

THE ANGULAR DIAMETERS, EFFECTIVE TEMPERATURES, RADII, AND LUMINOSITIES OF 10 WOLF-RAYET STARS

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ABSTRACT

Absolute continuum energies determined from *IUE* high-resolution spectra are combined with continuum energies determined from published visible-range photometry and spectrophotometric scans to find angular diameters and effective temperatures for 10 Wolf-Rayet stars: HD 50896, 92740, 93131, 96548, 151932, 165763, 184738, 191765, 192103, and 192163. On the whole, the new results confirm the results achieved previously using less satisfactory ultraviolet fluxes. The effective temperatures of eight of the Population I Wolf-Rayet stars fall between 24,800 and 30,000 K; the effective temperature of HD 192163 is 39,900 K, while that of HD 184738, the central star of a planetary nebula, is 18,000 K. Distances are adopted, and linear radii and luminosities determined.

The dependence on the inherent errors in the observed fluxes and the distance moduli, as well as in the choice of model atmosphere to represent the radiation field from the photosphere of each star, is studied for each derived quantity, θ_λ , T_{eff} , $R/R_\odot$, and $L/L_\odot$. It is shown that typically the error in θ_λ may be $\pm 7\%$, that in T_{eff} may be $\pm 5\%$, that in $R/R_\odot$ may be $\pm 15\%$, while that in $L/L_\odot$ may be $\pm 91\%$. It is unlikely that any of the derived effective temperatures are in error by more than 10%.

Maximum velocities of outflow, determined from *IUE* spectra, are presented for 10 Wolf-Rayet stars, 13 O stars, 13 B type supergiants, and 2 A0 supergiants. These values show that v_∞ varies about as $\log T_{\text{eff}}^4$ from type A0 to O3. They confirm that the density of the continuum radiation field from Wolf-Rayet stars is similar to that from early B type stars, as is indicated by the similar effective temperatures found for Wolf-Rayet and early B stars. It is noted that until it is possible to relate conditions in the line-forming region (mantle) of the atmosphere of a Wolf-Rayet star uniquely and unambiguously to information derived from the theory of stellar evolution, it will be impossible to use a Wolf-Rayet subtype as an index to the stage of evolution of a star.

Subject headings: spectrophotometry — stars: atmospheres — stars: mass loss — stars: Wolf-Rayet — ultraviolet: spectra

I. INTRODUCTION

The effective temperature of a normal star with an absorption-line spectrum is a parameter which represents the total amount of radiative energy emerging from each square centimeter of surface of the star. It may be found from the integrated continuum flux from the star; it is an important parameter for indicating the stage of evolution of a star. Another important parameter is the radius of the photosphere of the star. When observed parameters are compared with the results of the theory of stellar evolution, the radius is usually combined with the effective temperature to determine the luminosity of the star in solar units, $\log L/L_\odot$.

In the case of a Wolf-Rayet star, the spectrum consists of a continuum and many emission lines, a few absorption troughs displaced shortward from the nominal wavelength for the line, and an infrared to radio-wavelength excess flux generated by free-free emission in low-density plasma surrounding the star. A characteristic feature of the spectrum of a Wolf-Rayet star is the presence of strong, rather broad emission lines from *high ions* of C, N, and O in addition to strong He II emission lines. To form the high ions requires electron temperatures of the order of 10^5 K; to account for the strong He II lines in Wolf-Rayet spectra also requires T_{eff} of the order of 10^5 K if radiative heating alone is invoked (Rublev 1975). However, it is known (Willis and Wilson 1978; Underhill 1980*a*, 1981) that the effective temperatures of Wolf-Rayet stars are of the order of 30,000 K. Consequently, since the theory of stellar spectra shows that electron temperatures exceeding the effective temperature of the star cannot occur in the outer atmosphere if an atmosphere is in radiative equilibrium

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(see, for instance, the model atmospheres by Mihalas 1972, Kurucz 1979, Mihalas and Hummer 1974, Kunasz, Hummer, and Mihalas 1975, and Gruschinske and Kudritzki 1979), we must infer that nonradiative heating is occurring in the line-forming atmospheres of Wolf-Rayet stars.

In addition the following should be noted. Castor (1970) has demonstrated (see his Fig. 2) that in order to obtain emission lines having the shapes of Wolf-Rayet lines, the density in the extended atmosphere must be such that there are few ions close to the photosphere, and many in the range from 1.3 to 3 R_* , and that the numbers decrease as r increases beyond 3 R_* . Such a distribution of high ions cannot be obtained without T_e being larger than T_{eff} in at least some parts of the outer atmosphere. This need also indicates that heating by nonradiative energy occurs in the outer atmosphere. The conclusion that nonradiative energy is deposited in the outer layers of Wolf-Rayet atmospheres is reached no matter how one models the outer atmosphere.

We shall estimate the effective temperatures of 10 Wolf-Rayet stars by integrating the *continuum* flux for these stars. We consider the line and free-free emission to be representative of nonradiative energy deposited in the outer atmosphere of the star. At most the additional amount of energy is equivalent to one-half the integrated continuum flux. Including it (wrongfully, in the author's opinion) in the energy used to find T_{eff} would increase T_{eff} by a factor $(1.5)^{1/4}$ or 1.107 from the results which are obtained in this paper.

Deposit of nonradiative momentum in addition to nonradiative energy near the critical point is necessary in order to *initiate* the outflow of a wind (Castor and Cassinelli 1973; Thomas 1973). After flow has been initiated, the force of radiation may accelerate the motion, much as has been calculated by Castor, Abbott, and Klein (1975). Absorption in the wind generates the shortward displaced absorption troughs which are seen in the spectra of Wolf-Rayet stars; see the discussion in Underhill (1983).

We shall denote by the word "mantle" the outer parts of the atmosphere of a star where the physical state is determined chiefly by the amount of nonradiative energy and nonradiative momentum deposited there; *cf.* Underhill (1980*b*, 1981); Underhill and Doazan (1982, chaps. 1, 4, and 8). The physical state of the outer part of the atmosphere is determined by different constraints than those which determine the physical state of the photosphere of a star. Consequently, the mantle must be modeled in a different way than is suitable for a photosphere. Requiring that radiative and hydrostatic equilibrium exist, and giving values for the composition of the atmosphere and the parameters T_{eff} and $\log g$, is insufficient to define the physical state of the mantle of a star. It is sufficient to define the physical state of the photosphere.

