SUBLUMINOUS WOLF-RAYET STARS: OBSERVATIONS

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I. INTRODUCTION

Fully ten percent of the Wolf-Rayet stars known in our galaxy are central stars of planetary nebulae. These stars are highly-evolved stars of approximately one solar mass. The existence of WR characteristics in the spectra of central stars as well as in massive, younger stars proves conclusively that WR spectra are a phenomenon that occurs in hot stars of widely different masses and evolutionary histories. Just what this phenomenon is -- the nature of the instability that drives the wind -- is not known, but the phenomenon is associated with a prior event in the star's evolutionary history. The common event that links Wolf-Rayet stars is loss of most, if not all of the outer, hydrogen-rich envelope just prior to the onset of WR characteristics. As Tutakov (this volume) and others have emphasized, there are many ways for a star to lose its H-rich envelope. These ways include mixing, ejection via a wind, or, in the case of a close binary, ejection via Roche-lobe overflow. The existence of WR-type central stars implies simply that we should include one more path leading to the Wolf-Rayet phenomenon, and that is, ejection to form a planetary nebulae.

There are some definite advantages in working with central stars to study the Wolf-Rayet phenomenon. First of all, the surrounding nebula provides a means of determining some basic properties of the central star. In the Zanstra method, the nebula is used as a counter of ionizing photons to derive an EUV color-temperature of the exciting star. In the Shklovsky method, the nebular flux and angular diameter are used to derive the distance to the system. The nebular radius and expansion velocity then yield the age of the star since the time of ejection. Finally, the relative strengths of radio and optical emission are used to infer the amount of interstellar extinction. The main point is that these nebular data provide an internally consistent set of stellar properties. There may be systematic errors, (for example in the distance scale to planetaries) but these are less important because we are most interested in comparisons among WR-type

C. W. H. de Loore and A. J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, 423–445.

central stars. A second advantage in working with central stars is the broad baseline for comparison, as shown by the range of spectral types from WC2 to WC11 (Section II). This broad baseline is important because it makes it possible to discern overall trends in what would otherwise be deemed noisy data -- noisy not so much due to observational error, but due to an intrinsic dispersion of characteristics within a given spectral type (Garmany, this volume; Leep, this volume). A third advantage in working with central stars is that the evolutionary history, status, and ultimate fate of central stars are relatively well understood. This evolution will be described in detail by Renzini (this volume), but there are several points that we shall make use of in this study.

A central star is the remnant of a red-giant that has ejected its envelope to form a planetary nebula. After ejection, it evolves from the red-giant branch to higher temperatures at a constant luminosity that is set by its mass (Paczynski, 1970):

$$L \approx 60000\ (M - 0.522). \qquad (1)$$

As it gets hotter, its envelope contracts and becomes more dense until it is fully degenerate, at which point, the star is a white-dwarf. Further evolution of the central star consists of cooling at a constant radius. As it turns out, Wolf-Rayet central stars belong to the penultimate evolutionary stage of approach to their final fate as white dwarfs. The time scale of evolution from nebular ejection to the white-dwarf stage depends critically on the mass of the star; it takes tens of thousands of years for a 0.6 $M_\odot$ star to become a white-dwarf, but it takes only a few years for a star with twice the mass. This dependence argues for a relatively small range in the masses of stars visible as central stars of planetary nebulae (Schönberner 1981).

Although loss of the outer, H-rich envelope may be necessary condition for forming WR stars, it is clearly not a sufficient one, since the majority of planetary nuclei does not have a WR-type spectrum. Why some central stars are WR stars and others are say, O stars, is a question that I have used as a focal point in preparing for this talk. The way I have gone about attempting to answer this question, is to step back one step, and ask how the properties of WR-type central stars differ from those of O-type stars. So this study will start at the beginning -- the classification and calibration of WR spectra -- and then go on to the physical properties of WR-type central stars, and at the end, to return to the question of what distinguishes a Wolf-Rayet star. The observational data for central stars are neither complete nor precise. Nevertheless, they suggest that what distinguishes a WR central star is not so much its present physical properties (e.g., temperature, gravity), but rather, its fundamental properties (initial mass and evolutionary history).

https://doi.org/10.1017/S0074180900029181 Published online by Cambridge University Press

TABLE 1

Sources of Observational Data

ID	Spectral Type	X-ray Einstein	Ultraviolet ANS	Ultraviolet IUE	Visual $m_{\star}$	Visual pg	Visual red	IR $L_{IR}/L_{Ly\alpha}$
NGC 2371-2	OVI		∞	L	14.76	Al 68		
NGC 2452	"				19:		Al 77	
NGC 2867	"			L	14.9 pv		Al 77	
NGC 5189	"			L	13.4 pv	Bl 68	MeNi82	
NGC 6905	"	ND		L	14.2 pg	Al 68	Al 77	0.5
NGC 7026	"			L	14.0 pg	Al 68	Al 77	2.0
NGC 1501	"				14.14		Al 77	
IC 1747	"				14.17	Al 68	Al 77	
IC 2003	"			L	13.79	Al 68		
A 30	OVI	ND		L(Gr80)	14.50	GrMi64	Coet77	7.8
A 78	"	ND	140,000	L(He79)	13.45	GrMi64	Coet77	4.6
NGC 246	"	*	100,000	L, H	11.95	He75		
NGC 6751	WC 6				12.93	Al 68	Al 77	5.5
NGC 5315	WC 6			L	11.32			
NGC 40	Wc 8		30,000	L(Beet82)	10.65	Al 68	Al 77	
He 2-99	WC 9				13.5			
BD +30°3639	WC 9		30,000	L, H	9.95	SmAl71	Al 77	13
CPD -30°15469	WC 9						Al 77	
SwSt1	WC 10				11.0			
CPD -56°8032	WC 11				12.2			
V 348 Sgr	WC 11							
M 4-18	WC 11							
He 2-113	WC 11				>12.5			
NGC 6543	WR-Of		30,000	L(Caet80) H(He80)	10.39	Al 68	Al 77	2.7

Notes to Columns

1. Identification given is usually that of the surrounding nebula. Cross references are given by van der Hucht and Conti (1981).

2. Spectral type given by Smith and Aller (1969), van der Hucht and Conti (1981).

3. X-ray data from the Einstein satellite (C. Canizares, priv. comm. 1981): ND = not detected, * = detected with IPC.

4. UV photometry from the ANS satellite (Pottasch et al. 1978): values listed are blackbody temperatures.

5. Ultraviolet spectrophotometry from the IUE satellite: L = low dispersion spectrum, H = high dispersion spectrum obtained.

6. Stellar magnitude: values listed to two decimal places are the V magnitude of the central star (Liller and Shao, 1970).

7, 8. References for photographic and red spectral tracings: Al 68 = Aller 1968; Al 77 = Aller 1977; Beet 82 = Benvenuti et al., this volume; Bl 68 = Blanco et al. 1968; Caet 80 = Caster et al. 1980; Coet 77 = Cohen et al. 1977; Gr 80 = Greenstein 1980; Gr Mi 64 = Greenstein and Minkowski 1964; He 75 = Heap 1975; He 79 = Heap 1979; He 80 = Heap 1980; Me Ni 82 - Mendez and Niemela, this volume.

