*RevMexAA (Serie de Conferencias)*, **7**, 42–49 (1998)

# RING NEBULAE AROUND EVOLVED MASSIVE STARS: OBSERVATIONAL CLUES

César Esteban

Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain; cel@ll.iac.es

RESUMEN

La observación de nebulosas anulares asociadas a estrellas masivas evolucionadas (Wolf-Rayet y Variables Luminosas Azules) es una herramienta muy potente para comprender cómo se produce la interacción de los vientos estelares y las expulsiones de material estelar con el medio circunestelar. Más aún, las propiedades morfológicas, dinámicas y químicas de estas nebulosas son fiel reflejo de la historia pasada de la estrella progenitora. En este artículo, reviso algunas propiedades observacionales de las nebulosas anulares: censo, morfología, cinemática, abundancias químicas y parámetros de las estrellas centrales.

ABSTRACT

Observations of ring nebulae associated with evolved massive stars (Wolf-Rayet and luminous blue variables) are powerful tools for understanding the interaction of stellar winds and ejecta with the circumstellar medium. Moreover, the morphological, dynamical and chemical properties of these nebulae reflect the past history of the progenitor star. In this paper, I review and discuss some important observational properties (census, morphology, kinematics, chemical abundances, and progenitors of the central stars) related to ring nebulae.

*Key words:* **ISM: ABUNDANCES — ISM: BUBBLES — ISM: KINEMATICS AND DYNAMICS: — STARS: VARIABLES: OTHER (LUMINOUS BLUE VARIABLES) — STARS: WOLF-RAYET**

## 1. INTRODUCTION

The evolution of the most massive stars ($M_{\rm i} \geq 25\ M_\odot$) is determined mainly by two physical parameters: the initial mass and the mass loss rate. During their relatively short lives, massive stars can interact with the surrounding interstellar medium (ISM) by means of: i) their strong UV photon flux ionizing large amounts of gas; ii) the mechanical action of their stellar winds affecting the kinematics of the surrounding medium, and iii) the processed material ejected in their final stages of evolution: chemically enriching the ISM. Some massive stars evolved beyond the main sequence (Wolf-Rayet and luminous blue variable type stars) are in fact surrounded by arched nebulae whose shape and origin can be explained by this interaction.

In this paper I will review observational results about nebulae associated with Wolf-Rayet (WR) and Luminous Blue Variable (LBV) stars in our Galaxy and beyond. I will focus on different aspects of their morphology, kinematics, chemical abundances and the fundamental parameters of the progenitor stars. Previous very good reviews on ring nebulae are those by Chu (1991) and Smith (1994, 1997).

## 2. WR RING NEBULAE

### *2.1. Observational Properties, Classification and Census*

Johnson & Hogg (1965) were the first in correctly identifying these objects as produced by stellar winds sweeping up the ambient ISM. Previously, some were classified as H II regions, planetary nebulae or even supernova remnants. Attending to their optical appearance, Smith (1967) defined them simply as "arcs of nebulosity centered on and ionized by a WR star". Among their main observational properties we can distinguish: i) large angular sizes (up to several tens of arcmin); ii) linear sizes ranging from 2 to 20 pc; iii) very low surface brightness, and iv) ionized masses between 1 and 40 $M_\odot$.

It was not until the beginning of the 80s when the first optical surveys —based on photographic plates— are available for the Galaxy (Heckathorn, Bruhweiler, & Gull 1982; Chu, Treffers, & Kwitter 1983). In a series of papers published between 1981 and 1983, Chu and colleagues (see Chu et al. 1983 and references therein), carried out a systematic kinematical study for a substantial part of the known Galactic rings by means of Fabry-Perot spectroscopy and presented a list of 15 definite Galactic ring nebulae. Chu (1981) classified these objects into 4 types according to their morphology and kinematics. R-type nebulae have subsonic expansion velocities, with a dynamical timescale larger than the lifetime of the WR phase. Chu distinguished two subtypes: $R_s$, having apparent shell structure and $R_a$, showing an amorphous shape. W-type nebulae —wind-blown bubbles— present shell structure and high expansion velocities, corresponding to dynamical timescales larger than the lifetime of the WR phase. E-type nebulae correspond to objects composed of stellar ejecta material and are chemically enriched.