The effective temperature and angular diameter of a hot star may be determined by measuring the absolute flux from the hot star over a wide range of wavelength from ultraviolet to visible or near-infrared, and making use of the predicted spectra from model atmospheres which represent well conditions in the photosphere of the hot star. The method has been explained in Underhill *et al.* (1979) and in Underhill (1980*a*, 1981, 1982). Effective temperatures have been estimated by this method for nine Wolf-Rayet stars (Underhill 1980*a*, 1981). The published results confirm the conclusion of Willis and Wilson (1978), reached from considering the shape of the continuous spectra of Wolf-Rayet stars between about 1400 Å and 5000 Å, that T_{eff} is of the order of 30,000 K, no matter what the exact subtype of the Wolf-Rayet star. However, Underhill's results are somewhat uncertain because they make use of spectrophotometric information extending only to 1380 Å for five stars (Underhill 1980*a*) and to only 1550 Å for four stars (Underhill 1981).

Barlow, Smith, and Willis (1981) have adopted a blackbody energy distribution having a temperature of 25,000 K for describing the shape of the continuous spectra of Wolf-Rayet stars longward of 5500 Å. This choice was made because Nussbaumer *et al.* (1982) find for 13 Wolf-Rayet stars that the shape of the spectrum between 2000 Å and 5000 Å can be fitted by a blackbody having a temperature in the range $25,200 \pm 3700$ K.

The present paper uses new ultraviolet spectrophotometric data extending to 1250 Å, acquired by means of the *IUE* satellite, to make improved solutions for the effective temperatures of the nine Wolf-Rayet stars studied previously and to provide new results for HD 184738 = BD 30°3639, a Wolf-Rayet-type central star of a planetary nebula. The effective temperatures of HD 50896, 92740, 93131, 96548, 151932, 165763, 191765, and 192103 are found to lie in the range 24,800 to 30,000 K; T_{eff} for HD 184738 is 18000 K, and T_{eff} for HD 192163 is 39,900 K.

The method followed is summarized in § II. The observational material used is described in § III. Particular attention is directed to the problem of finding the absolute level of the continuous spectrum throughout the spectral range observed. Care is taken to ensure that the measured fluxes are contaminated as little as possible by line emission. The results for the 10 program stars are given in § IV, while in § V the expected uncertainty of the results is discussed.

The significance of the results is discussed in § VI. So far as T_{eff} , radius, and mass (Massey 1981) are concerned, Wolf-Rayet stars, like nine of the stars studied here, are very similar to early B type stars. The star HD 184738 is found to be small, $R = 1.6 R_\odot$, as is appropriate for the central star of a planetary nebula. The energy distribution in the continuum of this star is normal for a star with $T_{\text{eff}} = 18,000$ K. The flattened

energy distribution noted by Pottasch *et al.* (1978) for Wolf-Rayet-type central stars appears to be an artifact created by the neglect of appropriate corrections to the photometry for the energy radiated in lines. The fallacy of treating color temperatures, T_{BB} , which give a slope equivalent to the observed slope of the continuous spectrum near 1300 Å as being equivalent to the effective temperatures of the stars (Barlow, Smith, and Willis 1981) is noted. It is shown that the luminosities given by these authors for Wolf-Rayet stars generally are high, and it is argued that until it is possible to relate conditions in the mantle of a Wolf-Rayet star uniquely and unambiguously to information derived from the theory of stellar evolution, it will be impossible to use a Wolf-Rayet subtype as an index to the stage of evolution of a star.

II. METHOD

The method followed has been described several times since Underhill *et al.* (1979) published the first results attained in this way for early-type stars. Here we follow the formulation of Underhill (1982). There it is noted that angular diameter and effective temperature can be found from the following equations:

$$\theta_\lambda = 2[f_\lambda / \pi F_\lambda(\text{model})]^{1/2}, \quad (1)$$

and

$$\sigma_R T_{\text{eff}}^4 = \frac{4G(\text{model})}{\theta_\lambda^2} \int_{\lambda_1}^{\lambda_2} f_\lambda d\lambda, \quad (2)$$

where

$$G(\text{model}) = 1 + \left(\int_0^{\lambda_1} F_\lambda d\lambda + \int_{\lambda_2}^\infty F_\lambda d\lambda \right) / \int_{\lambda_1}^{\lambda_2} F_\lambda d\lambda. \quad (3)$$

Here, F_λ is the monochromatic flux predicted for a model atmosphere by Kurucz (1979), and λ_1 and λ_2 represent the limiting wavelengths between which the observed absolute fluxes are measured. The quantity f_λ represents the measured absolute flux from the continuum of the star at wavelength λ corrected for wavelength-dependent interstellar extinction. Graphical interpolation is used to find the required values of $A_\lambda/E(B-V)$ from the average interstellar extinction curve determined by Savage and Mathis (1979). A value for $E(B-V)$ is adopted for each star; see Table 2.

A model atmosphere is selected, and θ_λ and T_{eff} are derived from equations (1) and (2). The process is repeated for several choices of model atmosphere, and one solution, or one set of solutions in the case that more than one wavelength is used to estimate θ_λ , is selected as best. Usually the solution for which the

absolute value of the difference $\delta T = T_{\text{eff}} - T(\text{model})$ is the smallest, within a range of a few hundred degrees, is accepted as "best." Because of the uncertainties in the observed fluxes, it is wrong to attempt to make δT smaller than a few hundred degrees. The question of what constitutes a "best" solution has been discussed by Underhill (1982).

Equations (9), (11), and (8) of Underhill (1982) give, respectively, the uncertainties in $\log T_{\text{eff}}$, $\log R/R_\odot$, and $\log L/L_\odot$ resulting from uncertainty in the observed value for the integrated flux, ΔF_{obs} , and in the monochromatic flux used to find the angular diameter, Δf_λ , from uncertainty in the choice of effective temperature for the model atmosphere, ΔT ($\log g$ is assumed known; it is an insensitive parameter), and from the uncertainty in the distance modulus for the star, ΔMod .

In the present study λ_1 is 1250 Å. The upper limit for the observed wavelength range is $\lambda_2 = 11084$ Å for HD 50896, 165763, 191765, 192103, and 192163; it is 5500 Å for HD 92740, 93131, 96548, 151932, and 184738.

III. OBSERVATIONAL MATERIAL USED

Relative absolute ultraviolet continuum fluxes between 1250 Å and 3100 Å have been found for all of the program stars except HD 184738 from continua drawn on 2 Å per inch CalComp plots of small-aperture *IUE* spectra. The program stars and the *IUE* spectra used are listed in Table 1. The spectra were obtained from the National Space Science Data Center (NSSDC) and large-scale (2 Å per inch) CalComp plots were prepared at the Goddard Space Flight Center.

