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SHELL NEBULAE AROUND LUMINOUS EVOLVED STARS

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RESUMEN. Las cáscaras nebulares alrededor de estrellas de tipos Wolf-Rayet luminosas de población I, Of y P-Cisne, son de interés en la astrofísica ya que son indicadores de la pérdida de masa en fases previas a supernovas y de la manera en que esas estrellas masivas preparan el medio interestelar que las rodea antes de la explosión. Se conocen una veintena de esas nebulosas, para las cuales, apenas en esta década,se han empezado los estudios detallados de sus características espectroscópicas. En este artículo se revisan algunas de estas características en lo general y se presentan nuevas observaciones realizadas por el autor y sus colegas. Se hace énfasis en varios objetos "prototipo "(NGC 7635, NGC 2359, NGC 6888 y las condensaciones de Eta Carinae) para ilustrar la variada pérdida de masa producida por estrellas masivas, la física de sus vientos y de sus cascarones eyectados, así como la composición de los vientos y los efectos de nucleosíntesis que los afectan.

ABSTRACT. Shell nebulae around luminous Population I Wolf-Rayet, Of, and P-Cygni stars are astrophysically interesting since they are indicators of pre-supernova mass loss and how such massive stars prepare their surrounding interstellar medium prior to explosion. Some twenty-odd such nebulae are known, for which detailed study of their morphological and spectroscopic characteristics have only begun in this decade. In this paper, some of these characteristics are reviewed in general, and new observations by the author and colleagues are reported. Emphasis has been placed on several "prototype "objects (NGC 7635, NGC 2359, NGC 6888, and the Eta Carinae condensations) to illustrate the varied massive-star mass-loss, the physics of their winds and shell ejecta, and related nucleosynthesis effects in the compositions of the winds and shells.

Key words: **INTERSTELLAR-SHELLS — INTERSTELLAR-SUPERNOVA REMNANTS — STARS-WOLF-RAYET — STARS-Of TYPE**

I. INTRODUCTION

Stars with masses in excess of 0.8 $M_\odot$ have significant mass loss during their post main sequence evolution before reaching a final stellar remnant state. Intermediate mass stars eject planetary nebulae during the latter phases of their evolution to a white dwarf remnant state. More massive stars eject substantial fractions of their mass during core collapse to a neutron star or black hole state during their SNe II stage. Studies of the remnants ejected by stars over the range of masses are relevant towards understanding mass loss mechanisms in stars of advanced evolutionary states, the physical processes of wind–shock interactions, and their effects on the ISM from both energetics and chemical evolution aspects.

Historically, the stellar ejected nebulae receiving the most attention have been planetary nebulae and supernova remnants. However, during the past decade there have been numerous studies of nebulae around Wolf–Rayet and evolved O–stars which suggest that some consist of ejected shells or at least wind–enriched material expanding outwards from the stars *before they explode as SN II.* The morphology and spectra of several of these nebulae around evolved Population I stars are currently being studied by the author and colleagues, and some of the results are the subject of this review.

II. SIMILARITIES BETWEEN W-R AND O-STAR SHELLS

a) *Overview and Classification*

Chu (1981) summarized the characteristics of fifteen W-R shell nebulae and classified them into three groups: R — radiatively excited H II regions; E — stellar ejecta; and W — wind-blown bubbles. In addition, she distinguishes between two subtypes of class R: R_a — those with amorphous structure and R_s — those having shell structure. Among the fifteen W-R nebulae she lists, two are classified as R_a, four as R_s, two as E, and seven as W. Therefore, only two of the W-R associated nebulae can be characterized as simply ionized volumes around the stars, all of the others have been influenced by winds or ejecta from the evolved stars.

Analogous to the W-R nebulae are four "shell"nebulae surrounding evolved O-stars that have not (yet?) developed W-R characteristics. These nebulae are listed in Table 1 along with characteristics that enable us to classify them according to Chu's system for the W-R nebulae. With the exception of the spectroscopic classification of the central star being Of or P–Cygni, we find the characteristics of these objects overlap completely with those of the W-R nebulae. The characteristics include morphology, kinematics, and composition; all of which will be noted in some detail in the discussion which follows.

TABLE 1
Of – P-Cygni Shell Nebulae

Nebula	Type	Star	Spectrum	Nebula Morphology
NGC 6164-5	R_s-W-E	HD148937	O6.5fp	ejecta/bubble/H II
NGC 7635	R_a-W	BD+60°2522	O6.5III	H II Region/bubble
AG Carinae	E	AG Car	P-Cygni	ejected ring
η Carinae	E	η Car	OB–P-Cyg(var)	ejecta

b) *Ionization Structure of Three Shells from CCD Imagery*

During the past two years the author and collaborators J.J. Hester at Caltech and R.A.R. Parker at NASA–JSC have been conducting an imaging survey of all prominent galactic emission nebulae north of −30° declination using a TI CCD and focal–reducing lens system on the Palomar 60–inch telescope. The system operates at an effective focal ratio of f/1.66 and covers a 16 arc-min square field with 1.2 arc-sec pixels. Images are made through various interference filters isolating strong emission lines of H I, [O III], [N II], [S II], [S III], and adjacent line–free continuum regions. The emission–line images are processed by standard procedures to produce continuum–free calibrated emission–line maps of the nebulae, including corrections for line–of–sight reddening (from the observed Hα/Hβ ratio). The imagery results for NGC 6888 constitute part of the Ph. D. dissertation research of P. Mitra, and that for NGC 2359 and NGC 7635 are part of the dissertation research of T. Jernigan at Rice University. Some of their (unpublished) results are incorporated in the discussion of these objects which follows.

i) NGC 7635: A Young Developing Wind–Driven Bubble in an H II Region

NGC 7635 is appropriately called the "Bubble Nebula"; Figure 1 shows a drawing and grey–scaled [O III]λ5007/Hβ ratio map side–by–side, taken from Jernigan (1989). Emission–line photographs and discussion of its structure and kinematics has been presented by Lynds and O'Neil (1983), which also included the superb Hale 5m prime focus photograph showing remarkable detail of the bubble filaments. For a distance of 3.4 kpc, the bubble has a radius of 1.25pc and is expanding outward by 25 km s^{-1} from the central Of6.5III star BD + 60°2522. The system is part of a larger elongated H II region (13.5 × 8.5pc) located in the Perseus Arm of the Galaxy. The [O III]/Hβ image shows that the ionization level within the bubble is higher than that of the surrounding H II region, except for "shadowed"cones east and west of the Of star (cf. Figure 1). While the shadowed cone to the west of the star is clearly associated with optically thick clumps of material just to the west of the star, the material blocking the starlight to the east of the star is not seen on surface brightness imagery. The existence of the shadowed regions suggest that the ambient density of ionized material in and around the bubble is very low, such that the diffused nebular radiation density is negligible compared to the direct starlight. Additional shadows are produced by the knots to the northeast of the star which are apparently embedded in the H II region (interpreted to be the ionized face of a molecular cloud).

