SESSION VI. ENRICHMENT – *Chair: Joseph P. Cassinelli*

Anne Underhill, Joe Cassinelli chairing

ENRICHMENT BY WOLF-RAYET STARS AND OTHER MASSIVE STARS IN GAS, DUST AND ENERGY

MARTIN COHEN
Radio Astronomy Laboratory
University of California
Berkeley
USA

ABSTRACT. I update previous estimates of the separate contributions for radiative energy, integrated total stellar wind mass and dust mass from Wolf-Rayet stars and other massive (OBA) stars. In the context of the intriguing dusty WC9 stars, I: (1) discuss the observability (or otherwise) between 0.4 and 23 μm of the condensation route from hot gas to carbon-rich grains; (2) urge caution in the use of 10 μm infrared spectra of these luminous stars to deduce the importance of silicates as a component of the interstellar medium; and (3) speculate on a possible new method for discovering new members of this relatively rare subtype based on IRAS Low Resolution Spectra. I review the observational evidence for dust condensation around SN 1987A.

1. INTRODUCTION

The first part of my talk will focus on an updated version of a popular topic, namely the relative importance of the Wolf-Rayet (WR) stars' influence on the interstellar medium compared with the effects of other stars in the Galaxy ([1],[2]=[HCW],[3],[4]). What role do the WRs play as contributors of energy, momentum, ionizing photons, overall luminosity, and dust through their radiation and powerful stellar winds? It is customary to compare the attributes of WRs with OBA stars for their energetics. To assess the WRs' dust contribution requires consideration of the abundant lower mass stars whose red giant phases provide most of the dust to the interstellar medium.

My second subject will be the intriguing WC9 stars and the likely pathway to dust condensation in their carbon-rich winds. This will be discussed in the context of a combination of recent airborne spectroscopy with IRAS Low Resolution Spectrometer (LRS) data. Detailed LRS surveys of successively fainter IRAS point sources have resulted in a comprehensive spectral classification scheme now validated by optical spectroscopy and IRAS photometric color indices. These surveys have brought to light an unusual shape of LRS energy distribution which may correspond uniquely to dusty WCL stars. I would like to present this as

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a potential method for seeking new WC stars with dust.

The final item will cite the evidence for dust condensation in SN 1987A, again through airborne infrared spectra.

2. THE FLUX OF RADIATION, MASS, MOMENTUM, AND ENERGY FROM MASSIVE STARS

2.1 OB and WR Star Counts and Caveats

It has been traditional when undertaking a review of this field to build heavily upon Abbott's [1] presentation for both WR and OBA stars and merely to reflect changes in the WR literature that directly affect estimates of mass loss rates. The literature does not convey the impression that there are any fundamental shortcomings with the OB catalogue of Garmany, Conti, and Chiosi [5] beyond a minor concern about its completeness, particularly for the dwarf component. However, Garmany [6] has expressed a number of serious caveats about "GCC". Among those concerns are: (1) the absence of two-dimensional spectral classifications for a substantial number of stars; (2) potentially specious O-star classifications; (3) the inclusion of stars in "OB associations" which not may represent truly physical groupings. These affect the value of the catalogue as a whole for stellar census work in which distances and estimates of physical parameters, such as mass loss rate and even bolometric luminosity, are important.

Consequently, since I wished to re-evaluate all aspects of the problem that might have undergone change since previous reviews, I have followed [1] but have used a subset of "GCC" kindly supplied to me by Dr. Garmany. This subset consists of 981 stars in the northern hemisphere between galactic longitudes 59^{o} and 148^{o} that are definitely established to belong to real OB associations. My subsample consists of 406 O,B, or A members of associations whose distances are <3 kpc, and spans all luminosity classes. This quadrant provides perfectly valid estimates for the parameters of interest per kpc^{2}, the customary format, without the need to study the entire 3 kpc volume centered on the sun and without recourse to the considerable uncertainties in distance and spectral type inherent in the entire version of "GCC". The earlier WR catalogue by van der Hucht et al. [7] has been superseded by an updated version [8](=HHASD) which includes new spectral subtypes and distances for an appreciable number of stars. The WR content of the 3 kpc vicinity centered on the sun has consequently changed significantly since earlier reviews of this field ([2],[3]). I have, therefore, revised the 3 kpc WR census using [8]. There are 61 WRs within this volume: 24 WN, 36 WC, and 1 WO type.