The ultraviolet spectra of Wolf-Rayet stars shortward of 1900 Å are full of emission lines. In this range of wavelength only small sections of spectrum, of the order of 2–4 Å long occurring every 25–50 Å, are found to be free of line emission. Placing the continuum accurately shortward of 1900 Å is difficult, and high-resolution spectra must be used. Regions of continuum were found

TABLE 1
ULTRAVIOLET OBSERVATIONAL MATERIAL USED

HD	IUE IMAGES		PERCENTAGE OF LIGHT IN CONTINUUM ALONE		
	SWP	LWR	[18]	[22]	[25]
50896 ...	2860	2538	0.97	1.00	...
92740 ...	1614	1549	0.96	1.00	...
93131 ...	1591	1527	0.98	1.00	...
96548 ...	1616	1550	0.55	1.00	...
151932 ...	2154	1923	0.77	...	1.00
165763 ...	2872	2548	0.78	0.73	...
191765 ...	2873	2530	0.90	1.00	...
192103 ...	2843	2529	0.70	1.00	...
192163 ...	2841	2528	0.99	1.00	0.95

by noting that apparent absorption dips should occur only at wavelengths where shortward displaced troughs from resonance lines from abundant species or from subordinate lines from low-lying levels of abundant species may be expected. Comparisons were made with the spectra of O stars and of early B type supergiants to find regions where line emission or absorption may be expected to be minimal.

Because the element of resolution of low-resolution *IUE* spectra shortward of 1900 Å is 6–7 Å, it is unsatisfactory to attempt to use low-resolution *IUE* spectra to determine the far-ultraviolet continuum energies of Wolf-Rayet stars. The apparent continuum will always be high owing to unresolved line emission.

Longward of 1900 Å, the ultraviolet spectra of Wolf-Rayet stars contain fewer emission lines than at short wavelengths. Between 1900 Å and 3100 Å, several stretches of continuum can be found, and it is relatively straightforward to define the level of the continuum both on high-resolution and on low-resolution *IUE* spectra.

Relative absolute energies can be determined from *IUE* spectra obtained with the small aperture by means of the calibration factors established by Cassatella, Ponz, and Selvelli (1981). It is essential to work from large-scale CalComp tracings in order to view long ranges of spectrum at one time at good resolution. The relative absolute energies may be put on an absolute scale by scaling to energies measured by means of the *ANS* satellite. The bandwidths, central wavelengths, and absolute-energy calibration of the *ANS* passbands are given by van Duinen *et al.* (1975). The *ANS* ultraviolet magnitudes of nine of the program stars of Table 1 can be found in van der Hucht *et al.* (1979). These are the values used; they differ slightly from those of Wesselius *et al.* (1982).

The *ANS* magnitudes measure the total energy in lines and continuum which is included in each rectangular passband. The equivalent widths of the lines in the bands used to calibrate the relative absolute energies from *IUE* small-aperture spectra were measured, and the percentage of the energy contained in the continuum was found. These numbers are given in Table 1. They have been used with the observed *ANS* energies in the [18], [22], or [25] bands to scale the *IUE* relative absolute energies to absolute energy. Observations made using SWP spectra were scaled using *ANS* observations in the [18] band. In all cases except HD 151932, observations in the [22] band could be used to scale the LWR spectra. In the case of HD 151932, the *IUE* spectrum is very weak, thus uncertain, at 2200 Å, so this spectrum is scaled using energy measured by means of the *ANS* [25] band.

The star HD 191765 has been noted by Wesselius *et al.* (1982) to be variable in the ultraviolet. We found scaling factors for this star which were not in accord with the results from the other stars. We used the *ANS*

observations of van der Hucht *et al.* (1979) to tie the SWP and LWR energies together and then scaled the full set of relative absolute energies to absolute energy by tying to the energies determined by Willis and Stickland (1981) from low-resolution *IUE* spectra at wavelengths longer than 2450 Å. The long-wavelength energies found by Willis and Stickland for HD 50896 and HD 192163 from low-resolution, large-aperture *IUE* LWR spectra agree within the photometric uncertainties with our results for these stars.

The degree of success at finding ultraviolet continuum energies for the Wolf-Rayet stars can be assessed by means of Figures 1–9. In these figures $\log f_\lambda$ in the ultraviolet, corrected for interstellar extinction, is plotted against wavelength. Also shown is the energy distribution from the Kurucz (1979) model atmosphere adopted as representative for the photosphere of the star, and the energy distribution from a model having $T_{\text{eff}} = 50,000$ K and $\log g = 4.5$. The models have been fitted together at about 3700 Å; their spectra longward of this to 6000 Å differ very little. A few of the adopted energies from ground-based observations (described in Underhill 1980a, 1981) are shown by crosses. The background

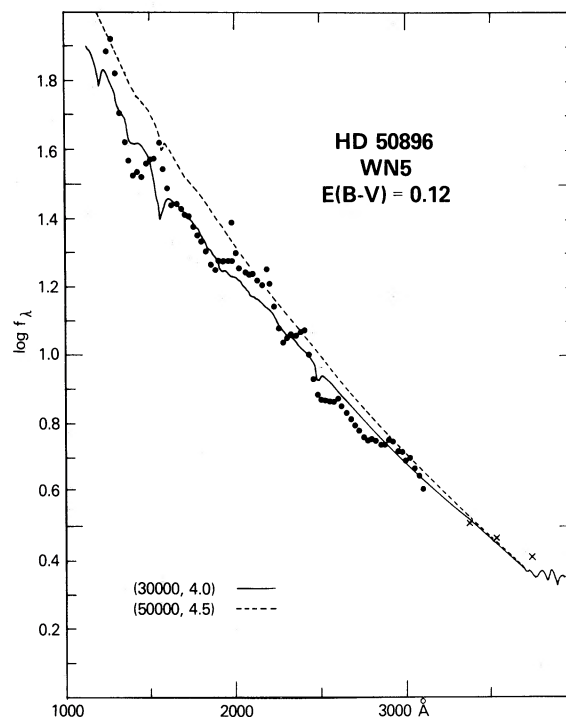


FIG. 1.—The energy distribution of HD 50896 (corrected for interstellar extinction) compared to model-atmosphere energy distributions. The unit of energy is 10^{-11} ergs $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$. The energies determined from *IUE* spectra are shown by small dots; the visible range energies are shown by crosses.