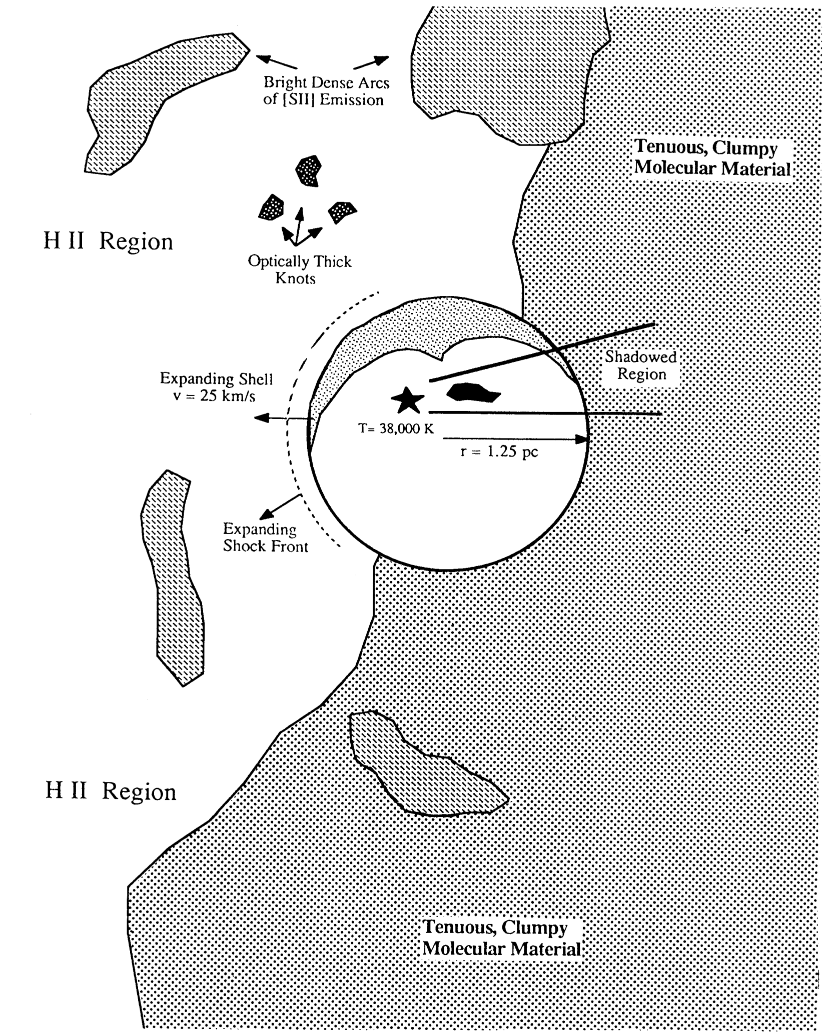


Fig. 1. Illustration of the "Bubble Nebula" NGC 7635 (left, taken from Jernigan 1989) and a grey-scaled log [O III]/Hβ ratio map (right), where strong [O III]/Hβ is characterized by darker grey levels. Note that the bubble interior is of higher excitation than surrounding exterior regions and the "shadow" produced by the nebulous knots to the northwest of the star (light grey), as well as a fainter large diffuse shadowed region to the southeast of the star. The field size on the ratio map is 16 arcmin diameter.

The age of the bubble is only about 1×10^6 yrs for the observed velocity of expansion of 25 km s^{-1} (Jernigan 1989), which is only slightly supersonic (necessitating a W classification rather than R_s). She further estimated the mass of the bubble material to be 5.8 $M_\odot$.

Spectrophotometry of the northern rim of the bubble and various knots have been presented by Talent and Dufour (1979), who note that the [O III]λ5007/Hβ ratio in the bubble is about 2 compared to ~ 0.5 for the ambient H II region. When the surrounding H II region light is subtracted however, the [O III]/Hβ ratio in the bubble is as high as ~ 7 (Jernigan 1989), suggesting that it has (incomplete) shock characteristics much like the NGC 2359 bubble, which is discussed next.

ii) NGC 2359: A W-R Wind–Driven Back–Ionized Bubble in an H II Cavity

NGC 2359 consists of a two–component system around the WN4 star HD 56925; a 3pc diameter wind–driven bubble expanding at 30 km s $^{-1}$ in a radiation bounded H II conical cavity seen "edge on"(as opposed to NGC 7635, which is believed to be more "face on"in the line of sight). Excellent photographs of this object have been presented by Schneps *et al.* (1981). In Figure 2 we present a diagram of the system and [O III]λ5007/Hβ ratio map from Jernigan (1989). The system is essentially interpreted to have been a "blister"H II region previously formed by the O star before it evolved into the WN phase and developed the strong wind, which is now seen propagating through the cavity in the form of a thin–edged spherical sheet. The age of the bubble is estimated by Jernigan to be only 3×10^6 years, a factor of about three larger than the Of star bubble NGC 7635, which suggests that the evolution from the Of to WN phase of massive stars may occur on only a few million year timescale.