Recently, several new searches based on CCD deep narrow-band filter imaging (Miller & Chu 1993; Marston et al. 1994a,b; Marston 1997) have been published covering all the Galactic WR stars catalogued by van der Hucht et al. (1981). These authors find a total of about 56 possible and confirmed WR ring nebulae accounting for a 35% detection rate. Of this number of possible ring nebulae only 19 have kinematic studies available, 33% of the total number of nebulae (Chu et al. 1983 and previous papers of the series; Smith et al. 1984; Marston & Meaburn 1988; Goudis, Meaburn, & Whitehead 1988; Goudis et al. 1994; Dopita & Lozinskaya 1990; Esteban & Rosado 1995). Of these, only 12 nebulae have chemical abundance studies available (Kwitter 1981, 1984; Esteban et al. 1990, 1991, 1992; Esteban & Vílchez 1992).

The different types of ring nebulae seem to be correlated with the spectral type of the central WR star as is shown in Table 1. All the $R_a$ nebulae are associated with WN7 stars. The $R_s$ objects are apparently associated with stars of different spectral subtypes but especially to the WC sequence. In contrast, W nebulae preferentially surround early-type WN stars. The last group, the E objects, are associated with both early- and late-type WN stars. This correlation between nebular and spectral types can be understood in the light of an evolutionary scheme. The theoretical models for the evolution of massive stars (e.g., Maeder & Meynet 1994) predict that WN stars appear after the RSG or LBV phase and before the WC stage. This could explain the preferred association of WN stars with E-type objects and the scarcity of WC stars surrounded by W or E nebulae, objects with dynamical timescales of the order of $10^4$ yr.

TABLE 1

CORRELATION BETWEEN NEBULAR AND SPECTRAL TYPES

| $R_a$ | $R_s$ | W | E or E+W | W or E |
|---|---|---|---|---|
| WN7 | WC6+O9.5I | WN4 | WN5 | WN8 |
| WN7 | WC4 | WN5 | WN8 | WN4.5+O9.5I |
| | WC8+O8-9IV | WC6 | WN5 | |
| | WN4 | WN6 | WO1 | |
| | WN6/WCE+O | ... | WN8 | |
| | | | WN6 | |

TABLE 2

RELATIVE IMPORTANCE OF EACH WR SEQUENCE

| WR sequence | N[WR(seq.)] / N(WR) | N[RN(WR seq.)] / N(RN) |
|---|---|---|
| WN | 55% | 74% |
| WC | 43% | 21% |
| WO | 2% | 5% |

The relative importance of the WN sequence in ring nebulae is further illustrated in Table 2. The second column gives the fraction of the number of WN stars over the total number of Galactic WR stars. The third column of Table 2 gives the fraction of ring nebulae with WN central stars over the total number of confirmed objects (the 19 nebulae with kinematic data available). As can be seen, the WN sequence seems to be more favoured in ring nebulae, a result which is consistent with the theoretical prediction that WN stars appear before WC stars.

Surveys and kinematic studies devoted to ring nebulae in other galaxies of the Local Group are also available. The Large Magellanic Cloud (LMC) contains about 115 WR stars (82 excluding the crowded 30 Dor region). The first identifications and kinematic studies of ring nebulae in this irregular galaxy was performed by Chu & Lasker (1980) and Chu (1982, 1983). Dopita et al. (1994) have carried out a complete survey of the environment of all the WR stars of both the LMC and Small Magellanic Cloud (SMC), finding 28 confirmed and possible ring nebulae in LMC and none in SMC. This result gives a 34% detection rate for the LMC, strikingly similar to the value obtained for Galactic objects. There are few kinematic and chemical abundance studies available for WR ring nebulae in the LMC. Chu (1983) finds 2 wind-blown bubbles —W-type nebulae— from Fabry-Perot data. Garnett & Chu (1994) find one E nebula around the WR star Br 13. For M 33, Drissen, Shara, & Moffat (1991) discovered 19 possible ring nebulae around isolated WR stars from a survey based on deep CCD H$\alpha$ imaging of several fields in that galaxy. Esteban, Víchez, & Smith (1994), from spectroscopic observations of some nebulae of that sample, found 2 $R_s$-type nebulae and 3 additional objects showing complex structures consisting of a combination of an inner wind-blown bubble and an external stalled amorphous or shell structured H II region. There are also some other findings of single ring nebulae around isolated WR stars, as for example in NGC 1569, where Drissen & Roy (1994) find a 30 pc ring around a small cluster containing a WNL star and in IC 1613, where D'Odorico & Rosa (1982) discover a WO3 star surrounded by a nebula with He II emission.

