nebula. The comparison between the distributions of the ionized, neutral atomic and molecular gas, along with the relatively large values of the CO(1-2)/CO(1-0) intensity ratio, are consistent with the existence of a photodissociation region (PDR) at the surface of the molecular cloud. Figure 1 (bottom panel, right) shows the distribution of the ionized, neutral and molecular gas associated with NGC 2359.

CO was also observed towards Anon(WR 16), RCW 104 (around WR 75), NGC 3199 (around WR 18), and RCW 78 (around WR 55) (Marston et al. 1999; Marston 2001; Cappa et al. 2005). A stellar wind origin was suggested for the molecular gas related to Anon(WR 16), while an interstellar origin is implied for the molecular material related to the other nebulae.

Rizzo, Martin-Pintado, & Desmurs (2003) observed CS, HCO$^+$, CN, HCN towards NGC 2359, Anon (WR134) and NGC 6888, finding evidences for the presence of shock fronts.

More studies of molecular lines are necessary to investigate the origin of the molecular material and the processes that originate the molecular emission. Very probably, both PDRs and shock fronts are present in interstellar bubbles. Particularly, studies of the PDR in NGC 2359 using molecular lines sensitive to high density regions are also required.

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5. THE ENERGETICS

According to evolutionary models of interstellar bubbles, the expected energy conversion efficiency is $\epsilon\ (= E_k/E_w) = 0.20$ for the energy conserving model and $<<0.20$ for the momentum conserving model (McCray 1983). E_k is the kinetic energy of the interstellar bubble, and E_w, the mechnical energy of the stellar wind. Values derived from both optical and radio observations are ≤ 0.02, indicating that large energetic losses occur. Similar results were obtained for interstellar bubbles in the LMC (Oey 1996).

The presence of neutral clumps within the bubbles and the probable leakage of energy through breakout regions in the shells may be responsible for the large energetic losses (Chu et al. 1983; Cooper et al. 2004).

The energy conversion efficiency ϵ depends on the stellar wind and the expanding bubble parameters, which have large uncertainties (e.g. Cazzolato & Pineault 2005). Both the expansion velocity and the amount of material in the interstellar bubble may be underestimated. One source of error is the fact that, in most of the cases, only atomic gas was taken into account. However, the observed low ϵ-value also holds for NGC 2359, for which the ionized, atomic and molecular material have been taken into account.

More high resolution studies of WR ring nebulae including the ionized, neutral atomic, and molecular gas components are necessary to investigate the energetic conditions of these nebulae.

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