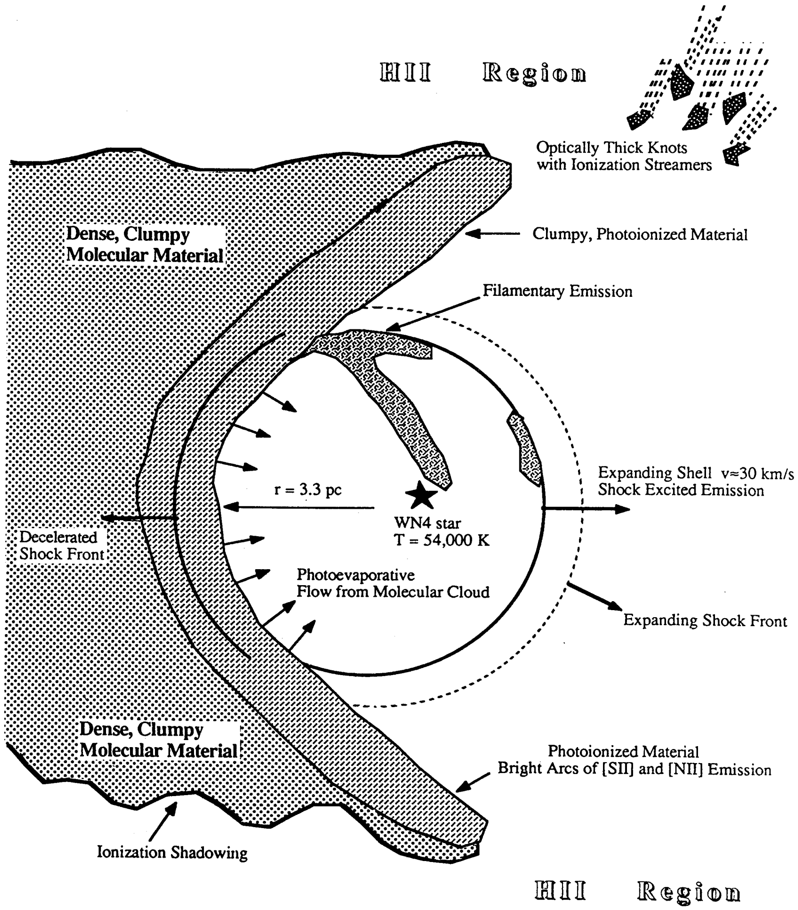
It should be pointed out that the bubble is only seen in the lines of [O III] and H I, but not in [S II] or [N II] — similar to the NGC 7635 bubble (but more extreme in degree). This is a first glance surprising due to the low expansion velocity measured, for which adiabatic shock models suggest that such slow shocks would show extremely strong [S II] and [N II]. The explanation for this is that the wind–shock is propagating through an already preionized medium and back illuminated by *UV* ionizing photons from the W-R star, which prevents a full recombination region to form behind the shock where S^+ and N^+ would normally exist, as well as enhancing the [O III] emission due to the high temperature in the shock. Spatially resolved spectra of the western edge of the bubble obtained by the author at Mauna Kea using the CFHT indicates that I(5007)/I(Hβ) ≥ 13, and that the electron temperature in the bubble is in excess of 25 000 °K.

iii) NGC 6888: A Wind–Wrapped Stellar Ejected Nebula?

NGC 6888 is considered to be a "prototype"example of a wind–driven shell surrounding a Wolf–Rayet star (HD 192163, WN6). At a distance of 1.45 kpc it appears as an elliptical nebula of dimensions 7.6 × 5.0 pc. CCD images of the nebula in the light of Hα+ [N II] and a corresponding ratio map of [O III]/ Hα + [N II] is shown together in Figure 3 (Mitra 1989).

By virtue of its brightness, size, and morphology, NGC 6888 has been the subject of many studies. Excellent image–tube photographs in numerous emission lines have been presented by Parker (1978). Correlation between its optical and radio morphology has been discussed by Wendker *et al.* (1975). Optical spectra of various positions by Kwitter (1981) suggest that the numerous knots comprising the nebula are nitrogen– and helium–rich. Most recently, Marston and Meaburn (1988) studied the detailed kinematics of the nebula, and found that it closely approximates a shell of radius 3 pc expanding at 85 km s^{-1} for which the mass of ionized material was estimated to be 3.5 ± 1.2 $M_\odot$. They also note that the nebula appears as an extended infrared source from *IRAS* imagery, whereby they conclude that the nebula also includes 40 $M_\odot$ of neutral material participating in the expansion. By contrast, Van Buren and McCray (1988) attribute the infrared emission to be predominantly from emission lines of [O III] (and possibly [N II] as well).

The morphology of NGC 6888 is rather remarkable in [O III] compared to the other emission lines (notably H I and [N II], cf. Figure 3) in that it appears much more circular in [O III] with large arcs extending 4 pc to the northwest of the WN star and semicircular filaments of similar extension to the southeast. To the northeast and southwest (along the major axis of the nebula in Hα, the boundary of the [O III] emission is nearly coincident (but just exterior) to the H I and [N II] emitting material. We interpret the arcs and filaments of [O III] to be the wind–ISM boundary of the nebula. The expansion velocity of this wind is unknown, since kinematical studies of the nebular expansion have been limited to the H I, [N II] and [S II] lines representing morphologically different features of the nebula. The [O III]/Hβ I(5007)/(4861) ratios in the outer filaments are in excess of 20 in some regions, a ratio impossible to produce by photoionization or shocks with complete recombination regions. However, as in the previous case of the NGC 2359 bubble, we believe that the exceptionally high ratio is a result of a modest velocity (~ 100 km s^{-1}) shock at the wind–ISM boundary which has a very incomplete recombination region due to the *UV* ionizing field of the WN star. These shocks are similar in degree of ionization to the incomplete outer strong [O III] shocks seen



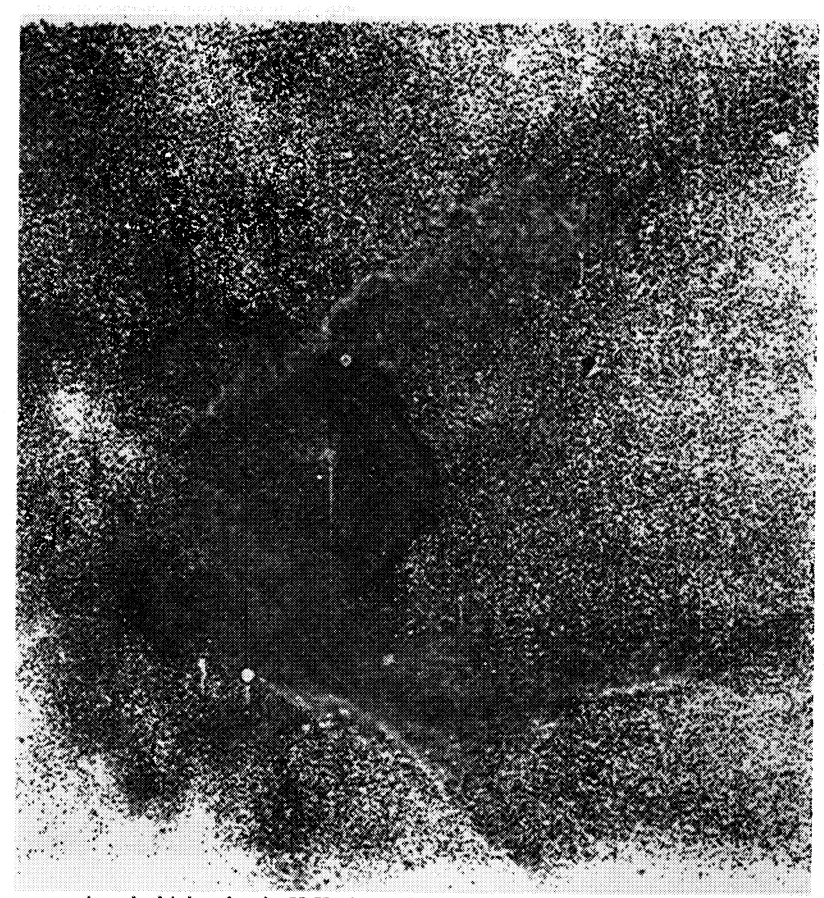
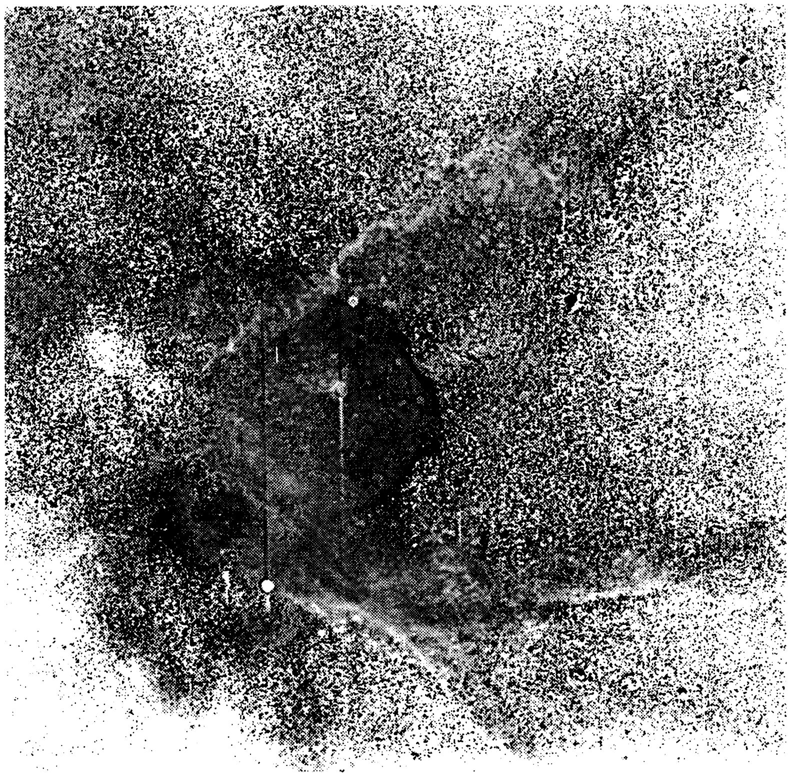