### *2.2. Morphology and Dynamics*

The classical theory for the formation of ring nebulae has been described by many authors and is based on the interaction of stellar winds with the ISM to produce an expanding bubble (e.g., Pikel'ner 1968; Dyson & de Vries 1972; Weaver et al. 1977). However, the dynamical, morphological and chemical abundance studies indicate that they are far from good examples of the classical wind-blown bubble phenomenon. First, the dynamics of the bubbles are more consistent with momentum driven flow than an energy driven flow. Secondly, the presence of stellar ejecta objects cannot be explained by the classical model of energy conserving flow because the hot gas of the expanding bubble cannot mix with the cold swept-up shell (see Dyson & Smith 1985).

There are also indications of inhomogenities in the morphology, kinematics and ionization conditions in a significant fraction of ring nebulae. Goudis et al. (1988) found high-speed knots over the filamentary edge of RCW 104 with a different [N II]/H$\alpha$ ratio. These authors suggest the presence of localized flows around globules or nitrogen-rich ejecta material from the star to explain the observations. Another interesting result is that reported by Mitra (1990) and Dufour (1994) who obtain CCD imaging and spectroscopy of NGC 6888. They find a bipolar structure for the nebula in H$\alpha$ and [N II] and a circular shape in [O III]. Also, they found T([O III]) = 55 000$\pm$20 000 K and [O III]/H$\beta \approx 20$ in the [O III] rim of the NE edge of the nebula. They interpret this fact as the first measurement of a pure wind-shock spectrum in a WR ring nebula. Moreover, Jernigan (1988) and Dufour (1994) find a similar result for the wind-blown bubble of NGC 2359. They found T([O III]) = 20 000 to 40 000 K from the inside to the edge of the bubble and an [O III]/H$\beta$ higher and an [S II]/H$\alpha$ lower than in SN adiabatic shock models, probably due to the fact that the wind-shock propagates through a pre-ionized medium (Dufour 1994). RCW 58 is another example of a ring nebula with complex structure. Optical images obtained by Chu (1982) show a clumpy and filamentary morphology in H$\alpha$ inside a diffuse and more extended [O III] emission. Smith et al. (1988) find that the clumps are moving at a lower velocity than the shell defined by [O III].

Several alternative models for the formation of ring nebulae have been proposed to explain these puzzling observational results. Smith et al. (1984) and Hartquist et al. (1986) propose a model of radiative cooling by evaporation of cold clumps of stellar ejecta trapped in a hot bubble to explain the peculiar kinematics of RCW 58. In a later paper, Arthur, Dyson, & Hartquist (1993) have extended this model to include time evolution.

The most promising models combine the hydrodynamics of the interaction of the different stellar wind regimes and ejection processes occurring during the different evolutionary stages of massive stars. These models include prescriptions of theoretical models of stellar evolution as input conditions for hydrodynamic codes. For example, D'Ercole (1992) and Brighenti & D'Ercole (1995a,b) have constructed models of fast WR wind interacting with a previous low-velocity RSG wind. The most sophisticated models to date are those by García-Segura et al. (1996a,b). These authors compute the dynamical interaction of the stellar winds associated with 60 $M_\odot$ and 35 $M_\odot$ stars with their respective circumstellar medium, as they evolve from O stars to the WR phase, passing through an intermediate LBV or RSG stage. These models are successful in explaining, among other properties, the nebular shapes, the filamentary and clumpy structure —produced by the development of hydrodinamical instabilities— and the presence of stellar ejecta material. The results of these models clearly indicate that WR ring nebulae are very sensitive to the wind velocity and mass loss history of their progenitor stars.