9. IR photometry (Cohen and Barlow, 1975): values listed are the ratio, L(IR)/L(Lyα), a measure of the amount of dust within the surrounding nebula.

II. SPECTRAL CLASSIFICATION

Emission-line spectra of central stars were first classified over ten years ago by Smith and Aller (1969). By examining strong features on photographic (3300-4800 Å) spectrograms, they were able to assign each spectrum to one of several groups: Wolf-Rayet, with spectral types assigned according to the same classification system as that used for massive WR stars (Smith 1968); OVI spectral class, meaning that the OVI λ3811, λ3834 doublet is present in emission; WR-Of, meaning usually that HeII λ4686 emission is broad but that other emission lines are sharp like those of Of stars; and finally, Of spectral type. Since then, Aller (1968, 1977) and others published spectrophotometric tracings for many of these emission-line stars (see Table 1), so it is now possible to refine the original classification scheme, particularly for the OVI stars. Table 2 defines the new scheme, which, like the standard classification system for WC stars, is based solely on features in the visual region of the spectrum.

TABLE 2

Criteria for Spectral Classification

Spectral Type	OVII 5670	$\frac{FW\ (OVI\ 3811)}{FW\ (CIV\ 4658)}$	$\frac{FW\ (OVI\ 5292)}{FW\ (CIV\ 5806)}$
WC 2, C 2	present		
WC 3, C 3	absent	> 0.5	> 0.3
WC 4, C 4	absent	< 0.5	< 0.3
WC 5 - WC 9	[as given by Smith (1968)]		
WC 10 - WC 11	[as described by Webster and Glass (1974)]		
WN 2, N 2	NV λλ4603, 4619 strong; NIII, NIV lines absent		
WN 3 - WN 8	[as given by Smith (1968)]		

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It turns out that OVI central stars are a diverse lot. First, while most OVI central stars are WR stars in having a pure emission line spectrum, three OVI stars (the nuclei of NGC 246 (Figure 1),

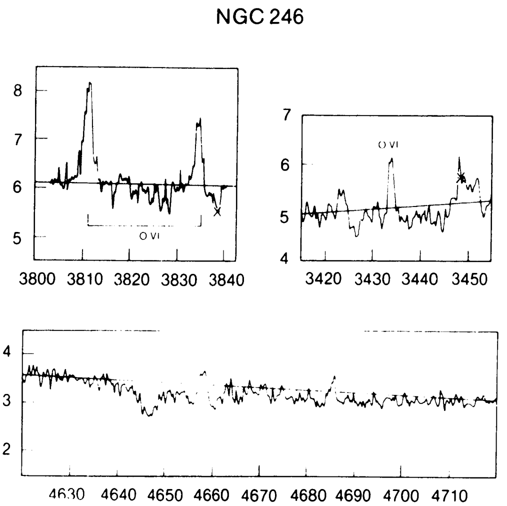

Figure 1. Photographic spectrum of a C-type star, the nucleus of NGC 246 (from Heap 1975). The spectrum differs from that of a WC star by the presence of absorption lines (primarily C IV) and the sharpness of the emission lines.

A 30 and A 78) have a mixed absorption-emission line spectrum. I have designated stars with mixed spectra as C (as opposed to WC) or N (as opposed to WN). I used the excitation of the emission lines only to determine the spectral types, so as to remain consistent with the classification of WR stars. Second, there is a wide range in the general level of excitation of the OVI stars (Figures 2, 3): in some OVI stars, such as IC 1747 or IC 2003, the OVI doublet at λ3811 - 34 (χ_u = 83 eV) is weak and represents the highest excitation state in the spectrum; in other OVI stars, such as NGC 5189, high-n lines of OVI at 3434 (χ_u = 128 eV) and at λ5292 (χ_u = 130 eV) are present, which suggests that the OVI emission lines are recombination lines from O^{+6}; and finally, in a few central stars, such as the nuclei of NGC 6905 and NGC 7026, OVII lines at λ3887 and λ5670 are actually present. Spectra having one of these three levels of excitation among the OVI sequence correspond to spectral types, WC4, WC3, and WC2, respectively. A third distinction among OVI stars is that while the spectra of most are dominated by carbon and oxygen, the spectra of several nuclei, such as NGC 6751 and Abell 78, show moderately strong nitrogen lines in the photographic and visual regions of the spectrum. I have designated such spectra showing a mixture of C and N lines as WC-WN.

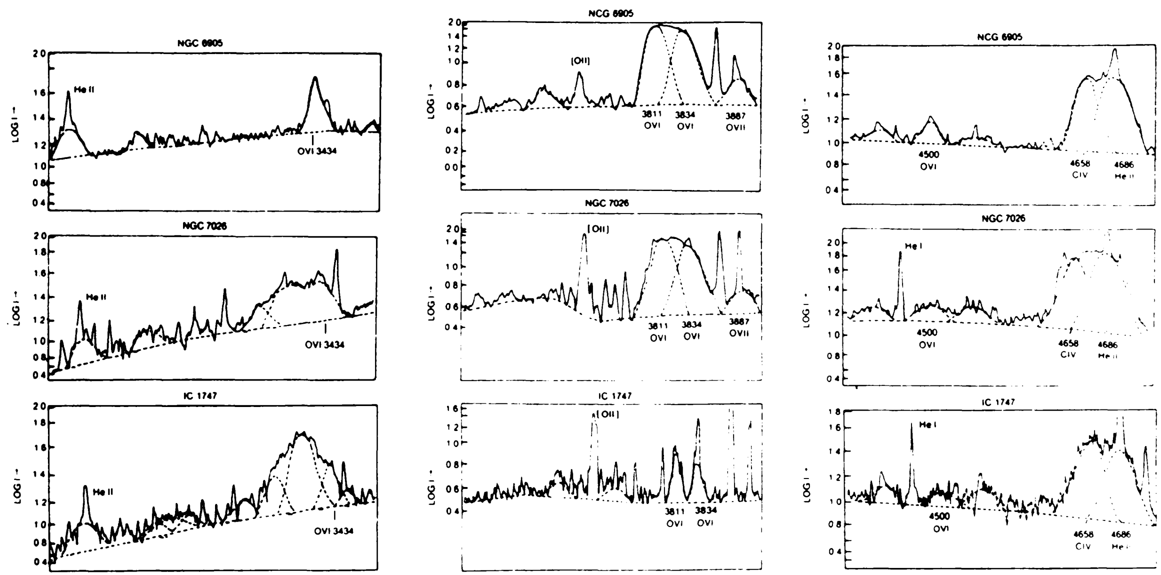

Figure 2. Photographic spectra of three WC/OVI stars. The tracings are taken from Aller (1968) with new line identification superposed. Sharp, low-excitation lines, such as [OII] λ3727, are nebular in origin.