Conti and Vacca ([9]=CV) have very recently studied the distribution of WR stars in the Galaxy based upon new spectra, some obtained after those incorporated into [8]. CV also assign distances on the basis of a different set of intrinsic colors for WRs [10] than HHASD used. This leads to a somewhat different WR census for the 3 kpc zone: 65 stars, 35 WN, 29 WC, and 1 WO type. I, therefore, recalculated all parameters described below, separately for HHASD and CV.

2.2 Luminosity and Ionizing Flux

As part of a substantial study of O-stars, Howarth and Prinja [11] provide a recalibration of the physical parameters, in particular their luminosities. I have incorporated this revised calibration into the assessment of radiative output from the O-stars. I have reverted to Panagia [12] for the early B types and to Allen [13] for the late B and early A types. The estimates of ionizing flux for all types still follow the tabulations of N_L in [12].

Barlow, Smith, and Willis [14] present bolometric luminosities and ionizing photon fluxes for most WR types. Schmutz, Hamann, and Wesselowski [15] model WRs and their luminosities agree well ($\lesssim$0.2 dex) with those in [14] except for the earliest WN and WC types. Smith and Maeder [16] argue for a constant B.C. (−4.5) for all WRs based on theoretical mass-luminosity relationships. I adopted the scale of [14], replacing the values for WN3 and 4 (4.5), and incorporating the data for WN2, from [15]. For WO2 and WC9 I took M_v from HHASD and a B.C. of −4.5. For types lacking N_L I used the average ratio (from [14]) of $N_L/L_{bol} = 3.80\text{x}10^{43}$.

2.3 Mass Loss Rates

The recent analysis of IUE high-resolution spectra by Howarth and Prinja [11] contains a re-examination of the issue of terminal velocities in O-star flows. Turbulence and shocks can lead to maximum observed velocities exceeding the true far-field velocity (e.g. in rarefactions: [17]). They argue [18] that the terminal velocity is best estimated from the central velocity asymptotically approached over time by narrow absorption components or, statistically equivalent, a scaled down value for the violet limit (zero residual intensity) of saturated P Cyg profiles. Use of these revalued terminal velocities yields a robust predictor for the mass loss rate of O stars of all luminosity classes dependent only on luminosity, namely, $\log(\dot{M}/M_\odot \text{ yr}^{-1}) = 1.69 \log(L_*/L_\odot) - 15.4$. A very similar slope resulted from previous empirical determinations ([19],[20],[1]) and is consistent with evolutionary models for high mass stars [21]. I, therefore, used this formula for the OB (and A0) stars from Garmany's [6] new subcatalogue.

Mass loss estimates for WRs have undergone several recent revisions stemming from four independent causes, namely: carbon abundances in the winds; low ionization state of the winds; redetermination of distances to some stars (e.g. HHASD; CV); and revisions in terminal velocities. HCW increased the estimates made from VLA radio continuum fluxes [22] to include the high abundance of carbon in the stellar winds determined by Prantzos et al. [23]. Support for these high C/He values has come from other work ([24],[25],[26],[27],[28]). However, Smith and Hummer [26] suggest that HCW's increases are too large because they used too low a carbon ionization balance. Both Schmutz and Hamann [29] and Hillier [30] have shown that the radio-emitting region in WRs shows a strong gradient in He ionization with radius so that He^+ is more important than He^{++}. Allowance for the reduced free-free emissivity elevates the original mass loss rates [22] by a factor ~2 for all types [29].

Work in press on terminal velocities by Prinja, Barlow, and Howarth [31], kindly advanced to me by Dr. Barlow, re-evaluates terminal velocities in WRs by the same methods as those applied to O-stars [11]. The average change in v_∞ is 0.76 for the WRs, leading to reduced values of mass loss rate. In the discussion below, I have used the new results for individual stars to determine mean velocities and mass loss rates for WR types because these authors have incorporated all the above changes. For WR types not treated in [31], I have scaled the terminal velocities used by HCW by 0.76 and have extrapolated the known mass loss rates to types for which these are not known exactly as HCW did, but using Prinja et al.'s work [31]. There are ~10 WC9s within 3 kpc of the sun; therefore, it is important to estimate their mass loss rate carefully rather than merely setting it equal to that for WC8s. $\dot{M}$ depends on ionization balance through three factors: the Gaunt factor; the mean number of free electrons per nucleon; and the r.m.s. ionic charge. I rescaled HCW's mean WC9 $\dot{M}$ according to the change in these three parameters between their own ionization balance (of He and C) and that in [26], and by a further factor of 0.76 for the terminal velocity. $\dot{M}$ for type WO2 comes from Barlow's paper at this meeting.