Fig. 2. Illustration of the NGC 2359 bubble and conical H II cavity (left, taken from Jernigan 1989) and [O III]/Hβ ratio map (right), where strong [O III]/Hβ is characterized by darker grey levels. Note that the strongest [O III] is seen on the western edge, due to the bubble propagating through a very low density preionized cavity; while the bubble merges into the higher density H II edge to the east. The outer white edges of the cavity to the north and south indicate the edge of the stellar ionization front into a large molecular cloud.



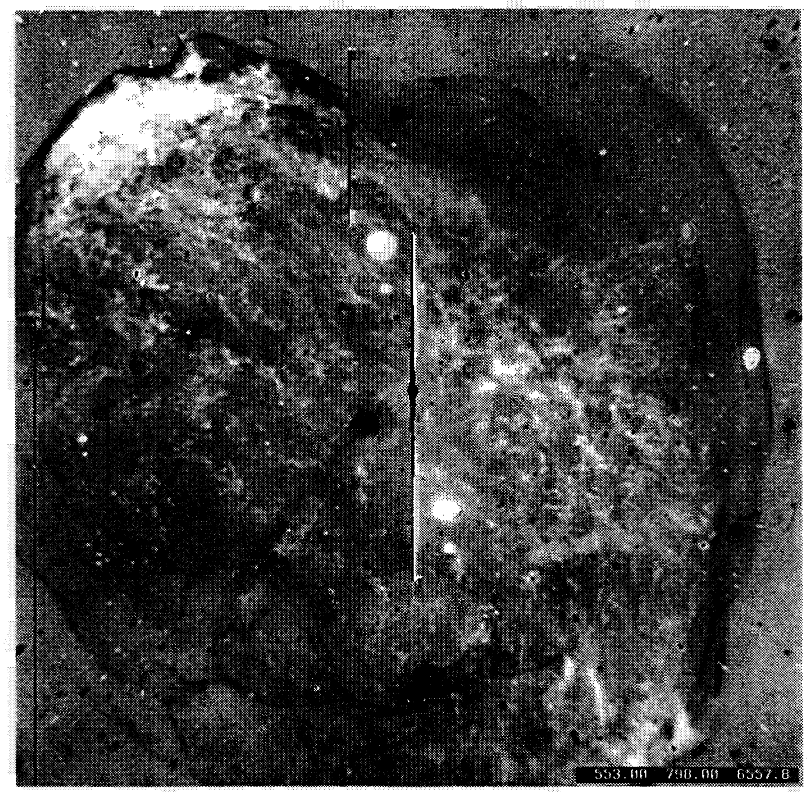


Fig. 3. Grey-scaled CCD images of the Wolf-Rayet shell nebula NGC 6888 in Hα+[N II] surface brightness (left) showing its knotty structure, and grey-scaled [O III]/Hα+[N II] (right) showing the wind-driven nearly circular bubble (dark arcs) around the star and extending just beyond the knots to the northeast (and southwest), but well beyond them to the northwest and southeast. This suggests that NGC 6888 is composed of two componets– stellar ejecta possibly in a thick ring around the WN star seen nearly edge-on, and a nearly spherical wind-driven bubble.

in the Cygnus Loop SNR (Hester, Parker and Dufour 1983); but the incompleteness there is due to the relative recent impact of the shocks onto ISM clouds.

An example of a "pure"optical spectrum of one of the strong [O III] wind–shocks is shown in Figure 4 (Mitra 1989), which is of the concave bright [O III] arc just outside the bright H I and [N II] knots of the northeast edge of the nebula (marked by the number "1"in Figure 3). The spectrum is dominated by the [O III] with the ratio of I(5007)/I(4681) ≈ 19 and the temperature sensitive ratio of [O III] I(5007)/I(4363) ≈ 14 — corresponding to an electron temperature of ≈ 40 000° K. Such characteristics are possible from models of ~ 100 km s^{-1} incomplete shocks, for which spectra have been recently modeled and discussed by Raymond *et al.* (1988) for the Cygnus Loop SNR.

The exterior wind–shock boundaries of NGC 6888 seen in [O III] are rather smooth in form and do not correlate with the clumpy or knotty nature of the H I and [N II] emitting material; nor are the knots surrounded by stronger [O III] emission. This morphology, coupled with the roughly radially decreasing ionization level of the knots with distance from the star (Sabbadin, D'Odorico and Minello 1977; Parker 1978) suggest to the author that the knots (which are He– and N–rich) represent *ejected* material from the central W-R star, rather than windswept ISM material. Finally, we note that NGC 6888 consists of a two–component medium: photoionized stellar ejecta expanding at 85 km s^{-1} permeated by a rarefied and hot wind–swept medium. Therefore, care must be taken in interpreting the spectra of any region or feature in NGC 6888 (or that in any wind–driven shell nebula), since the spectrum consists of contributions from both gas phases.