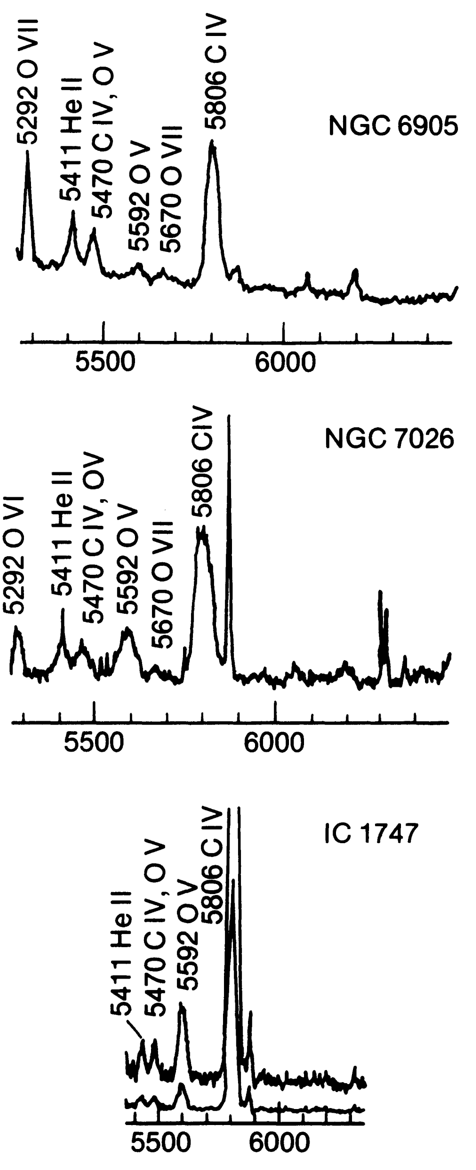

Figure 3. Visual spectra of three WC/OVI stars. The tracings are taken from Aller (1977) with new line identifications superposed.

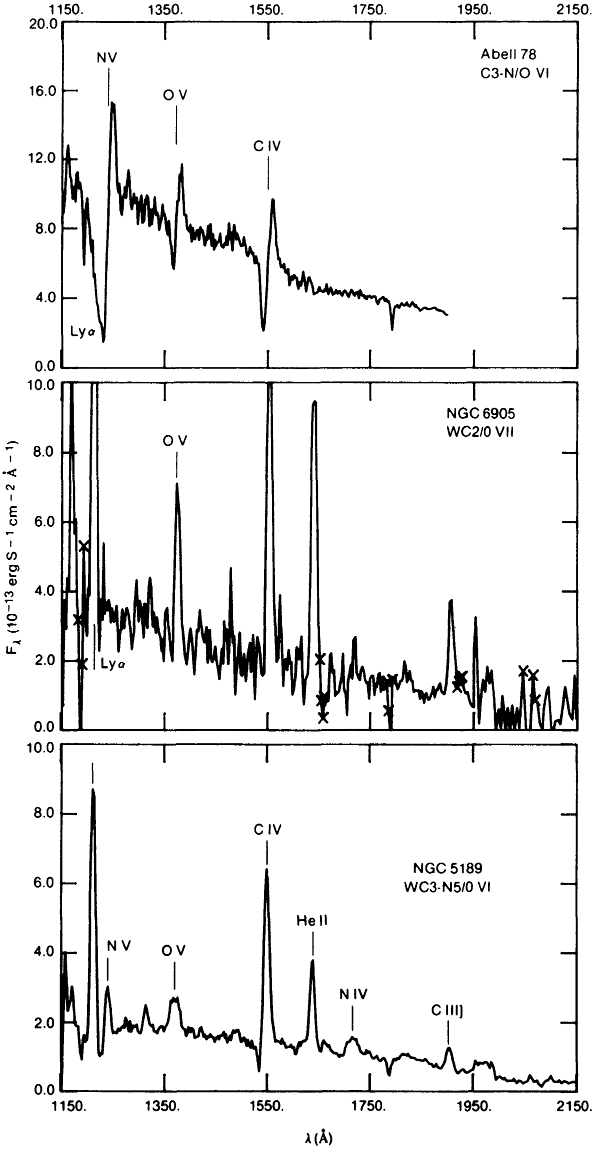

Figure 4. Ultraviolet spectra of three stars of the OVI sequence. The spectral data were obtained with the IUE satellite.

Most of these distinctions among OVI stars carry over into the ultraviolet (Figure 4): the dominant features of C or C-N stars (e.g., Abell 78) have P Cygni profiles rather than pure-emission line profiles; and the resonance doublet of NV λ1240 becomes a strong or even dominant wind feature in the WC-WN stars (e.g., NGC 5189) and C-N stars (e.g., Abell 78). Differences among OVI stars in the general level of excitation, however, are hard to detect in the ultraviolet. I have searched the UV spectrum of NGC 6905 for the really high-excitation lines, such as CV λ2277, or OVI λ2070, with no success. Probably, high-dispersion spectra or even low-dispersion spectra having high S/N will reveal these high-excitation lines.

Recent discoveries of low-excitation, compact planetary nebulae with WR-type nuclei have led to the extension of the WR sequence to types later than are known among massive WR stars. So far, four WC10 or WC11 central stars are known (Carlson and Henize, 1979; Webster and Glass, 1974; van der Hucht and Conti, 1971).

My new spectral classification for Wolf-Rayet central stars is given in column 2 of Table 3. The two main points to be drawn from this list are, first, most Wolf-Rayet central stars are WC or C stars with only a few WC-WN or C-N stars. No purely WN-type central star is known now that M1-67, which was on Smith and Aller's list, has been deleted from the list of bona-fide planetary nebulae (Kohoutek, 1978). Second, the general level of excitation among Wolf-Rayet central stars spans a tremendous range -- from WC 11 up to WC 2. These two characteristics, the prevalence of carbon and the diversity of excitation, can be explained in the light of current evolutionary models for central stars (Renzini and Voli, 1981).

III. CALIBRATION OF SPECTRAL TYPES

a. Absolute Magnitudes

In the late 1960's, Liller and Shao (1970) determined UBV magnitudes of the 150 brightest central stars. Among them are 11 Wolf-Rayet stars (column 6 of Table 1). The results of this photometric survey, which used special filters to exclude the strong nebular lines, represent a major improvement over earlier photographic magnitudes of central stars. In addition, estimates of distances to planetaries have been improved. In fact, at the most recent IAU smposium on planetary nebulae, Liller (1978) remarked,

> "At the Tatranska Lomica meeting 10 years ago [in 1966], there seemed little hope that one day soon planetary nebulae distances would become reliable. That day is near if not here already."