2.4 Momentum and Energy Output

The momentum and energy carried by these hot stellar winds are taken to be $\dot{M}v_\infty$ and $0.5\dot{M}v_\infty^2$, respectively. Table 1 summarizes the adopted mean parameters of the WRs and their outputs of mass, momentum and energy per star per kpc^2 and their numbers within 3 kpc according to both HHASD and to CV. Only spectral types necessary to the 3 kpc census are listed.

Table 2 compares the physical influence of WR and OBA stars upon the local medium, separating fractions attributable to WR, O, BA stars and giving the totals per kpc^2 near the sun. In spite of the obvious differences inherent in the two WR catalogues (HHASD and CV), the analyses for Table 2, and even the total quantities in the final column, differ remarkably little ($\lesssim$5%). Table 2, therefore, presents the averages derived from both HHASD and CV.

There have clearly been so many changes between different versions of Table 2 that it is not surprising to find differences. However, the WRs still dominate the input of both mass and momentum to the local medium. The principal new change is that their energy output now more closely resembles Abbott's [1], essentially because the reduction in WR terminal velocities affects their wind energy by the cube of 0.76, and the new mass loss scale for the OBA stars [11] elevates their mass loss rates over those used in [1]. Other differences, principally in the totals of the quantities, may well reflect the usage of the new subset [4] of hot stars and the implicit assumption that this quadrant is representative of the whole 3 kpc neighborhood. Garmany's [32] Fig. 4 suggests that this is likely to be a reasonable assumption but one must view the distribution of hot stars as mapped out by her entire catalogue with some caution.

2.5 Enrichment of the medium in heavy elements by WRs

Following [1], one can calculate the degree of enrichment of the interstellar medium by the nucleosynthetic products carried by WR winds. The abundances of heavy elements used by HCW [23] were converted from a table by number to elemental mass fractions (Table 3). The yield of any element is estimated as the product of the difference in mass fraction between WR wind and local medium and the mean mass loss rate per kpc^2, summed over all WN, WO, and WC stars ([1],[4]). Mean mass loss rates within 3 kpc averaged over HHASD and CV_2 are: WNs, 5.61(−5); WOs, 6.11(−7); and WCs, 5.01(−5) $M_\odot$ yr^{-1} kpc^{-2}. These yields are normalized by the net rate of input of gas to the medium from star formation [4], 4(−3) $M_\odot$ yr^{-1} kpc^{-2}, and are tabulated for He, C, N, and O (Table 3).

Comparing with the expected yields from supernovae alone (Tables 1 and 2 of [33]), WRs provide ~50% of the enrichment in He, and 33% of that in CNO combined.

3. DUST

3.1 Dust Output in the WRs and other Massive Stars

The dust contribution of WRs to the interstellar medium is that of only the WC7 and later stars, dominantly that of the WC9s ([34],[35],[36]). By contrast, OBA stellar winds are not observed to condense dust.

3.2 Dust Output of Lower Mass Stars

Both Gehrz [37] and Tielens ([38],[39]) have estimated the magnitude and/or composition of stardust for a wide variety of dust-producing objects on a Galactic scale. They do not always agree on dust-to-gas ratios, or average mass loss rates. [38] isolates the carbon stardust. To make estimates more relevant to the solar neighborhood I utilized the detailed Galactic model by Wainscoat et al. [40] to predict the breakdown of stellar population close to the sun in terms of its AGB M and C stars, red supergiants, and planetaries. Table 4 combines results from the model predictions with those in [37], [38], and [39]. The model agrees better with Tielens's more conservative estimates than with Gehrz's, and I have therefore used the average of the model's and Tielens's numbers in case of disagreements. For supernovae there is only a lower bound on dust formation (>0.004 Table 4 units) from the small amount observed in SN 1987A (Wooden [41]: section 5 below). Tielens's figures (in {}), reproduced here, represent the maximum amounts assuming all C and Si condense into grains in SN. Gehrz [37] estimates ~5 (Table 4 units) for the dust yield of all supernovae, or one third of the sum of Tielens's maxima for type I and type II SN combined!