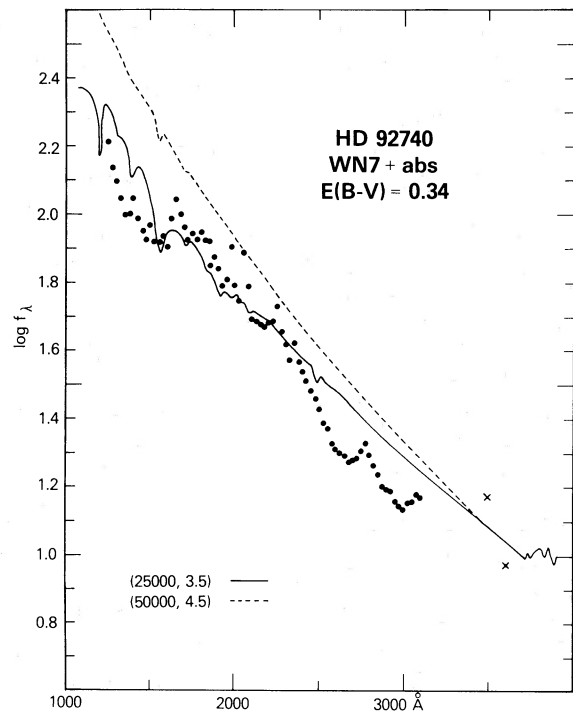


FIG. 2.—As in Fig. 1 for HD 92740

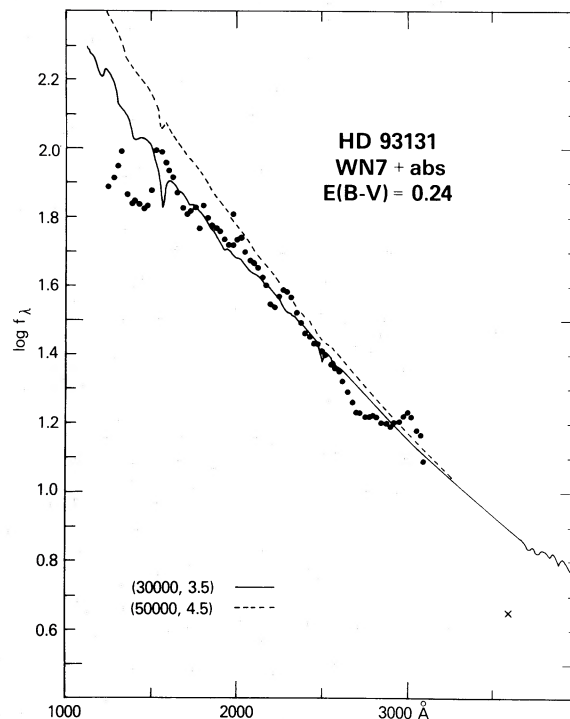


FIG. 3.—As in Fig. 1 for HD 93131

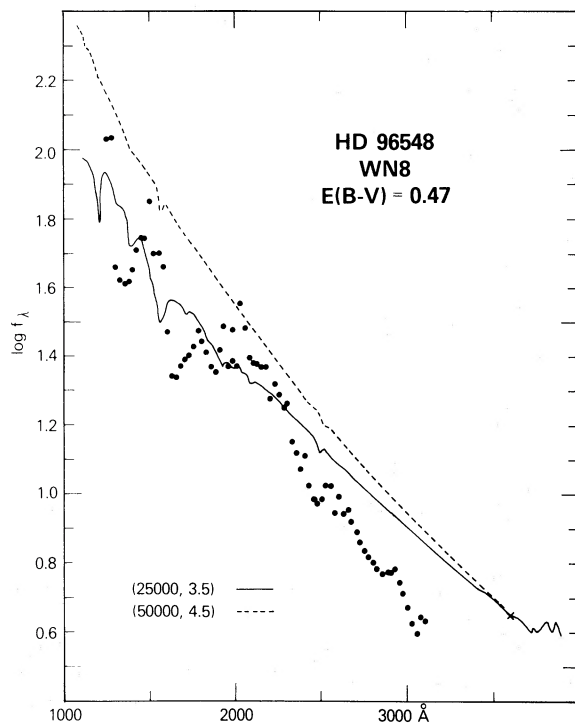


FIG. 4.—As in Fig. 1 for HD 96548

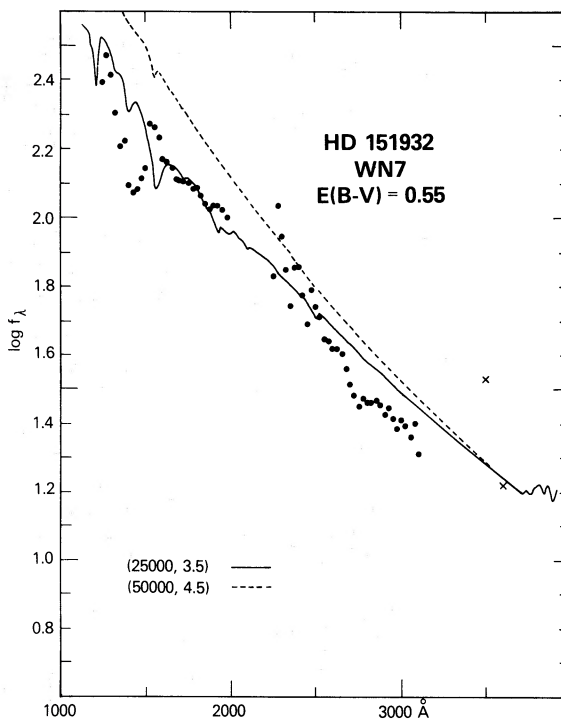


FIG. 5.—As in Fig. 1 for HD 151932

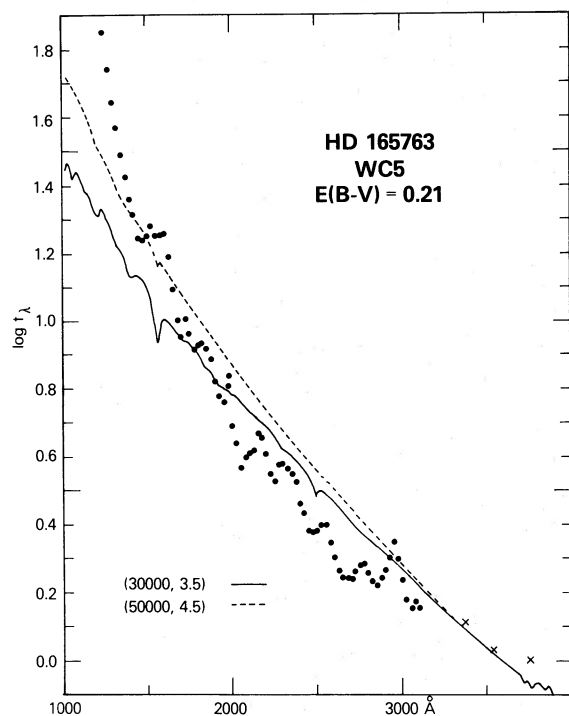


FIG. 6.—As in Fig. 1 for HD 165763

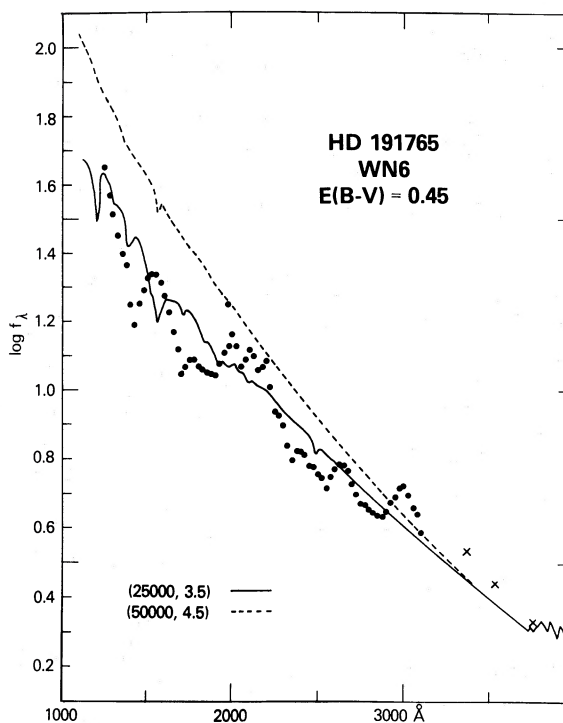


FIG. 7.—As in Fig. 1 for HD 191765

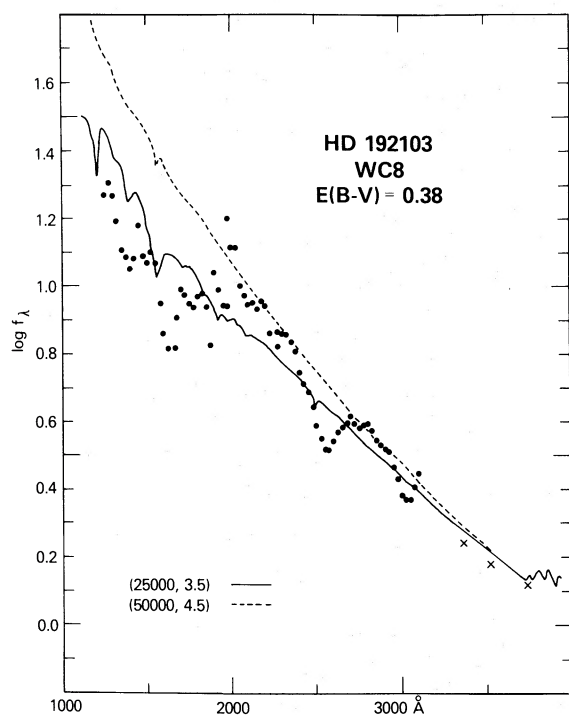


FIG. 8.—As in Fig. 1 for HD 192103

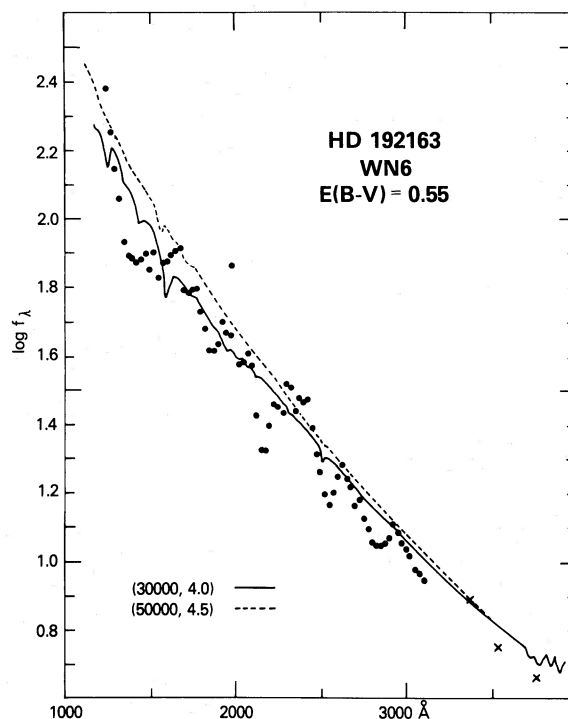


FIG. 9.—As in Fig. 1 for HD 192163

corrections applied to the short wavelength orders of each spectrogram are uncertain. Consequently, the continuum energies are more uncertain and subject to systematic error in the wavelength ranges 1250–1400 Å and 1975–2125 Å than they are elsewhere.

The scatter of the observed continuum energies about the predicted energy distributions correspond typically to an uncertainty $\Delta \log f_\lambda$ of the order of ± 0.1 . There are no systematic humps or dips in the region of the 2175 Å interstellar band suggesting that the adopted values of $E(B - V)$ are seriously in error. Some of the monochromatic fluxes have been estimated high, while others have been underestimated. Probably the uncertainty in each value for the integrated flux is of the order of $\Delta \log F_{\text{obs}} = \pm 0.15$. It is quite clear that the shapes of the continua from the program Wolf-Rayet stars correspond to the shapes of the spectra from the adopted model atmospheres. In most cases there is too little energy shortward of 1500 Å relative to the amount longward of 2500 Å for an effective temperature of the order of 40,000–50,000 K to be considered.

Comparing the shape of an observed stellar continuous energy distribution corrected for interstellar extinction with that predicted from a hot model atmosphere is a very inexact way in which to determine the effective temperature of a Wolf-Rayet star; see Underhill (1982, Appendix) for an application to early O stars. The result is sensitively dependent on the accuracy of the correction for interstellar extinction and on the accuracy with which the level of the continuum can be determined at short wavelengths. Often for Wolf-Rayet stars, the spectrum has been underexposed for the continuum level in order to avoid overexposure for the strong lines shortward of 1700 Å. This means that the level of the far-ultraviolet continuum is determined by low count rates, and that it is therefore very uncertain. Greater certainty is attached to determinations of T_{eff} which make use of integrated fluxes; see § IV.