The observations of O stars —the main sequence progenitors of WR stars— indicate that they also have strong high-velocity stellar winds. Evolutionary and hydrodynamical models predict the presence of a wind-blown bubble created in the main sequence phase (see for example, García-Segura et al. 1996a,b) with linear radii in the order of 30–50 pc. Although they are not easily detected in the optical, there has been increasing evidence supporting their existence, mainly in other spectral domains. For example, Arnal, & Mirabel (1991), Niemela & Cappa de Nicolau (1991) and Arnal & Cappa (1996) have shown the presence of large H I cavities around WR stars —some of them with ring nebulae— with linear radii of several tens of pc, and larger than the optical ring nebulae. A case study in this sense is NGC 6888, Marston (1995) reports the presence of an IR shell of 19 pc from HIRES data and Cappa et al. (1996) found its H I counterpart. Both teams interpret this structure as a shell blown out during the main sequence phase of the central WR star. The optical counterparts of possible main sequence bubbles have been reported very recently for Galactic objects (Marston 1995, 1997) by means of wide-field deep narrow-band CCD imaging. This authors find complex structures consisting of an inner bubble and an external shell or filament. Similar examples were discovered previously in M33 objects; in fact, Esteban, Vílchez, & Smith (1994) found several examples of double-shell structures of an extended stalled shell and internal expanding bubble around several WR stars in M33. The radius of the external shells are between 20 and 50 pc.

### *2.3. Chemical Composition*

Kwitter (1981, 1984) carried out the first studies devoted to the chemical abundances of Galactic WR ring nebulae. This author found that some objects are He and N rich; she interprets this as an effect of contamination of the swept-up ISM by the WR stellar wind material.

In a series of papers, Esteban et al. (1990, 1991, 1992) and Esteban & Vílchez (1992) carried out an extensive study of 11 Galactic WR ring nebulae establishing their chemical classification. They found 3 stellar ejecta (SE) objects (M1-67, NGC 6888 and S 308) with very similar enrichment patterns: He and N enriched and O deficient —products of the CNO processing— and composed by almost pure stellar material. Moreover, Esteban et al. (1992) also found 2 additional nebulae (G 2.4+1.4 and RCW 104) showing moderate or localized He and/or N enrichment. Esteban et al. (1992) find that the abundance pattern observed in the SE objects is consistent with predicted surface abundances in massive stars of initial masses in the range 25–40 $M_{\odot}$ at or very near the end of the RSG phase. In this context, the discovery of a SE object in LMC by Garnett & Chu (1994) is very interesting. These authors find that the nebulae around the WR star Br 13 is enriched in He and N and deficient in O, and that their abundance pattern is consistent with the expected surface abundance of a 25–40 $M_{\odot}$ progenitor.

### *2.4. Fundamental Parameters of the Central Stars*

Esteban et al. (1993) carried out the photoionization modeling of 8 Galactic ring nebulae making use of photoionization codes and pure He non-LTE model atmospheres for WR stars in order to derive the fundamental parameters of their central stars. These authors introduce all the known information about the chemical abundances, physical conditions, total radio flux and geometry of each nebula. Esteban et al. (1993) obtain some interesting results: i) a qualitatively well defined correlation between the effective temperature, $T_{\rm eff}$, and the spectral subtype (higher $T_{\rm eff}$ corresponds to earlier subtypes); ii) the ionizing continua are essentially correct for the hottest stars (WN 4–5 subtypes); iii) the possible importance of line-blanketing for the cooler stars (WN 6–8 subtypes); iv) the position in the HR diagram of the 8 central stars is consistent with the results obtained from the standard method based on the fitting of the stellar line profiles (e.g., Hamann & Koesterke 1996), which is more dependent on the assumed behavior of the stellar wind and mass-loss parameters. By comparison with stellar evolution tracks, the initial masses of the central WR stars are typically in the range 25–40 $M_{\odot}$, in agreement with the abundance results.

In Table 3, I show previous unpublished results I have obtained from photoionization modeling of WR rings in M33. In general, these are consistent with those obtained for Galactic nebulae and include 3 WC stars, a subtype which is absent in the Galactic sample. The $T_{\rm eff}$s obtained are consistent with a qualitative correlation with the spectral subtype; moreover, the temperatures obtained for the WN stars are similar to those of Galactic stars with the same spectral subtype. The position in the H-R diagram of the WN stars is similar to that obtained for Galactic objects and the positions of WC stars agree with the locus determined from the analysis of stellar spectra (see Hamann & Koesterke 1996)

TABLE 3

STELLAR AND NEBULAR PARAMETERS FOR CENTRAL STARS OF WR RING NEBULA IN M33

| Star | MC 27 | MC 44 | MC 46 | MC 57 | MC 65 |
|---|---|---|---|---|---|
| Spectral type | WN | WC 4-5 | WN E | WC 4 | WC 6 |
| $L$ ($10^3$ $L_\odot$) | 550 | 320 | 580 | 140 | 220 |
| $T_{\rm eff}$ ($10^3$) | 61 | 52 | 75 | 52 | 42 |
| $Q$(H) ($10^{49}$ s$^{-1}$) | 3.6 | 1.9 | 4.2 | 0.8 | 1.1 |
| $U$ ($10^{-4}$) | 2.2 | 2.0 | 3.4 | 3.0 | 1.5 |
| $M_{\rm H}$($M_\odot$) | 625 | 410 | 270 | 670 | 450 |