Well, as it turns out, several reliable distance surveys are now here, and the only problem is that the distance scale of different surveys

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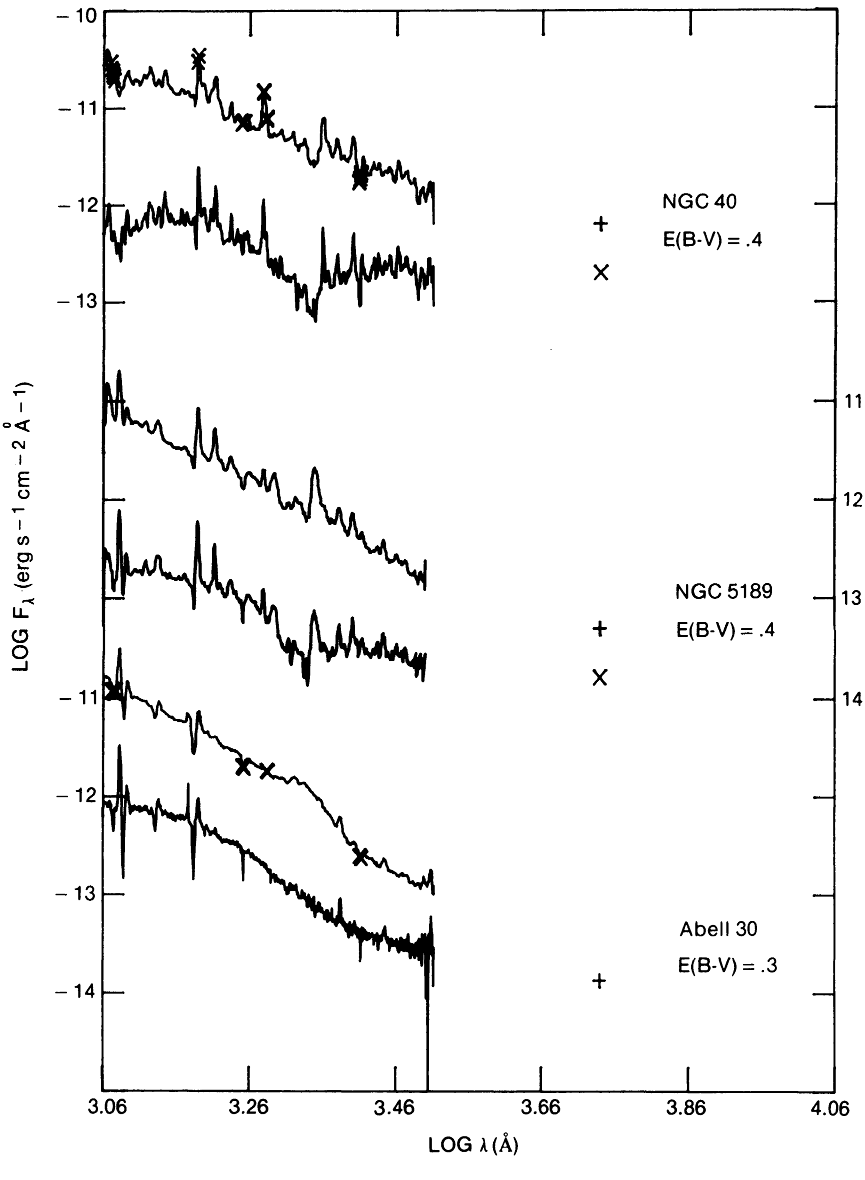

Figure 5. Continuous flux distributions for three central stars, the nuclei of NGC 40 (WC 8), NGC 5189 (WC 3), and Abell 30 (C 3). For each object, the observed and unreddened ultraviolet flux distributions are shown, as well as the flux corresponding to the observed (X) and unreddened (+) V magnitude. The flux distribution of Abell 30 is peculiar. Greenstein (1980) attributes this peculiarity to extinction by carbon soot in the nebula.

varies up to 60%! I have chosen to work with Cudworth's (1974) distances, which has one of the large distance scales. These distances and photo-electric magnitudes allow a consistent determination of the absolute magnitudes of WR-type central stars. The main result of this determination, listed in column 3 of Table 3, is that the absolute visual magnitudes of WR central stars are correlated with spectral type, with the early-type stars being up to 4 magnitudes fainter than the late-type stars. This variation, I will argue, is largely an effect of temperature: WR-type central stars have similar bolometric luminosities, but early-WR stars are hotter, so they have larger bolometric corrections, and therefore, fainter absolute visual magnitudes than do late-WR stars.

b. Temperature

Temperatures of central stars are usually estimated from the continuous flux distribution, with the use of some model (usually a blackbody) relating the flux distribution with effective temperature. One method of determining the continuous flux uses the nebula as a counter of ionizing photons from the central star and yields an EUV color temperature. Examples of this method are the Zanstra method (e.g., Harman and Seaton 1966) and the method of ionization balance, recently applied by Natta et al. (1980). The direct method uses the slope of the observable continuum to derive an ultraviolet or visual color temperature. Improved values of color temperature are possible now that ultraviolet fluxes from the ANS satellite (Pottasch et al. 1978) or the IUE satellite are available. The improvement offered by ultraviolet data results both from broadening the baseline of the color measurement and from having a direct estimate of the amount of interstellar extinction from the strength of the λ2200 extinction bump (see Figure 5). Even so, temperatures derived from (unreddened) flux distributions are in error to the extent that the nebula alters the flux distribution through emission, particularly Balmer continuum and 2-photon emission (e.g., Bohlin et al. 1978), and through extinction by nebular dust (e.g., Moseley 1980, Greenstein 1980) and gas such as H_2^+ (Heap and Stecher 1981). Because the effect of these alterations is smallest in the far-UV, I have weighted the short-wavelength fluxes obtained from IUE most highly.

Table 4 lists temperatures of Wolf-Rayet central stars as determined by the various methods. Despite the uncertainty in any one determination, it is clear that the ionization state of the wind (as specified by the spectral type) is correlated with stellar temperature (as specified by the Zanstra temperature). (I interpret the Zanstra temperature as the most reliable indicator of stellar temperature, since it is based on a major fraction of the star's continuous flux.) The UV-visual color temperatures show little relation to spectral type and, in general, are significantly lower than the Zanstra temperatures. I interpret this apparent discrepancey as an indication that, as is the case for massive WR stars (Schmutz, this volume; de Loore et al., this volume), the UV-visual continuum is actually formed in the WR wind.

TABLE 3

Properties of WR-Type Central Stars

ID	Spectral Type	M_V	M_{bol}	T	L	M	log g	V_{esc}	V_∞/V_{esc}
A 30	C 3-N 2/OVI	+2.8	-5.40	150	11170	.72	5.84	1272	3.9
A 78	C 3-N 2/OVI	+1.9	-5.2	110	9290	.68	5.36	951	4.8
NGC 246	C 3/OVI	+3.2	-5.00	150	7730	.65	5.96	1330	> 2.4
NGC 6905	WC 2/OVII	+2.8	-4.80	125	6430	.63	5.71	1140	
NGC 7026	"	+2.3	-5.30	125	10200	.69	5.55	1065	
NGC 2371	WC 3:/OVI	+2.6	-4.2	100	3700	.58	5.52	1000	
NGC 1501	WC 4/OVI	+0.5	-5.4	75	11170	.71	4.63	632	
IC 1747	WC 4/OVI	+0.4	-5.5	75	12250	.73	4.60	625	
NGC 6751	WC 4-N 4/OVI	-0.6	-5.7	60	14720	.77	4.16	490	
NGC 40	WC 8	-1.8:	-5.2	35	9290	.68	3.37	300	
BD +30°	WC 9	-1.0	-4.0	30	3080	.57	3.50	310	3.5