The ultraviolet continuum energies of HD 184738 were determined from high-resolution, large-aperture *IUE* spectra. Large-scale (2 Å per inch) CalComp plots of SWP 8591, 13333, and LWR 7334 were made available by W. A. Feibelman; image LWR 6924 was obtained from the NSSDC, and a large-scale CalComp plot of it was prepared at the Goddard Space Flight Center. Continua were drawn on these CalComp plots and reduced to absolute energies using the calibration factors of Cassatella, Ponz, and Selvelli (1981). Then mean values were found from the two images in each spectral range at each 25 Å between 1250 Å and 3100 Å.

The spectrum of HD 184738 is full of stellar emission lines, many of low intensity, and it is difficult to find regions longer than 2–4 Å which are clear of lines. Most of the apparent stellar lines were identified, in order to confirm the placement of the continuum. It would be

very difficult, if not impossible, to determine the continuum of HD 184738 accurately working from low-resolution *IUE* spectra owing to the great density of stellar emission lines and the modest number of absorption troughs which occur. In addition, nebular lines are superposed on the stellar spectrum.

Continuum energies at 3600 Å, 4400 Å, and 5500 Å have been deduced from *UBV* photometry provided by J. B. Kaler. The gross photometric magnitudes provided by Kaler are from the unpublished work described by Liller and Shao (1968). They represent light from the star alone in the *U*, *B*, and *V* passbands. The gross energies were corrected for the light in stellar emission lines. This was done by planimetry of the stellar atlas presented by Smith and Aller (1971) in order to find the equivalent widths of the stellar emission lines in each passband and allowing for the sensitivity functions for the bands (Azusienis and Straizys 1969; Buser 1978). It is estimated in this way that 0.77 of the energy measured in the *U* band is due to the continuum of the star; in the *B* and *V* bands the fractions are 0.68 and 0.71.

The observed energies for HD 184738 are shown in Figure 10 as plot (*b*). Plot (*a*) shows the observed energies corrected for interstellar extinction scaled using $E(B - V) = 0.24$. This value of $E(B - V)$ was recommended by Pottasch *et al.* (1977). Plot (*c*) shows the observed energy distribution for α Lyrae determined from smoothed S2/68 ultraviolet energies (Jamar *et al.* 1976), and *uvby* and *UBV* photometry.

Use of $E(B - V) = 0.24$ for HD 184738 results in a significant hump at 2200 Å. The corrected energy distribution has, more or less, the shape of the energy distribution from a model atmosphere $T_{\text{eff}} = 20,000$ K. No correction for interstellar extinction, plot (*b*), results in a moderately smooth energy distribution with no significant depression in the 2200 Å region. The uncorrected ultraviolet spectrum of HD 184738 has the general shape of the ultraviolet spectrum from an A0 star; see plot (*c*). The visible spectrum of HD 184738 however, does not show a large Balmer jump such as is known for A0 V stars.

The solutions for θ_λ and T_{eff} were made using $E(B - V) = 0.20$. This value of $E(B - V)$ was selected after considering the information shown in Figure 10, the distance of 0.69 kpc determined by Acker (1978) for this star, and the relationships between distance and $E(B - V)$ in and near the plane of the galaxy found by Lucke (1978). The usual methods for determining $E(B - V)$ from photometry are subject to large error in the case of HD 184738 because the stellar spectrum is very full of emission lines. The continuous spectrum of HD 184738 is not defined well enough on the available high-resolution SWP *IUE* spectra to make the apparent strength of the interstellar Ly α absorption line useful as an indicator of the true size of $E(B - V)$.

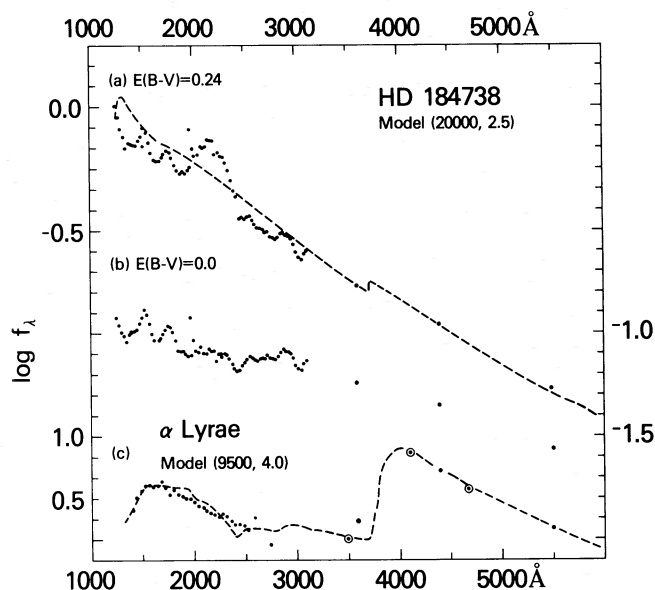


FIG. 10.—The observed and the dereddened energy curves of HD 184738 compared to the observed energy curve for α Lyrae. The units for flux, f_λ , are 10^{-11} ergs $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ for HD 184738 and 10^{-9} ergs $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ for α Lyrae. The scale for plot (b) is on the right. The energy curve of the (20000, 2.5) model of Kurucz 1979 is shown in plot (a); that of the (9500, 4.0) model, in plot (c). The theoretical energy distributions have been fitted to the observed energies near 4400 $\text{\AA}$. Large filled points indicate energies from *UBV* photometry; open circles indicate energies from *uvby* photometry; small points indicate energies from *IUE* spectra in the case of HD 184738 and from smoothed S2/68 scans for α Lyrae.

TABLE 2
ANGULAR DIAMETERS, EFFECTIVE TEMPERATURES, RADII, AND LUMINOSITIES OF 10 WOLF-RAYET STARS

HD	SPECTRAL TYPE	$E(B-V)$ (mag)	MODEL		NO. ^a SOLNS.	θ (10^{-4} arcsec)	T_{eff} (K)	DISTANCE (kpc)	R $R_\odot$	$\log L$ $L_\odot$	REFERENCES
			T_{eff} (K)	$\log g$							
50896	WN5	0.12	30,000	3.5	5	0.51	29,900	1.56	8.6	4.73	1
92740	WN7 + abs	0.34	25,000	3.5	1	1.17	25,100	2.74	34.5	5.63	2
93131	WN7 + abs	0.24	30,000	3.5	1	0.82	29,700	3.27	28.8	5.76	2
96548	WN8	0.47	25,000	3.5	1	0.78	24,900	3.13	26.2	5.38	2
151932	WN7	0.55	25,000	3.5	1	1.53	25,000	2.12	34.9	5.63	2
165763	WC5	0.21	30,000	3.5	5	0.32	30,000	2.62	9.0	4.77	1
184738	WC9	0.20	18,000	4.0	2	0.21	18,000	0.69	1.6	2.38	3
191765	WN6	0.45	25,000	3.5	5	0.55	24,800	1.93	11.4	4.65	1
192103	WC8	0.38	25,000	3.5	5	0.43	25,200	2.84	13.1	4.80	1
192163	WN6	0.55	40,000	4.0	5	0.55	39,900	1.48	8.7	5.24	1

^a1 means that the solution for angular diameter is made using the flux in the *V* band alone. Any possible contribution from lines or an infrared excess is ignored. 2 means that solutions for angular diameter were made using the observed fluxes in the *B* and *V* bands after correction for line emission; see text. 5 means that solutions for angular diameter were made using interpolated fluxes corrected for line emission and for an infrared excess at $\lambda\lambda 5183, 5827, 6356, 7241$, and 8000 ; see Underhill 1980*a*.