The photoionization modeling of ring nebulae can shed some light on some nebular parameters. For example, the largest part of the objects appear to be density bounded (low optical depths); i.e., a significant fraction of the ionizing photons escape the main body of the nebula. Another significant result is that all the nebulae show a remarkably very similar adimensional ionization parameter, $U$, of 0.6–2.6 × $10^{-3}$ for Galactic nebulae and 1.1–3.4 × $10^{-4}$ for those in M33. This fact deserves an interpretation.

## 3. LBV NEBULAE

The LBV or Hubble-Sandage variables are very luminous, blue irregular variable stars recognized originally in external galaxies. They are thought to be transition objects between the O and WR phases of the most massive stars ($M \geq$ 50–60 $M_\odot$). Some LBVs are located in the H-R diagram near the Humphreys-Davidson limit suggesting that they do not evolve into RSGs.

### *3.1. Census, Morphology, Dynamics*

Six LBVs are currently known in the Galaxy: $\eta$ Car, AG Car, HR Car, P Cyg, WRA 751 and HD 160529. The same number of LBVs has been discovered in the LMC and about 20 are known in nearby galaxies (cf., Humphreys 1989). The majority of the LBVs are surrounded by relatively low surface brightness nebulae. They have an overall shell and filamentary morphology aligned to a preferred axis of symmetry and frequently bipolar (for a comprehensive review of their characteristics see Nota et al. 1995). P Cyg presents a "peculiar" morphology because it is composed of clumps of material in a spherically symmetrical distribution. LBV nebulae show line splitting in their emission-line spectra indicating that they are hollow and expanding. The typical angular sizes of the Galactic LBV nebulae are $\leq$ 30 arcsec, corresponding to relatively small linear sizes of 0.2–2 pc. The ionized masses are also small 0.1–4 $M_\odot$. The dynamical timescale associated with the observed expansion velocities and linear sizes are very similar 3–5 × $10^3$ yr.

LBV nebulae are believed to be produced by giant eruptions in the central stars associated with huge mass ejections of order 0.01 to 1 $M_\odot$ (see Nota et al. 1995). For example, Walborn & Blanco (1988) from proper motion measurements of one of the "youngest" LBV nebulae, $\eta$ Car, find dynamical timescales of $10^2$–$10^3$ yr suggesting that most or all the material may have been ejected during the visual maximum of the 1830s and 1840s.

### *3.2. Chemical Abundances*

There is not much work on chemical abundances in LBV nebulae available in the literature. Despite the low surface brightness of much of the objects, the most important difficulty for abundance studies is the low ionization degree of these nebulae. This implies that it is necessary to have very deep spectra to obtain a good measurement of the auroral [N II] $\lambda$ 5755 Å line, which is essential for deriving an accurate value of the electron temperature. Studies to date have estimated abundances based on barely detected auroral lines and assumed electron temperatures. For example, Hutsemékers & Van Drom (1991) and Johnson et al. (1992) conclude that WRA 751 and P Cyg are N enriched on the basis of the high [N II]/[S II] ratio of their spectra.

The most studied LBV nebula for chemical abundances to date is AG Car. Mitra & Dufour (1990) found a normal N abundance and a high deficiency in O and S on the basis of a barely detected [N II] $\lambda$ 5755 Å line. Conversely, de Freitas Pacheco et al. (1992) derived a substantially higher electron temperature, finding an overabundance of N and an O deficiency. More recently, Smith et al. (1997) have performed a detailed chemical abundance study of AG Car based on good long-slit spectroscopy obtaining accurate direct determinations of the electron temperature in several positions. They find a strong N overabundance and an O deficiency.