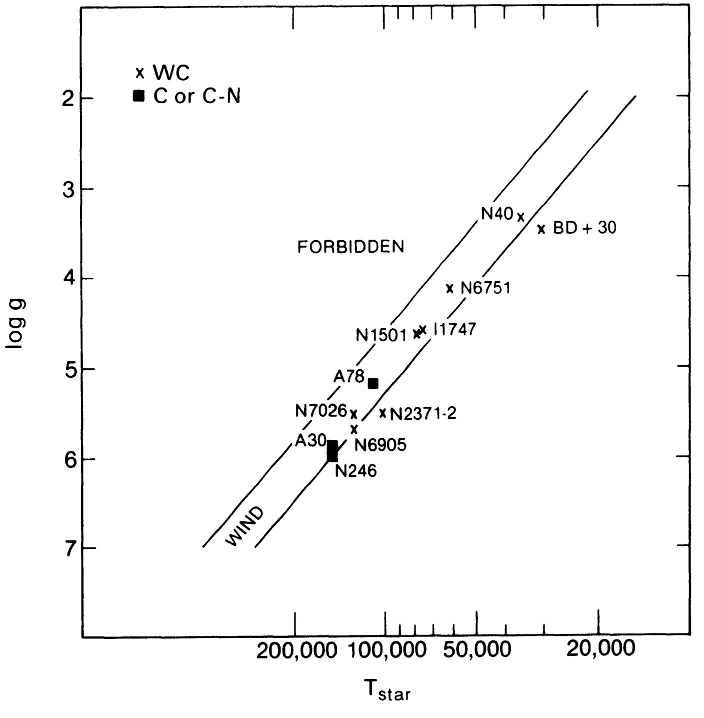

Figure 6. Temperature - gravity diagram for C and WC-type central stars.

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TABLE 4

Estimates of Stellar Temperature (in 10^3 °K)

ID	Spectral Type	Zanstra $T_z(HI)^1$	Method $T_z(HeII)^1$	UV-V ANS[2]	Continuum IUE[3]	Other
A 30	C3-N2				$\geq$ 100	100-200 Greenstein (1980)
A 78	C3-N2			140	$\geq$ 80	
N 246	C3	> 68	> 130	100		≈150 Heap (1975)
N 5189	WC 2				80	
N 6905	WC 2	> 64	110		50	
N 7026	WC 2	78	106			
N 2371-2	WC 3	> 61	121	∞	12:[5]	96 Natta et al. (1980)
N 2867	WC 3				30	
I 2003	WC 4				80	> 30 Natta et al. (1980)
N 5315	WC 6				50	
N 40	WC 8	> 30	...	30	30	
BD +30°	WC 9	16[4]	45	30		29 Natta et al. (1980)
CPD-56°	WC 10	26[4]			22[4]	

[1]Zanstra temperatures based on data from Liller and Shao (1970), Kaler (1976), and O'Dell (1963). The hydrogen Zanstra temperature, $T_z(HI)$, underestimates the stellar temperature if the nebula is optically thin to H-ionizing radiation.

[2]Values taken from Pottasch et al. (1978).

[3]Values based primarilly on the slope of the unreddened continuum within the SWP (1200 - 1950 Å) region and between the SWP and visual regions.

[4]Houziaux and Heck (this volume).

[5]Visual binary? The temperature listed refers to the composite.

c. Luminosity and Mass

Table 3 lists adopted temperatures, bolometric luminosities, and masses (Eq. 1) for WR stars whose absolute visual magnitude is known. Since the dispersion in luminosity and mass is relatively small, we may talk about a typical WR central star as having a luminsity of about 9000 $L_{\odot}$ and a mass of about 0.65 $M_{\odot}$. This means that the typical WR central star has a large luminosity-to-mass ratio. This ratio is important because it serves as an empirical criterion for the presence of a wind (Heap 1979, Lamers 1981). This point is illustrated in Figure 6, a temperature-gravity diagram for Wolf-Rayet central stars. Two lines of constant L/M are superposed on the figure: the line for L/M = 50,000 defines the Eddington limit, and the line for L/M = 11,000 is the empirical criterion for a wind. As expected, Wolf-Rayet central stars lie in the wind region or very close to it.

One exception that would seem to prove the rule is the nucleus of NGC 246 (C3). Its visual spectrum (Heap 1975) shows no evidence for a wind: the widths of the emission lines correspond to velocities far below the star's escape velocity (about 1300 km/s). The ultraviolet spectrum of the star, however, does show evidence for a weak wind in that the CIV resonance doublet has a P Cygni profile (Figure 7). The edge velocity of the wind is 3200 km/s or about 2.4 times the escape velocity, but the edge velocity must surely underestimate the terminal velocity of the wind since the P-Cygni feature is so weak.

IV. CHARACTERISITICS OF THE WIND

a. Velocities

It is a well-documented fact that the emission lines in the spectra of young WC stars are broader in early-WR stars than in late-WR stars. In fact, the classification of WC stars (Smith 1968) uses the width of the carbon λ4650 emission feature as a criterion for spectral type. A similar relation holds for WC-type central stars as well. Figure 8 shows the velocity corresponding to the full width of the C IV 5806 doublet in the spectra of WC- and C-type central stars and for young, massive WC stars. Notice that the characteristic velocity of the wind, as represented by the C IV feature, increases to earlier spectral types and that it is smaller in central stars than in young WC stars of the same spectral type. Both correlations can be explained in terms of the physical properties of WR central stars if you accept the notion that the characteristic wind velocity in a WR star is related to the escape velocity, as is the case for winds in O stars (Abbott 1978). Let me describe the reasoning.

i. Wind-velocity vs. Spectral Type. The course of evolution of central stars toward the white dwarf stage is one of increasing effective temperature at an approximately constant luminosity, which is set by the star's mass (Paczynski 1971). As the star gets hotter and smaller, its escape velocity increases according to the formula,

$$V_{esc} = \left(\frac{M^2}{60000\ (M - 0.522)} \right)^{\frac{1}{4}} \left(\frac{V_{esc}\ (\odot)}{T(\odot)} \right) T_\star\ . \qquad (2)$$

To say that the characteristic, or terminal velocity (v_∞) of the wind scales with the escape velocity completes the chain of logic relating the wind velocities of WR central stars with their effective temperature or spectral types.

There is some (rather sparse) observational evidence, as shown in Figure 8, that the escape velocity and terminal velocity are related:

$$v_\infty \approx 4\ V_{esc}\ , \qquad (3)$$

so that,

$$v_\infty = b_m\ t \quad \text{km/s}\ , \qquad (4)$$

where t is T/10000, and the constant b_m is 480, 380, and 340 for central stars of mass 0.55, 0.60, and 0.70 $M_\odot$ respectively. This equation says that we should expect a general trend of increasing wind velocity toward higher temperature, but that there should be considerable scatter in the trend because of the dispersion of central-star masses.

ii. Wind velocity vs. Mass. The characteristic wind velocity, as represented in Figure 8 by the full width of the C IV 5806 doublet, is about twice as large in young, massive WC stars as in WC-type central stars of the same spectral type. Since spectral type implies a unique temperature and gravity, it follows that the escape velocity scales as $M^{\frac{1}{4}}$ in stars of the same spectral type. If we take the masses of young WC stars as 12 - 25 $M_\odot$ and the masses of WC central stars as 0.6 - 0.7 $M_\odot$, then young WC stars should have escape velocities that are 2.0 to 2.5 times that of WC central stars of the same spectral type.

b. Line Profiles

We can be more specific in comparing the winds in late-WC stars, since both the central star, BD + 30° 3639, and the young WC star whose spectrum it imitates, HD 164270, have been observed with the IUE at high dispersion. Figure 9 shows sample line profiles in the two spectra. The similarity in line profiles supports Smith and Aller's (1971) conclusion that the wind of the central star is simply a scale model of the wind of the massive WC star.