Table 1 shows that WC8 and 9 stars contribute 12.6 (Table 4 units) of gas to the 3 kpc vicinity, implying (from Table 3) 4.9 units solely in carbon. For a dust-to-gas ratio of 0.01 I recover Tielens's global estimates of 0.05-0.06 units in carbon dust ([38],[39]).

TABLE 1. The adopted mean parameters of WR stars and star counts within 3 kpc of the sun according to HHASD and CV

Spectrum	V_∞	$\dot{M}$	———— kpc^{-2} ————			HHASD	CV
			$\dot{M}$	$\dot{M}V_\infty$	$0.5\dot{M}V_\infty^2$	#	#
	km s^{-1}	$M_\odot\ \text{yr}^{-1}$	$M_\odot\ \text{yr}^{-1}$	10^{29} g cm s^{-1}	10^{37} erg s^{-1}		
WN 2	3200	3.0(−5)	1.06(−6)	0.21	0.34	1	0
WN 3	2300	3.0(−5)	1.06(−6)	0.15	0.18	2	2
WN 4	1950	3.0(−5)	1.06(−6)	0.13	0.13	0	1
WN 4.5	1450	3.0(−5)	1.06(−6)	0.10	0.070	1	2
WN 5	1450	4.0(−5)	1.41(−6)	0.13	0.094	2	6
WN 6	1550	8.5(−5)	3.01(−6)	0.29	0.23	8	8
WN 7	1600	4.9(−5)	1.73(−6)	0.17	0.14	8	8
WN 8	825	4.9(−5)	1.73(−6)	0.090	0.037	1	7
WN 9	1150	4.9(−5)	1.73(−6)	0.12	0.070	0	1
WO 2	5600	1.7(−5)	6.11(−7)	0.22	0.60	1	1
WC 4	3050	3.2(−5)	1.13(−6)	0.22	0.33	2	1
WC 5	2550	3.2(−5)	1.13(−6)	0.18	0.23	7	4
WC 6	2150	3.2(−5)	1.13(−6)	0.15	0.16	6	4
WC 7	2000	7.2(−5)	2.55(−6)	0.32	0.32	8	9
WC 8	1450	6.3(−5)	2.23(−6)	0.20	0.15	3	3
WC 9	1100	1.8(−5)	6.26(−7)	0.044	0.024	11	8

TABLE 2. The influence on the medium of WR and OBA stars

Quantity	% contribution by			Total Rate
	WR	O	BA	(kpc^{-2})
Number of stars	4	23	73	59.65
Radiative luminosity	4	69	27	2.75×10^{40} erg s^{-1}
Ionizing photons	9	88	3	2.33×10^{50} s^{-1}
Mass	81	17	2	1.32×10^{-4} $M_\odot\ \text{yr}^{-1}$
Momentum	73	25	2	1.54×10^{30} g cm s^{-1}
Kinetic energy	38	61	1	2.82×10^{38} erg s^{-1}

TABLE 3. Element enrichment by WR stellar winds

	——— Relative mass fractions ———				
Element	X(WN)	X(WO)	X(WC)	X(ISM)	Yield
He	0.97	0.09	0.32	0.22	1.2×10^{-2}
C	0.00038	0.21	0.39	0.0034	4.9×10^{-3}
N	0.022	0.00	0.00	0.0012	2.8×10^{-4}
O	0.0011	0.66	0.25	0.0082	3.2×10^{-3}
CNO	0.024	0.87	0.64	0.013	8.4×10^{-3}

TABLE 4. A comparison of Galactic producers of "stardust"

Source	Contribution (10^{-6} $M_\odot$ yr^{-1} kpc^{-2}) carbon dust	silicates	SiC
M-giants		2.5	
C-giants	3		0.1
Red supergiants		0.2	
Novae	0.3	0.03	
Planetary nebulae	0.03		
WC8 & WC9 stars	0.05		
Type I SN (max.)	{2}	{12}	
Type II SN (max.)	{0.3}	{2}	

4. THE WC9 STARS

4.1 Dust Condensation in WC9s

The WC9s are the most prodigious dust producers of the WRs but precisely what they condense has been an ongoing problem. The high C/He suggests that the grains are carbon-rich, probably amorphous. One might imagine that any condensation route would involve neutral carbon, yet none is detected in their spectra. Indeed, Williams et al. [36] commented that, because most of the carbon in WC9s is CII and CIII, there is not sufficient CI for grain formation by the process that operates in C-giant atmospheres and grain growth by accretion of C ions was precluded by the positive charges on those ions. Smith and Hummer [26] find that the dominant C ion in WC9s is CIII, exacerbating this apparent problem.