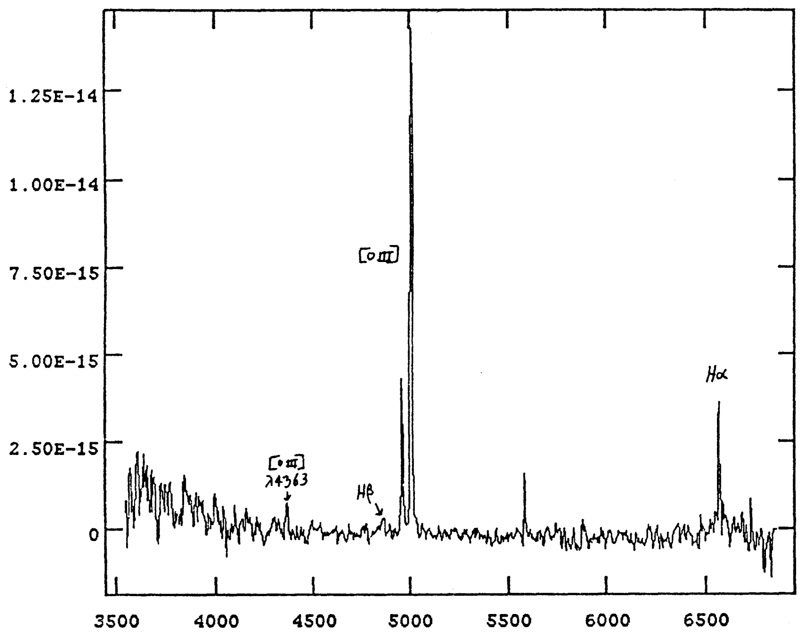


Fig. 4. Spectrum of the strong [O III] rim located on the northeast edge of NGC 6888 (labeled as "1"in Figure 3). The spectrum is similar to those of "non-steady flow"shocks as observed in the outer parts of the Cygnus Loop SNR, which have incomplete recombination regions behind the shock. However, here the incompleteness is believed due to back ionization by the WN star, rather than recentness of the shock impacting onto neutral ISM clouds.

c) *A Few Notes Regarding Two Other O-Star Shell Nebulae*

Two other Of–P Cygni central star shell nebulae listed in Table 1, for which space limitations prevent detailed discussion here, are NGC 6164–5, and the AG Carinae ring. A spectroscopic study of the AG Car ring nebula has been completed by Mitra and Dufour (1989). The very low excitation spectrum is characterized by strong [N II], but very weak or undetected [O II] and [O III] lines, for which abundance analysis showed it to contain stellar processed O–poor (relative to H) material similar to the situation found in the Eta Carinae condensations (discussed below).

The "pseudo–planetary nebula"object NGC 6164–5 around the O6.5?p star HD 148937 deserves special note, since it consists of three quite different components, as first noted by Bruhweiler *et al.* (1981), and more recently discussed in more physical detail by Leitherer and Chavarría–K. (1987): a 50 pc diameter ionized sphere, a 10 pc diameter wind–driven incomplete bubble, and the stellar ejected bipolar nebula NGC 6164–5 which has a major axis of about 2 pc. Spectrum analysis of the bipolar nebula suggest that it contains N–rich processed material which also may be O–poor (Dufour, Parker and Henize 1987; cf. § III). Of special compositional note is that Leitherer and Chavarría-K. observe extraordinarily high He I λ6678 line strengths in two regions in the eastern edge of the wind–driven ring, suggesting that it may be He–enriched by the wind and/or enhanced by shock effects. The spectra of this feature deserve further study (cf. also Fairall, Parker and Henize 1985) to derive detailed physical conditions, abundances, and models. These results indicate that HD 148937 is an evolved star which successively formed a large H II region, developed a wind and blew out a bubble, then underwent significant mass loss (≈ 2 $M_{\odot}$) over short timescales (cf. the excellent discussion and model in Leitherer and Chavarría–K. for details), but has not yet evolved into a Wolf–Rayet star. The interesting question arises as to whether it will explode as a SNII, as the case for the B–star progenitor of SN1987a in the LMC, before ever developing W-R or red supergiant characteristics.

d) *Eta Carinae Ejecta*

The morphology of the inner shell (homunculus) and ejecta (condensations) surrounding η Carinae has been described and illustrated in detail by Walborn (1976), which also gave references to the numerous previous studies. A diagram of the system using Walborn's nomenclature is shown in Figure 5. Proper motions of the system have been discussed by Walborn, Blanco and Thackeray (1978), who note that tangential velocities in excess of 1 000 km s^{-1} are indicated for condensations to the north of the homunculus. This suggests that they were ejected during the mid-nineteenth century outburst of the star; when its apparent visual magnitude dropped from −1 to +8, possibly due to the formation of dust in the homunculus (or a closer shell) around the star. The outer condensations move more slowly and have *UV*–optical spectra which indicate that they consist of processed material where almost all of the carbon and oxygen has been converted into nitrogen (Davidson *et al.* 1986).