In Table 4, we show a comparison of the most recent abundance determinations for different objects, including the SE WR ring nebulae, the LBV nebulae AG Car and $\eta$ Car and other comparison objects as the remnant of SN 1987A and the average values of a large sample of PNe. For each nebula we give the spectral type of the central star (Sp. Type); the nebular helium mass fraction ($Y$); the N/O ratios; the nitrogen enrichment factor $\Delta$N (defined as: $\Delta N = (X/H)_{nebula} - (X/H)_{H\ II}$, where $(X/H)_{H\ II}$ is the expected abundance of an H II at the galactocentric distance of the nebula); the oxygen depletion factor $1/\Delta O$; and the references for the abundance determinations. For comparison, Table 4 also includes the predicted abundances for an LBV nebula and a WR ring nebula with a progenitor of 60 $M_{\odot}$ and 35 $M_{\odot}$, respectively, from the hydrodynamic computations of García Segura et al. (1996a,b), and finally the predicted surface stellar abundances of a 40 $M_{\odot}$ and 60 $M_{\odot}$ star in different evolutionary phases from Meynet et al. (1994).

TABLE 4

COMPARISON OF ABUNDANCES

| Nebula | Sp. Type | $Y$ | N/O | $\Delta$N | $1/\Delta$O | Refs. |
|---|---|---|---|---|---|---|
| M 1-67 | WN8 | ≈0.47 | 3±2 | 8±3 | 5±3 | 1 |
| NGC 6888 | WN6 | 0.43 | 2±2 | 7±5 | 4±3 | 2 |
| S 308 | WN5 | 0.51 | 2±1 | 5±3 | 5±1 | 3 |
| Average | ... | 0.47 | 2±2 | 7±4 | 5±2 | ... |
| AG Car | LBV | ... | 6±2 | 5±1 | 15±7 | 4 |
| $\eta$ Car | LBV | 0.40 | 54 | 23 | 32 | 5 |
| SN 1987A | ... | 0.44 | 2±1 | 7±1 | 3±1 | 6 |
| <PN> | ... | 0.31 | 0.5±0.3 | 6±4 | 1.0±0.3 | 7 |
| 35 $M_{\odot}$ model | RSG | 0.35-0.4 | 0.5 | 3 | 1.5 | 9 |
| 60 $M_{\odot}$ model | LBV | 0.7-0.8 | 26 | 13 | 18 | 8 |
| 40 $M_{\odot}$ model | RSG | 0.43[a] | 2 | 7 | 2 | 10 |
| 40 $M_{\odot}$ model | WNL | 0.77[a] | 33 | 12 | 20 | 10 |
| 60 $M_{\odot}$ model | BSG | 0.35[a] | 2 | 9 | 2 | 10 |

[a] Surface stellar abundances
1. Esteban et al. (1991); 2. Esteban & Vílchez (1992);
3. Esteban et al. (1992); 4. Smith et al. (1997);
5. Glover et al. (1998); 6. Panagia et al. (1998, in prep.);
7. Kingsburgh & Barlow (1994); 8. García-Segura et al. (1996b);
9. García-Segura et al. (1996a); 10. Meynet et al. (1994)

From Table 4 it is evident that the SE WR ring nebulae have very similar abundance patterns, which is consistent with the surface stellar abundances of a 25–40 $M_{\odot}$ star at the end of the RSG phase, as stated in § 3.3. Another remarkable result is the similarity of the nitrogen enrichment factor between the SE WR ring nebulae and AG Car. Taking this fact, and the disagreement between the AG Car abundance pattern and that predicted by García-Segura et al. (1996a) for an LBV nebula (CNO-equilibrium abundances) into account, Smith et al. (1997) propose that the AG Car nebula may have originated in a massive ejection at an RSG phase of the progenitor (composed of mildly CNO-prosessed material), with important consequences in the evolutionary scheme in the upper part of the H-R diagram. On the other hand, the inner ring of SN 1987A is also believed to be composed of RSG material. In fact, the abundances obtained by Panagia et al. (in preparation) are very similar to those obtained for the precedent objects and mainly for the SE WR ring nebulae, reinforcing the whole scheme. In contrast, the abundances obtained by Glover et al. (1998) for the zones S2 and S3 of $\eta$ Car from *HST* spectra are very different from those obtained for AG Car. This abundance pattern is remarkably similar to that predicted by García-Segura et al. (1996a) for CNO-equilibrium abundances for nebulae produced by mass loss or outburst during the LBV phase itself and not in a previous RSG stage. These discrepant results for two apparently similar objects could imply somewhat a different evolution for the progenitors of both LBV nebulae.