Not until airborne 5-8 μm spectra were obtained of WC9s were dust features recognized [42]. When these spectra, of Ve 2-45 and GL 2104, are combined with IRAS LRS spectra and compared with blackbodies, a broad feature is seen in both stars between ~7.5 and 9 μm, with peak near 7.7 μm. No associated 6.2 μm (PAH) band is detected, nor any 3.3 or 11.3 μm feature (CH stretching and bending modes). The 7.7 μm peak corresponds to vibrations of the aromatic skeleton, but neither 3.3 nor 11.3 μm features is expected in the H-poor environment of a WC9 star.

All these characteristics derive from small (<30Å) aromatic domains, contained within small (perhaps 80Å) disordered grains. The disorder results from highly supersaturated winds with low temperature grain formation [42]. Possible pathways to dust formation in C-rich circumstellar envelopes are: neutral radicals, ions, PAHs, polyacetylenic chains, and fullerenes ("soccer balls"); all act as intermediaries to soot formation in flames. C-giants form dust via acetylene; C-rich planetaries via PAHs (with significant hydrogenation); but WC stars represent a situation more akin to laser vaporization of graphite in a H-poor atmosphere than to flames. In WC stars the absence of H precludes the acetylene route. Probably dust in the WC9s is built from polyynes (acetylene-like chains), into C_2, C_3, C_4, etc. [38], then large flexible structures (>20 atoms) that form aromatic rings but with many unfilled valences at the molecular peripheries (H would normally saturate these dangling edge bonds). Minimization of "surface free energy" drives dust formation in the WC9s via pentagons in the aromatic structures, which lead to warping, curling, and eventually closure in the form of fullerenes (C_{60},C_{70}: [38],[42]).

Because ion-molecule reactions are faster than neutral-radical ones, the first molecules are thought to form via ions in the late WCs, by radiative association of C with C^+ and C_2^+. C_3^+ may recombine dissociatively [38] leading to C_2 and initiating the sequence from acetylenic chain to large aromatic structures via ion-molecule reactions.

On a global scale the fullerenes are expected to be a very minor form of interstellar dust [38] because C-giants dominate the C-stardust scene (Table 4). Fullerenes may represent a dead-end in the dust formation process in WC stars too; consequently, they may be abundant around WC9s. There is rumored to be a fullerene band near 3860Å. It would be very interesting to search for such features in WC9 stars and for the bands of C_2 and C_3 ions (because one can already set limits on the neutral molecules from the wealth of WC9 spectra).

4.2 Silicate Absorptions and Aromatic Emissions

I simply want to urge caution in the interpretation of mid-infrared spectra of the WCL stars. Without airborne (5-8 μm) spectra it is all too easy to dismiss the overall spectral shape as a featureless hot continuum suffering substantial 9.7 μm interstellar silicate absorption. However, any continuum must fall below the aromatic emission structures near 8 μm, thereby removing an appreciable amount, if not all, of the supposed silicate feature [42]. Consequently, it is inadvisable to determine the visual extinction from τ(9.7 μm) without complete infrared spectra of these stars or, conversely, to assess the ratio A_V/τ(9.7 μm) from WC9s without due caution.

4.3 An IRAS LRS Search for New WC9 Stars

As part of an ongoing study of the 170,000 extracted LRS spectra, Volk and Cohen [43] have provided a complete catalogue of all IRAS point sources having S(12)>40 Jy, to supplement the published LRS Atlas [44]. The spectrum of GL 2104 appears in the Atlas; those of Ve 2-45 (Roberts 80) and GL 2179 in [43]. Their shape is quite unlike that of other LRS spectra although the closest match is to "group P" (PAH emission) spectra. This similarity is strengthened by the airborne spectra described above [42].