REFERENCES.—(1) Underhill 1980*a*. (2) Underhill 1981. (3) Acker 1978.

IV. RESULTS

The results of this study are given in Table 2. The spectral types listed in the second column are from van der Hucht *et al.* (1981); the values of $E(B-V)$ are those adopted in Underhill (1980*a*, 1981) for nine of the stars. The determination that $E(B-V) = 0.20$ for HD 184738 has been explained above. The values for linear

radius and luminosity are sensitively dependent on the adopted distances for the stars. These distances are those adopted by Underhill (1980*a*, 1981) and that given by Acker (1978).

V. EXPECTED UNCERTAINTIES

Expressions for the expected uncertainty in the logarithm of each derived quantity listed in Table 2 are

given in Underhill (1982). The expected uncertainties in $\log \theta_\lambda$ and $\log T_{\text{eff}}$ depend on the percentage errors in the integrated flux, $\Delta F_{\text{obs}}/F_{\text{obs}}$, and in the monochromatic flux used to find the angular diameter, $\Delta f_\lambda/f_\lambda$, on the error, ΔT , in the choice of the effective temperature of the model atmosphere, and on two model-dependent quantities $G^{-1}\partial G/\partial T$ and $F_\lambda^{-1}\partial F_\lambda/\partial T$. Typically, with the observational data that has been used, we may expect $\Delta F_{\text{obs}}/F_{\text{obs}}$ to be ± 0.15 , while $\Delta f_\lambda/f_\lambda$ may equal ± 0.10 . From the predicted model-atmosphere spectra of Kurucz (1979) one finds for models with $T_{\text{eff}} = 25,000$ K that the first model-dependent quantity is $0.29 \times 10^{-4} \text{ deg}^{-1}$, while the second is $0.77 \times 10^{-4} \text{ deg}^{-1}$. The uncertainty in the distance modulus for the star enters the expressions for the uncertainties in $\log R/R_\odot$ and $\log L/L_\odot$. We shall assume that $\Delta \text{Mod} = \pm 0.5$ mag.

The expressions for $\Delta \log \theta_\lambda$, $\Delta \log T_{\text{eff}}$, $\Delta \log R/R_\odot$, and $\Delta \log L/L_\odot$ given in Underhill (1982) combine the separate errors as though they are independent and their effects add quadratically. Each combination is multiplied by an appropriate numerical factor. The terms which are summed (different groups of terms being summed to find the typical uncertainty in each logarithmic quantity of interest), have the following values:

$$\begin{aligned} (\Delta f_\lambda/f_\lambda)^2 &= 0.0100 & \Delta T^2 (F_\lambda^{-1} \partial F_\lambda / \partial T)^2 &= 0.0237 \\ (\Delta F_{\text{obs}}/F_{\text{obs}})^2 &= 0.02250 & \Delta T^2 (G^{-1} \partial G / \partial T)^2 &= 0.00336 \\ (0.921 \Delta \text{Mod})^2 &= 0.21206. \end{aligned}$$

Here the factors arising from the observational uncertainties are listed on the left, and those due to the choice of model atmosphere are listed on the right. In this example, it is assumed that $\Delta T = 2000$ K and that $T(\text{model}) = 25,000$ K.

When these terms are added in the appropriate combinations, one finds that typically $\Delta \log \theta_\lambda = \pm 0.028$, $\Delta \log T_{\text{eff}} = \pm 0.013$, $\Delta \log R/R_\odot = \pm 0.062$, and $\Delta \log L/L_\odot = \pm 0.281$. In the case of the uncertainty in $\log \theta_\lambda$, one sums the two terms in the first line of the tabulation given above. The dominant source of error is the choice of model atmosphere. In the case of the uncertainty in $\log T_{\text{eff}}$, one sums the four terms in the first two lines of the tabulation. In the present case, the sum of the observational errors outweighs the sum of the errors due to the choice of model. In the case of the uncertainty in $\log R/R_\odot$, one adds the term in the third line of the tabulation to the sum of the terms in the first line. Uncertainty in the distance modulus is the dominant source of error. In the case of the uncertainty in $\log L/L_\odot$, one adds the term in the third line of the tabulation to the terms in the second line. The uncertainty in the distance modulus is the dominant source of error.

The size of the expected error in $\log T_{\text{eff}}$ constrains one's choice when selecting the best solution for θ_λ and

T_{eff} . If there is no error in the choice of model atmosphere, thus $\Delta T = 0$, then

$$\langle \Delta \log T_{\text{eff}} \rangle = \pm 0.054 \left[(\Delta F_{\text{obs}}/F_{\text{obs}})^2 + (\Delta f_\lambda/f_\lambda)^2 \right]^{1/2}. \quad (4)$$

We have seen that typically $\Delta F_{\text{obs}}/F_{\text{obs}}$ may be 0.15, while $\Delta f_\lambda/f_\lambda$ may be 0.10. In this case, the minimum uncertainty to be expected in $\log T_{\text{eff}}$ is ± 0.010 . This corresponds to an uncertainty of 3% in T_{eff} or about 750 K due solely to the uncertainties in the monochromatic fluxes which have been corrected for interstellar extinction. Proceeding as recommended by Remie and Lamers (1982) and iterating on the selection of $T(\text{model})$ until $|T_{\text{eff}} - T(\text{model})| < 1$ K is meaningless, and it does not result in a "best" solution. It leads only to that solution where the values for the model-dependent factors in equation (2) compensate exactly for the unavoidable uncertainties in the observed fluxes.

In this paper we have recognized the inherent, irreducible uncertainty in the solution for T_{eff} . We have selected a solution using a model which gives $|T_{\text{eff}} - T(\text{model})| < 500$ K and which provides an energy distribution like what is observed. Taking all things into consideration, including the uncertainty in the correction for interstellar extinction, it is fair to conclude that the typical uncertainty of each value of T_{eff} listed in Table 2 probably does not exceed 10%.