There are other important features that characterize the P Cygni profiles in these two late-WC stars. First, lines of widely different ionization states yield the same value for the terminal velocity of the wind. This fact implies that these ions are distributed throughout the

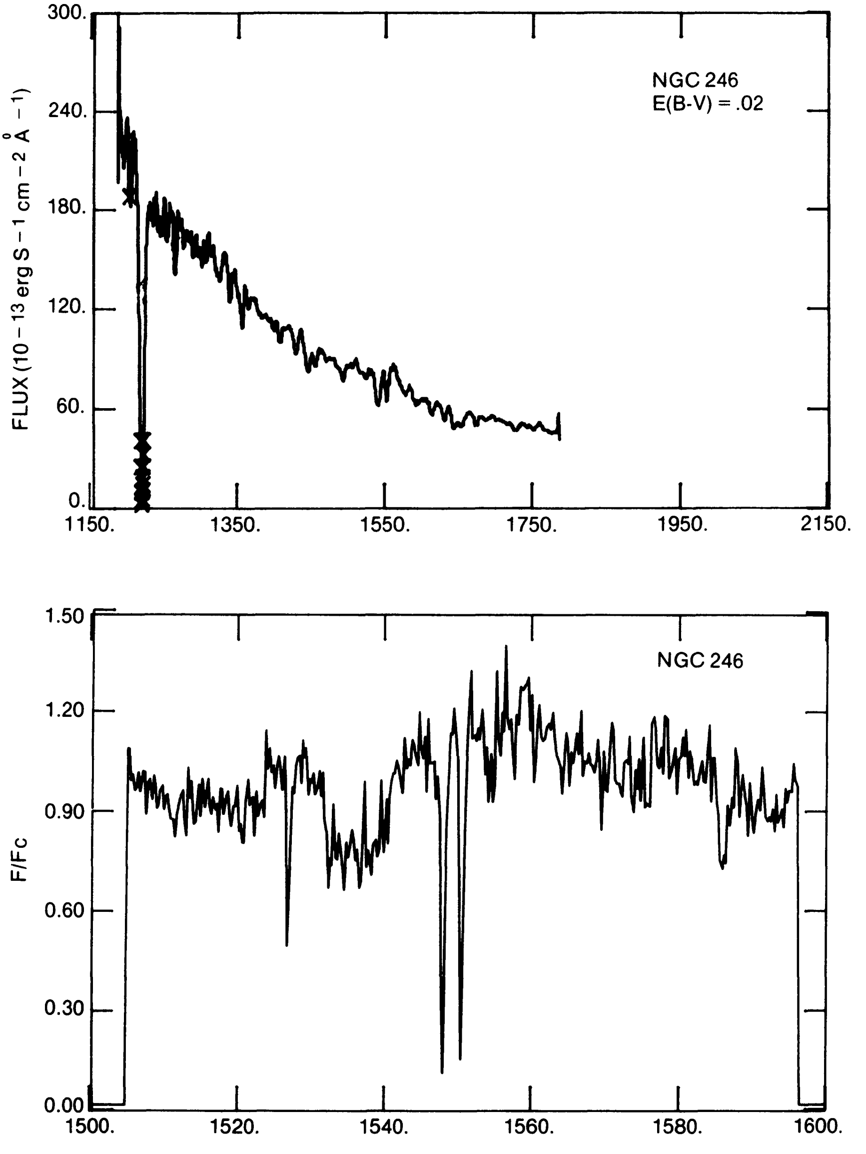

Figure 7. IUE spectra of the central star of NGC 246. The upper figure shows the unreddened flux distribution of the central star. The lower figure shows the CIV resonance doublet.

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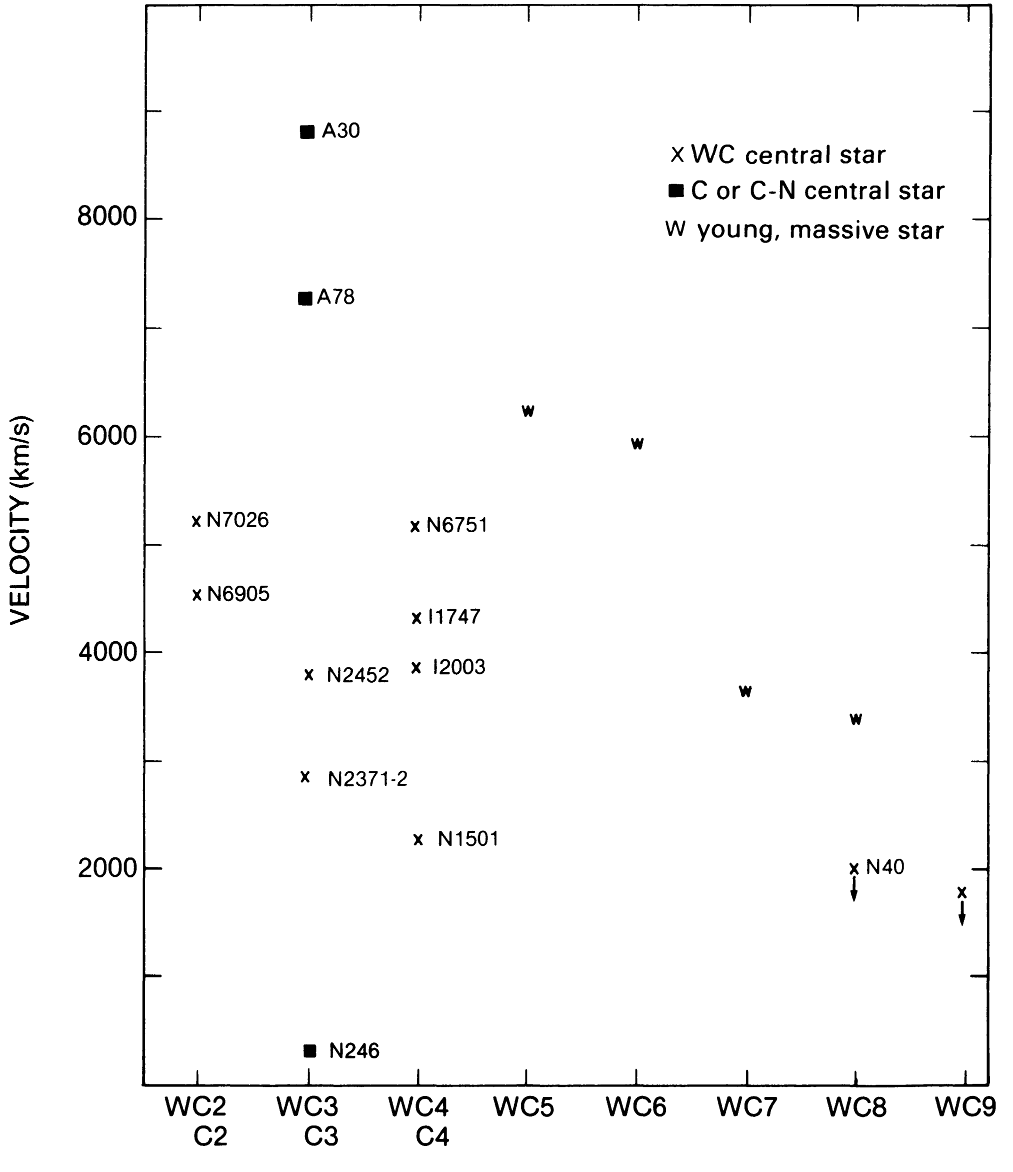