Among new, unidentified group P sources are IRAS 17380-3030 and 18405-0448. Fig. 1 is a montage of normalized λF_λ plots for 4 known WC9/10 stars and these 2 new potential WC9s, showing their kinship. It is the combination of broad polcyclic aromatic cluster emission ~7-9 μm and some possible interstellar silicate absorption near 10 μm that create this archetypical spectrum. As yet there is no proof that either of these IRAS sources is a WC9. Van der Hucht, Williams, and The (1989-90) have obtained infrared photometry but optical spectra are still lacking. Both are extremely faint optically but an AAO service request

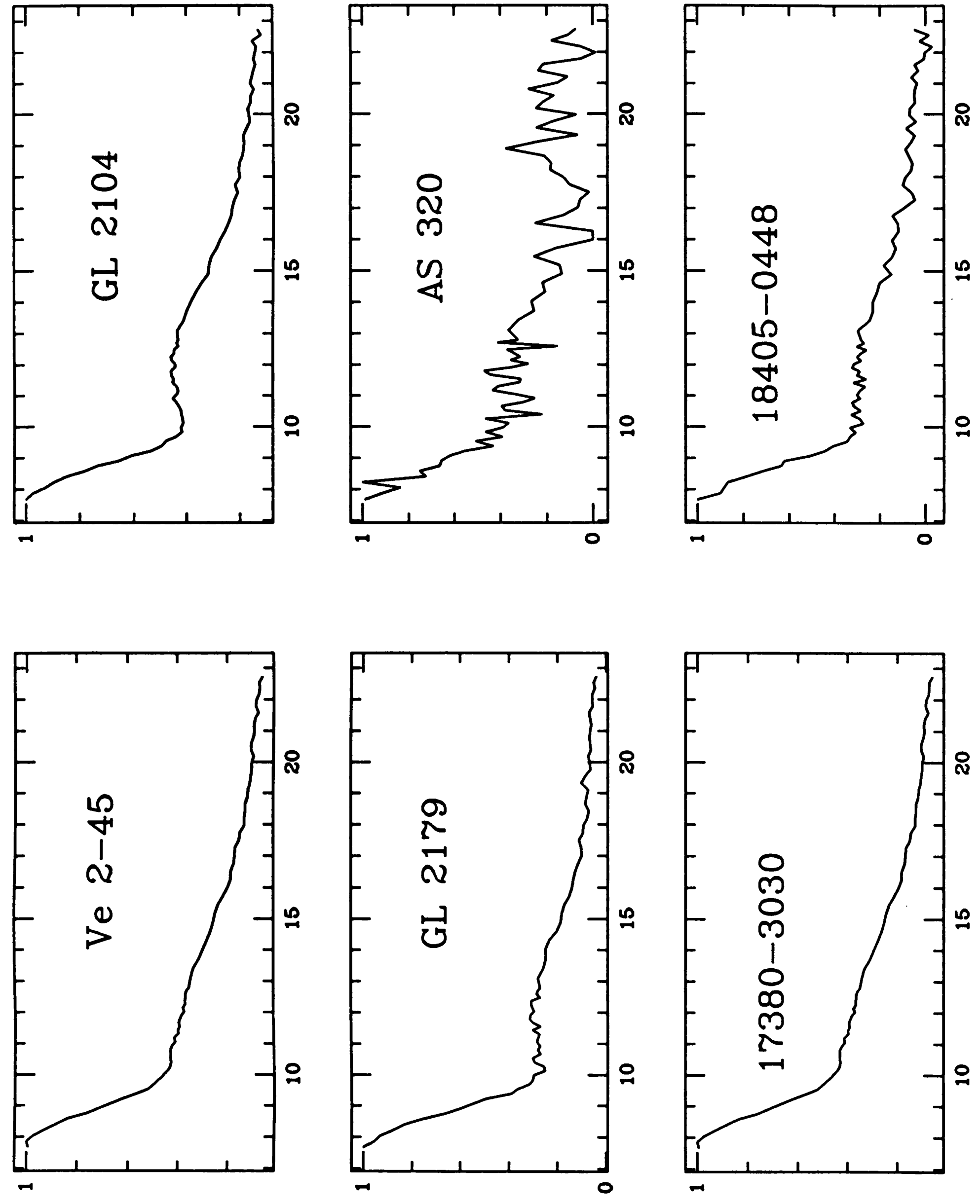

FIG. 1: Montage of LRS spectra for WC9/10 stars and the two possible new WCL objects, IRAS 17380-3030 and 18405-0448. Abscissa is wavelength in microns; ordinate is normalized λF_{λ} .

for spectroscopy of 17380-3030 is pending. We have our fingers crossed!