## 4. FUTURE WORK

There is still much work to be done on these interesting objects from both, ground-based and space telescopes. First, we need more dynamical and chemical abundance studies to classify the rest of WR ring nebulae for which we have no spectroscopic data available (about 65% of them). In the light of the puzzling results about the chemical abundance in LBV nebulae discussed above, it is obvious the necessity of obtaining accurate abundances for more LBV nebulae to establish whether mildly CNO-processed material (as in AG Car) is characteristic of more nebulae or not. Regarding the kinematics, I consider it very important to obtain high spatial resolution CCD Fabry-Perot observations in several emission lines of this objects in order to: i) map the global velocity field; ii) study the position, dynamics and ionization conditions of the possible inhomogeneities or localized shocks; iii) analyze the spatial scale of the inhomogeneities and clumps.

*HST* observations (imaging and low spectral resolution spectroscopy ) of WR ring nebulae would be essential to isolate the shock and ionization fronts, mainly because it is expected that the physical conditions in these zones change dramatically at the 0.003 pc scale (see García-Segura et al. 1996a,b). Also, the derivation of the carbon abundance from UV collisionally excited lines in WR and LBV ring nebulae is a very interesting task in understanding how the CNO processing operates in these stars and in quantifying the carbon yield associated with these objects.

I am deeply grateful to R. J. Dufour and M. Peimbert for their support and the opportunity to attend this meeting. I would like to thank L. J. Smith and J. M. Vílchez for their continous common effort on this subject during years of sharing ideas, problems and solutions. This work was in part made possible by IAC Project 14/86.

## REFERENCES

Arnal, E. M., & Cappa, C. E. 1996, MNRAS, 279, 788
Arnal, E. M., & Mirabel, I. F. 1991, A&A, 250, 171
Arthur, S. J., Dyson, J. E., & Hartquist, T. W. 1993, MNRAS, 261, 425
Brighenti, F., & D'Ercole, A. 1995a, MNRAS, 273, 443
____________. 1995b, MNRAS, 277, 53
Cappa, C. E., Dubner, G. M., Rogers, C., & St-Louis, N. 1996, AJ, 112, 1104
Chu, Y.-H. 1981, ApJ, 249, 195
____________. 1982, ApJ, 255, 79
____________. 1983, ApJ, 269,202
____________. 1991, in Wolf-Rayet Stars and Interrelations with other Massive Stars in Galaxies, ed. K. A. van der Hucht & B. Hidayat (Dordrecht: Kluwer), 349
Chu, Y.-H., & Lasker, B. M. 1980, PASP, 92, 730
Chu, Y.-H., Treffers, R. R., & Kwitter, K. B. 1983, ApJS, 53, 937
D'Ercole, A. 1992, MNRAS, 255, 572
Dopita, M. A., & Lozinskaya, T. 1990, ApJ, 359, 419
Dopita, M. A., Bell, J. F., Chu, Y.-H., & Lozinskaya, T. 1994, ApJS, 93, 455
D'Odorico, S., & Rosa, M. 1982, A&A, 105, 410
Drissen, L., & Roy, J.-R. 1994, PASP, 106, 974
Drissen, L., Shara, M. M., & Moffat, A. F. J. 1991, AJ, 101, 1659
Dufour, R. J. 1994, in Circumstellar Media in the Late Stages of Stellar Evolution, ed. R. E. S. Clegg, I. R. Stevens, & W. P. S. Meikle (Cambridge: Cambridge University Press), 78
Dyson, J. E., & de Vries, J. 1972, A&A, 20, 223
Dyson, J. E., & Smith, L. J. 1985, in Cosmical Gas Dynamics, ed. F. D. Khan (Utrecht: VNU Science Press), 173
Esteban, C., & Rosado, M. 1995, A&A, 304, 491
Esteban, C., & Vílchez, J. M. 1992, ApJ, 390, 536
Esteban, C., Vílchez, J. M., & Smith, L. J. 1994, AJ, 107, 1041
Esteban, C., Smith, L. J., Vílchez, J. M., & Clegg, R. E. S. 1993, A&A, 272, 299