Figure 8. Wind velocities for WR stars as indicated by the full widths of the CIV λ4658 emission features. Young WR stars, for which the data were taken from Kuhi (1973), are denoted by the letter W.

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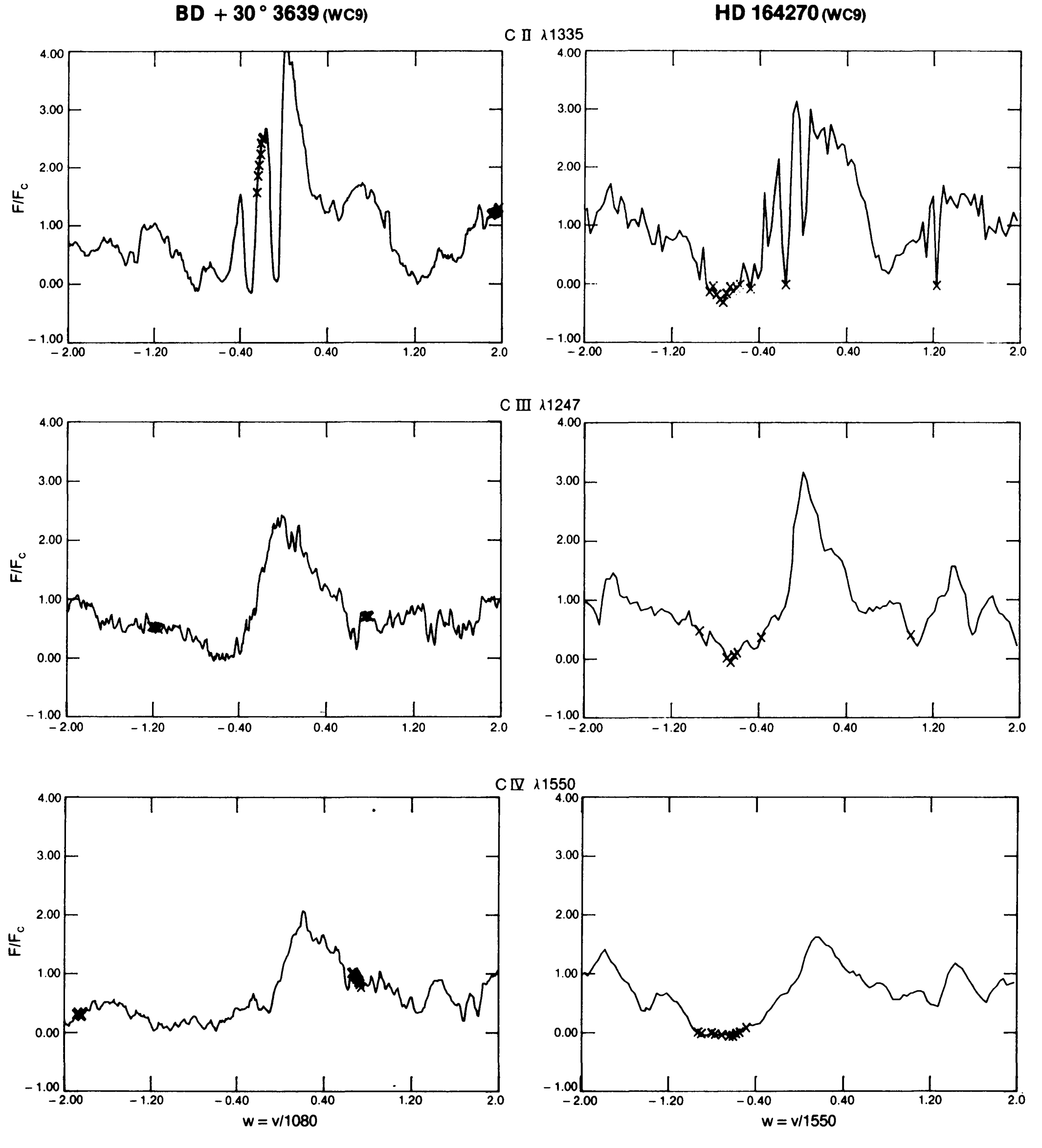

Figure 9. Selected line profiles in the spectrum of two WC 9 stars.

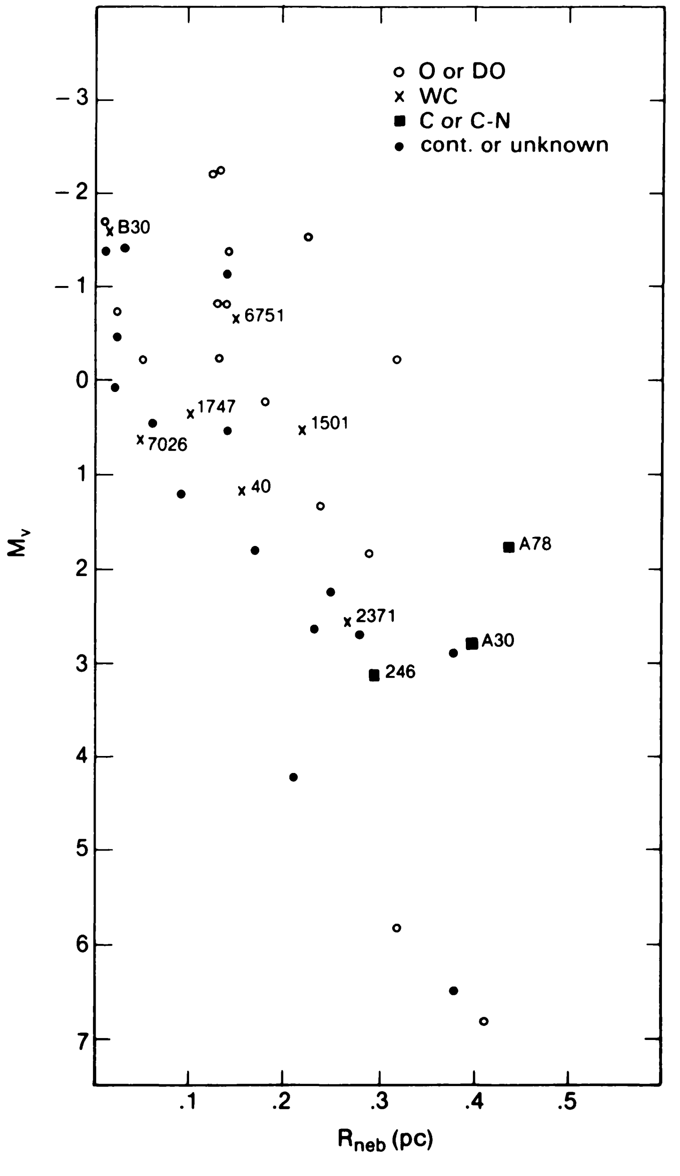

Figure 10. Absolute magnitude diagram for central stars of known magnitude (Liller 1970) and distance (Cudworth 1974).