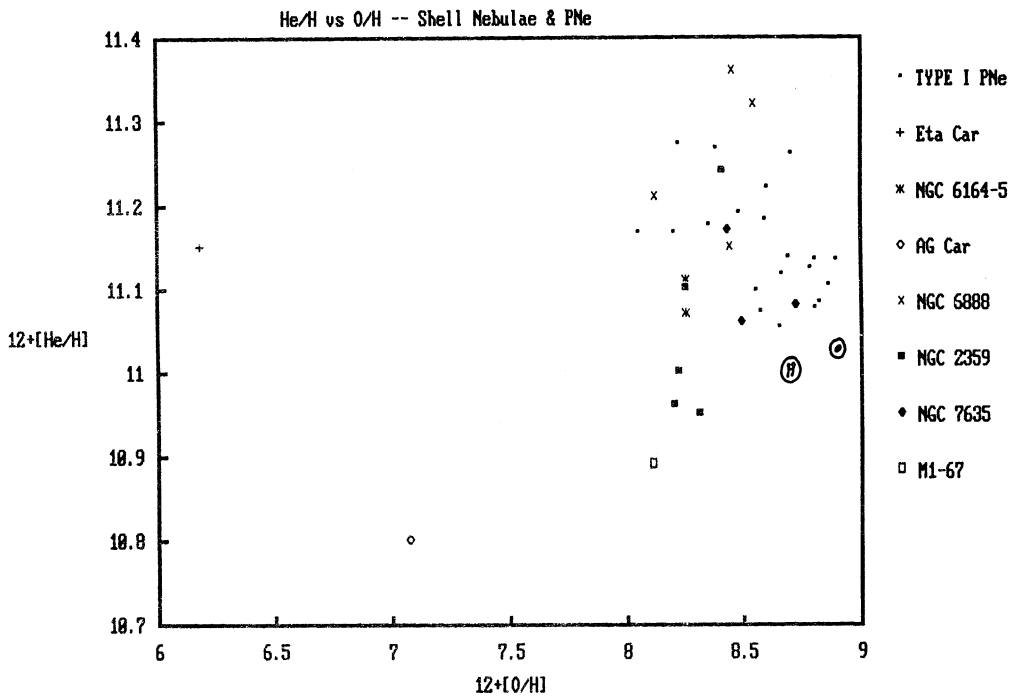


Fig. 5. Distribution of helium abundances versus oxygen for various shell nebulae discusssed herein and Type I PNe. The point ⊙ refers to the sun and the circled H to nearby H II regions. Not all of the shell nebulae around luminous Pop I stars have enriched He/H, but most seem to have depleted O/H, certainly for the cases of the η Car condensations and AG Car ring nebula.

During 1984, echèlle spectra of the condensation and homunculus system were taken by the author using the 4–m telescope at CTIO. Many of the condensations show a complex multi–component radial velocity structure which has no parallel among other shell nebulae known to the author. One of the spectra, with the slit placed along the "S"condensation "S ridge" "ES"condensation (PA = 120°) is shown in Figure 6. Remarkable kinematic features are seen in the Hα + [N II] triplet: the broad emission from the S condensation is redshifted (relative to η Car) by

+190 km s^{-1}, while that of the ES condensation is blueshifted by −575 km s^{-1}, and the radial velocity of the S ridge changes uniformly from that of S to that of ES along the ridge. Of special note are the existence of several high velocity knots emanating from the ridge and condensations with highest redshift knot having $V_r \sim +2150$ km s^{-1}, spatially

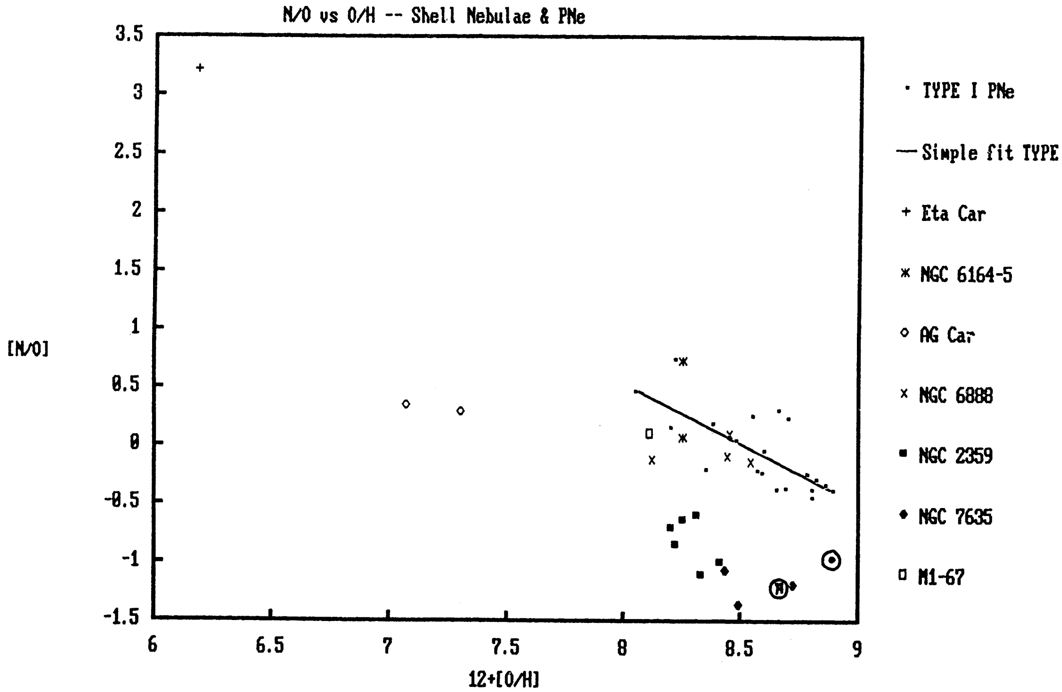


Fig. 6. Distribution of N/O with O/H for the shell nebulae and Type I PNe. The line drawn is a linear least squares fit through the Type I data. It should be noted that the high N/O in the η Car condensations and AG Car ring is in part due to O-depletion. The high N/O in the ejecta shells NGC 6164-5, NGC 6888, and M1-67 follow the trend for Type I PNe shells, while young wind-driven bubbles like NGC 2359 and NGC 7635 have essentially solar N/O, suggesting that the stellar wind has not significantly enriched the ambient H II region yet.

coincident with S and joined to it in velocity space by a "contrail", and including several *blueshifted* knots. The spectra of other condensations show similar blue– and/or red–shifted knots which are spatially related to the more prominent condensations themselves. The formation and acceleration mechanism for these knots are uncertain, possibly they are radiation pressure accelerated material from the homunculus which is penetrating through the condensations.

In Figure 5, we present the mean space, radial, and tangential velocities for the various features labeled on Walborn's diagram (excluding the high velocity knots). In general, the extended features seem to lie in a relatively flat disk with the northwest regions the most redshifted and the southwest regions the most blueshifted. The faster moving features suggest ejection during or just after the mid–nineteenth century light drop of the star. The slower features (most notably the E condensations) may have been ejected centuries earlier, but then they are part of the general trend in changing radial velocities of other faster condensations, suggesting the possibility that all of the condensations were ejected in the mid–nineteenth century, but some may have been since decelerated. Compositional peculiarities of the condensations are noted in the next section.

III. ABUNDANCES IN SHELL NEBULAE AROUND LUMINOUS STARS

Since the W-R and O-star shell nebulae represent ejected or at least wind–impacted material from evolved luminous stars, it is of interest to study the composition of the shells to assess if and how they are influenced by products of stellar nucleosynthesis. Further motivation comes from the well established results (e.g., Peimbert and Torres–Peimbert 1983) that Type I planetary nebulae, which are believed to originate from the more massive stars which form planetaries (~ 3–5 $M_\odot$ progenitors), are He– and N–rich.

Dufour (1989) has collected existing and obtained new spectrophotometry of all known shell nebulae around Pop I stars (including Type I PNe) and rederived physical conditions and abundances using modern atomic data.