5. DUST IN SN 1987A

Whether SN form dust grains is an interesting topic [45]. Dust observed in the Crab may be swept up, not condensed ([46],[47]). Critical observations by Wooden [41] that show that SN 1987A did produce grains are: 1. The bolometric luminosity of the SN declined faster after 600^d than predicted from Co^{56} decay while the infrared luminosity beyond $\sim$10 μm <u>increased</u>, and the sum of UV+optical+IR energy matched the Co decay curve (nor were any excess γ- or X-rays observed concurrently). 2. Her montage of infrared spectra includes the critical 5-8 μm region and illustrates the decline in luminosity of the IR component consistent with an "IR echo". Wooden calculated the location and temperature of dust during an echo and the mass of emitting dust observed at each epoch. The decline in the IR component halted abruptly near 615^d. The observed dust mass increased dramatically between 400 and 777^d, allied with a strongly increased absorption of visible light. 3. Finally, the profiles of optical and IR forbidden lines appeared blue-shifted after $\sim 500^d$, an effect well-shown by the 6.634 μm [NiII] line. Therefore, the red-shifted sides of these emission lines arising in the back of the shell of ejecta were internally extinguished within the line emitting zones after 615^d. Dust, therefore, condensed in SN 1987A.

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DISCUSSION

Shara: In session VIII I will announce the discovery of 13 new WR stars in a 12 degree ($l = 282°$ to $294°$) band centered on $b = 0°$ (where 24 were already known). The present WR census is at least 25% incomplete even locally ($0 - 3kpc$); and the fraction of WN stars is significantly higher than has been previously claimed.
Cohen: If you can tell me the exact numbers of WR stars of different subclasses that I need to include to make my census complete, that would be very interesting. That means I will have to do all of this again!

Conti: This was a very thorough discussion of hot star contributions to their global environments. The fact that in the mean our and van der Hucht's population totals were not too different suggests such spectroscopic parallax measurements are rather robust. I only would add one caution: using the accurate count of O stars within a single quadrant, compared to all WR stars, might be a little misleading since WR stars are not distributed equally in all four quadrants.
Cohen: I felt it was safer to define the OBA count in this way and assume that the OBA stars were not too differently distributed in the other three quadrants. Since everything is defined per kpc^2 I thought this was a reasonable approach.

Van der Hucht: Conti & Vacca (1990), in their determination of the WR distances in the Galaxy, first used the ones in galactic clusters and associations and in the LMC as M_v calibrators, and subsequently (and contrary to van der Hucht *et al.*, 1988) *recalculated* the distances of WR stars in galactic clusters and associations using their average M_v per subtype values. Since the WR stars in clusters and associations within 3 *kpc* from the Sun constitute about 50% of all the WR stars in that volume, this inconsistent approach by Conty & Vacca explains part of the discrepancy between the WR galactic distributions determined by Conti & Vacca and those of van der Hucht *et al.* One better leaves WR stars at the distances of their clusters or associations.
Conti: The question of membership of WR stars in galactic associations is by no means settled. A cursory examination of the fields of 40 WR association members indicates a substantial question of a connection for many of them. Most of our (Conti & Vacca) M_v calibration is given by the LMC WR stars. We treated all our distances to galactic stars in a statistical sense. The individual differences to van der Hucht *et al.* can be thought of as indicating the uncertainty in *both* approaches. Association membership for WR stars needs a critical examination, as Garmany is carrying out for galactic O stars.

Sreenivasan: Those of us who have modeled the evolution of the progenitor of SN 1987A have been concerned about whether or not the star goes through a red supergiant phase before the blue supergiant phase because of the detection of dust in a shell. Could you say whether the dust formed in the ejecta is sufficient to decide whether such a red supergiant phase is necessary or not? (You said that IRAS data cannot be used to decide whether there is sufficient swept up dust).
Cohen: I do not feel that the total amount of dust that was observed to condense is significant. The swept up (4-5 light day) shell of pre-existing dust has even less mass. The test for a RSG precursor would surely be through any silicate emission features but none is seen in SN 1987A. Perhaps such grains are present but are either too cool and/or too large to reveal optically thin features. Consequently, the observations of dust in SN 1987A do not address your concern.
Filippenko: We know without a doubt that the progenitor of SN 1987A went through the red supergiant phase before exploding as a blue supergiant. IUE spectra revealed narrow emission lines from a circumstellar shell highly enriched by CNO processing and photoionized by the initial UV flash of the supernova.