wind rather than stratified according to ionization potential. Secondly, the long-wavelength edge of the emission component extends little more than half way to the terminal velocity. This concentration of emission to low velocities is too great to be explained by occultation. Instead, it suggests a two-stage velocity law like that derived by Rumpl (this volume) for the young WR star, HD 50896. Thirdly, the emission component of strong P Cyngi feature is stronger than the absorption component. Its great strength suggest a wind so dense that thermal emission plays a role.

V. EVOLUTION OF WR CENTRAL STARS

The observational data shown in Figure 6 indicate that WR-type central stars form a sequence of high L/M with temperatures ranging from roughly, 20,000^{o}K to possibly 200,000^{o}K. The high L/M of WR central stars implies that they are in the stage of traverse from the red-giant branch to the white-dwarf sequence. Evolutionary tracks for central stars approaching the white-dwarf stage run from upper right to lower left in Figure 6 parallel to one of the constant L/M lines, with stars in the range, 0.7 $M_{\odot}$ to 1.44 $M_{\odot}$ (Chandrasekhar's limit) confined to the wind band. The WR spectral sequence may therefore be viewed as an evolutionary sequence in the sense that early-WR stars are at a more advanced evolutionary state than late-WR stars. However, the WR sequence is <u>not</u> an indicator of age, since the rate of evolution is so highly dependent on mass. That early-WR central stars are not necessarilly older than late-WR central stars is shown in Figure 10. Two WR stars of the same age -- for example, NGC 40 (WC 8) and NGC 6751 (WC-WN/OVI) -- may have widely different spectral types. And two stars of similar spectral types -- for example, BD +30° 3639 (WC 9) and NGC 40 (WC 8), or the two OVII nuclei of NGC 7026 and NGC 6905 -- have very different ages. Perhaps, the only generalization that may be made is that C and C-N central stars are all old.

VI. DISTINCTIVE PROPERTIES OF WR CENTRAL STARS

With the exception of a few stars like the nucleus of NGC 6543, that are truly "bi-spectral," it is easy enough to tell a WR star from an O star by the appearance of its spectrum. It is harder to tell how a WR star differs physically from an O star. Evidently, rate of mass-loss is not the sole distinguishing factor. At least among massive, hot stars, there exist some Of stars that are losing mass as fast as some WR stars (Conti, this volume). Nor are the atmospheric parameters, temperature and gravity, or L/M ratio the distinguishing factors, since the cool end of the wind band of Figure 6 is populated by both late-WC stars and by Of stars.

The lack of decisively unique atmospheric properties of WR central stars makes for a null conclusion, but it may be helpful as a pointer directing our attention to fundamental stellar properties: mass, chemical composition, and angular momentum. For a central star, these properties refer to, or witness, the interior properties of the progenitor red-giant at the time of ejection of the planetary nebula. Since nebular ejection strips away all but 10^{-3} $M_\odot$ or less of the envelope (Paczynski, 1971), the mass and rotational velocity of a central star are effectively the core-mass and core-velocity of the progenitor red-giant, and the chemical composition of the atmosphere of a central star is that at or near the core-envelope interface. Hence, by analyzing the fundamental properties of central stars, we are examining our original hypothesis that the key to the Wolf-Rayet phenomenon lies in the process by which a star loses its outer, H-rich envelope. Let me describe what is known or hypothesized about the fundamental properties of WR-type central stars.

a. Mass

Although there is a considerable region of overlap in Figure 10, WC stars are statistically fainter visually than O stars of the same age. If this separation by visual luminosity is real, it implies (Schönberner 1981, Fig. 8) that WR central stars are more massive than O-type central stars. And since core-mass increases with original mass, we might then expect that WR-type central stars are derived from more massive stars than are O-type stars. There are some suggestions (and only suggestions) that this is so. Some time ago, Cudworth (1974) showed that central stars are heterogeneous in population type. Two distinct classes of planetaries may be defined with "Class-B" central stars kinematically younger and hence originally more massive than "Class-C" central stars. As it turns out, this division according to population type follows along the line of division by spectral class: WC-type central stars belong to Class B, while absorption-line stars, O, C, and C-N-type central stars, preferentially belong to Class C. Hence, WC-type central stars were originally more massive than O-type central stars.

b. Rotation

What makes the distinction by population type intriguing is that the classes were defined by Grieg (1971) on the basis of nebular morphology. Class-B nebulae, by definition, are bilaterially symmetric with the brightest (most dense) regions lying along or at the ends of the minor axis of the nebula. Class-C nebulae are more radially symmetric, often annular or disk-shaped in appearance. There may be a good reason why WR central stars are embedded in nebulae with a bilateral structure, and that reason involves rotation. Rotationally-enhanced mass-loss has been discussed for a long time in connection with young WR stars and has recently been revived by observations indicating a concentration of the wind toward the equatorial plane (Rumpl 1980). If rotation plays a role in the progenitor of a WR-type

https://doi.org/10.1017/S0074180900029181 Published online by Cambridge University Press

central star, then rotationally-enhanced ejection would result in a nebula initially concentrated in a plane, and the wind of the newly-exposed WR star would exacerbate the assymmetry (Matthews 1978) by pushing out most effectively the less-dense polar regions.

c. Chemical Composition

Spectra of WR-type central stars are of two types (Section II): those dominated by carbon (WC and C-type spectra), and those in which carbon and nitrogen are of comparable strengths (WC-WN, C-N spectra). The conditions in the interiors of red giants necessary to produce these two types are described by Renzini (this volume).

In summary, let me generalize the arguments I have made in this talk. Although the WR phenomenon may occur in stars of any mass, it is limited to stars that have been stripped (or mixed) down to their cores. However, the fact of prior envelope-loss is not sufficient to predict which stars will develope WR characterisitics. Instead, a comprehensive description of envelope-loss, including a detailed accounting of interior conditions and processes at the core-envelope interface, will be necessary to explain the onset of WR characteristics.

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DISCUSSION FOLLOWING HEAP

Underhill: I should like to remark that the energy distribution of BD+30°3639, found from high resolution IUE spectra, is flat between 1300-3000 Å. There is no 2200 Å absorption dip and the shape of the observed energy curve, uncorrected for interstellar extinction, corresponds to the energy distribution of a star with effective temperature near 10000 K, not 30000 K as your analysis suggests for this star.

Smith: Can a theoretician remind me of the stability limit for a pure C C-burning star.

Maeder: 1.4 $M_{\odot}$.