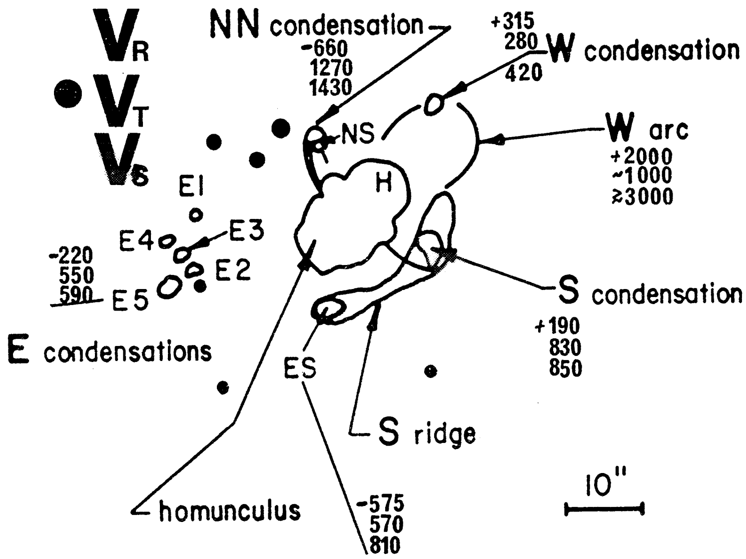


Fig. 7. Illustration of the nomenclature (Walborn *et al.* 1978) and distribution of the condensations and homunculus around η Car. Listed for several condensations (top to bottom) are the radial, tangential, and space velocities. Note the trend in positive radial velocities to the north and west regions, becoming negative for condensations to the south and east.

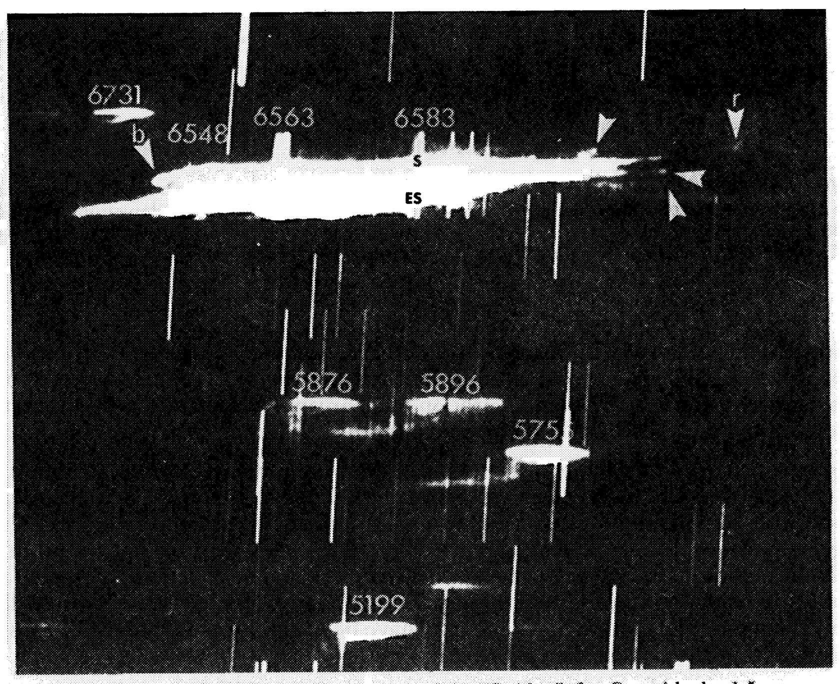


Fig. 8. Photograph of an echèlle spectrogram (CTIO 4-m telescope) of the "S-ridge"of η Car with the 1.5 arc sec wide slit placed along the S–ES line (PA = 120°), where the S condensation is near the center of the slit and the ES condensation is near the bottom. The wavelengths in A are given for several lines. Note the broad emission of the lines in the S condensation and the blue- and redshifted knots (arrows) with "contrails"connecting them to S in velocity space. The knot labeled "r"has a radial valocity of +2150 km s^{-1} and "b"of −200 km s^{-1} relative to the rest frame of η Car.

The results for seven shell nebulae and twenty Type I PNe are illustrated in Figures 7 and 8, which present respectively 12+[He/H] and [N/O] as a function of 12+[O/H] (where the brackets denote logarithmic abundance ratios). Excluding the η Carinae condensations and AG Carinae shell for the moment, some general conclusions about the compositions of the shell nebulae can be inferred form the two figures. First, O/H is generally lower in the shell nebulae compared to the sun or solar neighborhood ISM (represented by the Orion Nebula) by 0.2-0.6 dex. Second, some (notably NGC 6888 and the inner or shell regions of NGC 2359, NGC 6164–5, and NGC 7635) are He–rich by amounts (~ 0.1 dex), comparable to the average for Type I PNe. Third, N/O is high (and comparable to values in some Type I PNe) in the E–class (stellar ejecta) objects M1–67, NGC 6164–5, *and NGC 6888* (suggesting that the knots are indeed stellar ejecta rather than simply wind–swept ISM material). By contrast, N/O in NGC 2359 and NGC 7635 is approximately normal.

Two "shell"nebulae, the condensations around η Car (Davidson *et al.* 1986; Kendall 1987) and the AG Car shell (Mitra and Dufour 1989) show evidence of extremely low O/H compared to "solar"; in excess of two and one orders of magnitude, respectively. While these two O/H depletions are exceptional among known shell nebulae, they may be just extreme examples of an oxygen depletion "process"in the star prior to shell ejection for the Type I PNe and W-R/O-stars. Evidence that such a nucleosynthesis process exists which converts some of the O into N in these shells has been implied by Torres–Peimbert (1984) based on the result that O and N seem to be anticorrelated in Type I PNe, such that (N+O) ~ constant. In a study of the Type I PNe NGC 6357, which is among the most O–deficient known, Feibelman *et al.* (1985) suggest that the reaction $O^{16} + 2p \rightarrow N^{14} + \alpha$ may be significant in the envelope burning (EB) regions of certain PNe before shell ejection and result in the conversion of some of the O into N. However, this process requires exceptionally high temperatures, and evolutionary models by Renzini (1984) suggests that no more than 30% of the O^{16} gets converted into N^{14} in extreme cases. Therefore, a nucleosynthesis explanation for O–conversion and/or destruction has yet to be developed. A possibility to be explored is that part of the oxygen is selectively "hidden"in grains, since the η Car condensations and the AG Car shell nebulae are very dusty and are influenced by only a "soft"*UV* ionizing radiation field.

Carbon is the third element of consequence in H– and He–shell burning nucleosynthesis, since most of the C^{12} is likely to be converted into N^{14} in the H–burning shell, and thus $(N+O) \neq$ constant if most of the pre–existing C is transformed into N. Moreover, injection of C^{12} produced in the He–burning shell into the H–burning shell prior to mass loss can produce *primary* N^{14} and altogether destroy the (N+O) ~ constant relation. Dufour (1984) has proposed that the very high N/O values observed in some Type I PNe require some primary N production from new C injected into the H–burning shell before nebula formation. Therefore, determination of C abundances in the shell nebulae is crucial to our understanding of the origin of the N being secondary and/or primary, as well as the nature of C (and O) production and/or depletion.