Esteban, C., Vílchez, J. M., Manchado, A., & Edmunds, M. G. 1990, A&A, 227, 515
Esteban, C., Vílchez, J. M., & Smith, L. J., & Clegg, R. E. S. 1992, A&A, 259, 629
Esteban, C., Vílchez, J. M., Smith, L. J., & Manchado, A. 1991, A&A, 244, 205
de Freitas Pacheco, J. A., Damineli Neto, A., Costa, R. D. D., & Viotti, R. 1992, A&A, 266, 360
García-Segura, G., Langer, N., & Mac Low, M.-M. 1996b, A& A, 316, 133
García-Segura, G., Mac Low, M.-M., & Langer, N., 1996a, A& A, 305, 229
Garnett, D. R., & Chu, Y.-H. 1994, PASP, 106, 626
Glover, T. W., Dufour, R. J., Hester, J. J., Currie, D. G., van Orsow, D., & Walter, D. K. 1998, these proceedings
Goudis, C. D., Meaburn, J., & Whitehead, M. J. 1988, A&A, 191, 341
Goudis, C. D., Christopoulou, P.-E., Meaburn, J., & Dyson, J. E. 1994, A&A, 285, 631
Hamann, W.-R., & Koesterke, L. 1996, in Wolf-Rayet Stars in the Framework of Stellar Evolution, ed. J.M. Vreux, A. Detal, D. Fraipont-Caro, E. Gosset, & G. Rauw (Liège: Université de Liège), 491
Hartquist, T. W., Dyson, J. E., Pettini, M., & Smith, L. J. 1986, MNRAS, 221, 715
Heckathorn, J. N., Bruhweiler, F. C., & Gull, T. R. 1986, ApJ, 252, 230
Humphreys, R. M. 1989, in Physics of Luminous Blue Variables, ed. K. Davidson, A.F.J. Moffat, & H.J.G.L.M. Lamers (Dordrecht: Kluwer), 3
Hutsemékers, D., & Van Drom, E. 1991, A&A, 251, 620
Jernigan, T. E. 1988, Ph.D. dissertation, Rice University
Johnson, D. R. H., Barlow, M. J., Drew, J. E., & Brinks, E. 1992, MNRAS, 255, 261
Johnson, H. M., & Hogg, D. E. 1965, ApJ, 142, 1033
Kingsburgh, R. L., & Barlow, M. J. 1994, MNRAS, 271, 257
Kwitter, K. B. 1981, ApJ, 245, 154
__________. 1984, ApJ, 287, 840
Maeder, A., & Meynet, A. 1994, A&A, 287, 803
Marston, A. P. 1995, AJ, 109, 2257
__________. 1997, ApJ, 475, 188
Marston, A. P., & Meaburn, J. 1988, MNRAS, 235, 391
Marston, A. P., Chu, Y.-H., & García-Segura, G. 1994a, ApJS, 93, 229
Marston, A. P., Yocum, D. R., García-Segura, G., & Chu, Y.-H. 1994b, ApJS, 95, 151
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Miller, G. J., & Chu, Y.-H. 1993, ApJS, 85, 137
Mitra, P. 1990, Ph.D. dissertation, Rice University
Mitra, P., & Dufour, R. J. 1990, MNRAS, 242, 98
Niemela, V. S., & Cappa de Nicolau, C. E. 1991, AJ, 101, 572
Nota, A., Livio, M., Clampin, M., & Schulte-Ladbeck, R. 1995, ApJ, 448, 788
Pikel'ner, S. B. 1968, Astrophys. Lett., 2, L97
Smith, L. F. 1967, Ph.D. dissertation, Australian National University
Smith, L. J. 1994, in Circumstellar Media in the Late Stages of Stellar Evolution, ed. R. E. S. Clegg, I. R. Stevens, & W. P. S. Meikle (Cambridge: Cambridge University Press), 64
__________. 1997, in Wolf-rayet Stars in the Framework of Stellar Evolution, ed. J. M. Vreux, A. Detal, D. Fraipont-Caro, E. Gosset, & G. Rauw (Liège: Université de Liège), 381
Smith, L. J., Pettini, M., Dyson, J. E., & Hartquist, T. W. 1984, MNRAS, 211, 679
__________. 1988, MNRAS, 234, 625
Smith, L. J., Stroud, M. P., Esteban, C., & Vílchez, J. M. 1997, MNRAS, in press
van der Hucht, K. A., Conti, P. S., Lundström, I., & Stenholm, B. 1981, Space Sci. Rev., 28, 227
Walborn, N. R., & Blanco, B. M. 1988, PASP, 100, 797
Weaver, R., McCray, R., Castor, J. I., Shapiro, P. R., & Moore, R. 1977, ApJ, 218, 377