The author and collaborators have attempted to observe the *UV* C III] and C II] emission lines in several of the W-R/O-star shell nebulae using the *IUE* and have been successful only for the case of the brighter condensations of η Carinae (Davidson *et al.* 1986); for which we find that C/H is lower than solar by −1.4 dex (a factor of 25!). This coupled with the O/H depletion (−2.6 dex, or a factor of 400!!), and the N/H enrichment (+1.8 dex, or a factor of 60), results in $X(C+N+O) \approx X(N) \approx X(CNO)_\odot$. Therefore, *most of the pre-existing C and O in the η Car ejecta has been transformed into N.* In the other objects observed with the *IUE*, the lack of detectable C II] and C III] lines relative to the (weak) continuum observed suggests that C/H in the shells is likely no higher than solar and probably lower. *Therefore, currently there is no clear evidence for the primary production of either C or N in the shells surrounding Pop I W-R/O-stars.*

The above result for the Pop I W-R and O-star shells is similar to that found for the O–poor Type I PN NGC 6537 (Feibelman *et al.* 1985), which when compared to nearby H II regions, has logarithmic abundance differences of $\Delta[C/H] = -0.9$, $\Delta[N/H] = +1.4$, and $\Delta[O/H] = -0.5$, or conversely the N–enrichment can be due solely to the secondary conversion of both C and O. For such an object, (C+N+O) = constant, and not (N+O). By contrast, the Type I PN NGC 6302 (Aller and Czyzak 1983), which is N–rich and C–poor, has $\Delta[N+O] = +1.0$, but $\Delta[C+N+O] \approx 0$. Therefore, C and sometimes O contribute to the N enhancement in planetary nebulae from the more massive (Pop I) progenitors, and thus (C+N+O) is the relevant nucleosynthesis parameter to consider. If (C+N+O) in a nebula is higher than nearby H II regions values, then it is likely the result of primary C being injected into the H–burning shell (with some conversion into primary N likely), but such situations seem rare among PNe, as well as in the shells around more luminous progenitor stars. We end by noting that a spectroscopic study of shell nebulae around luminous stars in the Magellanic Clouds would be most interesting since the ISM of the Clouds have low N/O compared to the Galaxy.

IV. CONCLUDING REMARKS

It is apparent that the characteristics of the Wolf–Rayet and the Of– and P–Cygni shell nebulae overlap morphologically, kinematically, and chemically (and with some Type I PNe as well). It seems that the type of central star depends on the nature of local material around the star, rather than its progenitor mass or history of mass loss and wind formation. The characteristics of the shells provide no definitive clues to a systematic transition between the W-R (specifically the WN's), Of, and P–Cygni phases of massive stars in time or their ejection of nucleosynthesis processed material. Perhaps more detailed studies of the various objects, including the majority of the W-R stars that do not show shells or wind–driven bubbles at all, will result in some kind of chronological evolution link. Certainly SN1987a showed that SNII can arise from blue supergiants as well as red supergiants; similarly mass loss of processed material and wind–development occurs in a variety of spectroscopically labeled hot stars. Would the extent of the mass loss mandate the type of star it looks like when it undergoes an explosion as a SNII?

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REFERENCES

Aller, L.H. and Czyzak, S.J. 1983, *Ap.J. Suppl.*, **51**, 211.

Bruhweiler, F.C., Gull, T.R., Henize, K.F., and Cannon, R. D. 1981, *Ap. J.*, **251**, 126.

Chu, Y.-H. 1981, *Ap. J.*, **249**, 195.

Davidson, K., Dufour, R. J., Walborn, N. R., and Gull, T. R. 1986, *Ap. J.*, **305**, 867.

Dufour, R. J. 1984, *Ap. J.*, **287**, 341.

Dufour, R. J. 1989, in *IAU Symposium No. 131, Planetary Nebulae*, ed. S. Torres-Peimbert (Dordrecht: Kluwer Academic Publishers), p. 216.

Dufour, R. J., Parker, R. A. R., and Henize, K. G. 1988, *Ap. J.*, **327**, 859.

Fairall, A. P., Parker, R. A. R., and Henize, K. G. 1985, *Pub. A. S. P.*, **97**, 780.

Feibelman, W., Aller, L. H., Keyes, C. D., and Czyzak, S. J. 1985, *Proc. Natl. Acad. Sci. USA*, **82**, 2202.

Hester, J. J., Parker, R. A. R., and Dufour, R. J. 1983, *Ap. J.*, **273**, 219.

Jernigan, T. E. 1989, Ph. D. Thesis, Rice University.

Kendall, D. A. 1987, M. S. Thesis, Rice University.

Kwitter, K. B. 1981, *Ap. J.*, **245**, 154.

Leitherer, C. and Chavarría-K., C. 1987, *Astr. and Ap.*, **175**, 208.

Lynds, B. T. and O'Neil, E. J. 1983, *Ap. J.*, **274**, 650.

Marston, A. P. and Meaburn, J. 1988, *M.N.R.A.S.*, **235**, 391.

Mitra, P. 1989, Ph. D. Thesis, Rice University.

Mitra, P. and Dufour, R. J. 1989, *M.N.R.A.S.*, submitted.

Parker, R. A. R. 1978, *Ap. J.*, **224**, 873.

Peimbert, M. and Torres-Peimbert, S. 1983, in *IAU Symposium No. 103, Planetary Nebulae*, ed. D. R. Flower (Dordrecht: D. Reidel), p. 39.

Raymond, J. C., Hester, J. J., Cox, D., Blair, W. P., Fesen, R. A., and Gull, T. R. 1988, *Ap. J.*, **324**, 869.

Renzini, A. 1984, in *Stellar Nucleosynthesis*, eds. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 99.

Sabbadin,, F., D'Odorico, S., and Minello, S. 1977, *Astr. and Ap.*, **57**, 331.

Schneps, M. H., Haschick, A.D., Wright, E. L., and Barrett, A. H. 1981, *Ap. J.*, **243**, 184.

Talent, D.L. and Dufour, R.J. 1979, *Ap. J.*, **233**, 888.

Torres-Peimbert, S. 1984, in *Stellar Nucleosynthesis*, ed. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 3.

Van Buren, D. and McCray, R. 1988, *Ap. J. Letters*, **204**, L17.

Walborn, N.R., Blanco, B.M., and Thackaray, A. D. 1978, *Ap. J.*, **219**, 498.

Wendker, H.J., Smith, L.F., Israel, F. P., Habing, H. J., and Dickel, H. H. 1975, *Astr. and Ap.*, **42**, 173.

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