The uncertainties in $R/R_\odot$ and $\log L/L_\odot$ are strongly conditioned by the uncertainties in the adopted distances to the Wolf-Rayet stars. Typically we find that θ_λ can be estimated to within 7%, T_{eff} to within 5%, $R/R_\odot$ to within 15%, and $L/L_\odot$ to within 91% if the corrections for interstellar extinction are correct. The large uncertainty in $L/L_\odot$ cannot be avoided given present knowledge about the distances to the Wolf-Rayet stars. The size of this uncertainty makes caution desirable when one interprets the apparent positions of the Wolf-Rayet stars in an H-R diagram relative to the positions of a set of evolutionary tracks. The positions of the tracks can be very uncertain in the $\log L/L_\odot$ coordinate, the theoretical result achieved being quite sensitive to the assumptions made in the calculations, especially about the rate of mass loss, and how convection is treated.

VI. DISCUSSION

The effective temperatures given in Table 2 agree very well with those published previously (Underhill 1980a, 1981) for HD 50896, 92740, 96548, 151932, 165763, and 192103. In the cases of HD 93131, 191765, and 192163, the new results compare to the old results as 29,700/25,500, 24,800/30,000, and 39,900/29,800, respectively. These differences are barely significant given the uncer-

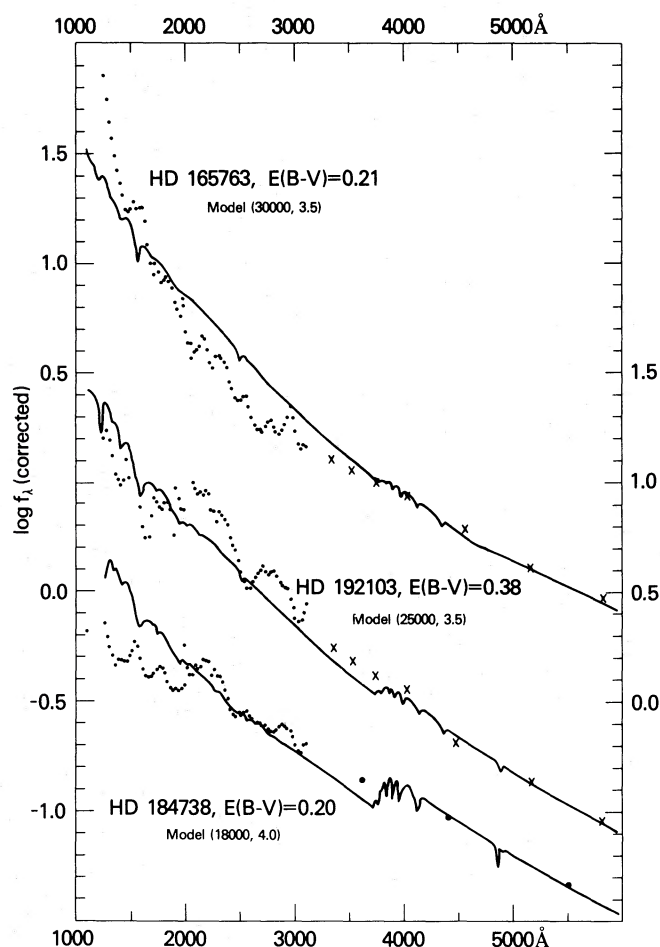


FIG. 11.—Energy distributions corrected for interstellar extinction of three WC stars compared to energy distributions from Kurucz 1979 model atmospheres. The theoretical energy distributions have been fitted to the observational data between 4000 Å and 5500 Å. The visible energies, corrected for the infrared excess longward of 4030 Å, are shown by crosses; the *UBV* photometry of HD 184738 corrected for nebular light and for line emission is shown by large filled points; the *IUE* continuum energies are shown by small filled points.

tainties in the different sets of photometric data used. The results of Table 2 are recommended over those published earlier.

The effective temperature of HD 184738, WC9, is definitely lower than that of the other stars. The value 18,000 K may be uncertain by ± 2000 K, chiefly owing to the uncertainty in the correction for interstellar extinction for this star. The estimate by Pottasch *et al.* (1978) that T_{eff} is 31,600 K is surely too high. This result was found by running a blackbody curve through the set of eight energies determined from the 5 *ANS* magnitudes for this star and the 3 *UBV* magnitudes, as well as by integrating these energies and estimating the flux of the star beyond the Lyman limit. When attention is paid to correcting the observed energies for line emission in the star, the spectrum has a normal shape for a star with T_{eff} near 20,000 K; see Figure 10. Natta, Pottasch, and Preite-Martinez (1980) have estimated T_{eff} for this star after considering fluxes shortward of the Lyman limit

inferred from the relative intensities of nebular lines in several stages of ionization. They find $T_{\text{eff}} = 28,700$ K. Natta and Panagia (1981*b*) suggest that the effective temperature should be increased to 34,200 K in order to allow for all the energy radiated by the dust in the nebula. It is not obvious that all the energy radiated by the nebula originates in the radiation field from the photosphere of the star. According to the model of Underhill (1983), it might come, in part, from the non-radiative energy which excites the Wolf-Rayet-type spectrum of the central star.

In this paper we have shown that each Wolf-Rayet star has a continuous spectrum over the range from 1250 Å to 5500 Å that has a shape close to that predicted for a model atmosphere having about the same effective temperature as the star; see Figures 1–10. The continuous spectra of the three WC stars are inter-compared over the range 1250–5500 Å in Figure 11. Some small systematic departures, of the order of ± 0.1

in $\log f_\lambda$, from the model energy distributions fitted in the visible range (after correction for the line emission and for an infrared excess) can be seen, but they are representative more of the difficulty of determining the level of the continuous spectrum of a Wolf-Rayet star than of systematic trends suggesting that the adopted model atmospheres are unacceptable for representing the photospheres of these stars.

There is no reason to conclude that the effective temperatures of any of the Wolf-Rayet stars studied here are higher than 40,000 K. Likewise, none of the Wolf-Rayet stars studied here show a "flat" spectrum over the range 1250–5500 Å.

The five Wolf-Rayet stars studied by Underhill (1980*a*) have strong infrared excesses which extend well into the visible range; see the data presented in that paper. Little has been published about the infrared spectra of the four Wolf-Rayet stars studied by Underhill (1981), those with spectral types WN7 and WN8, beyond the 10 μm excesses derived by Barlow, Smith, and Willis (1981). The star HD 184738 (= BD 30°3639) and its planetary nebula radiate a strong excess indicating the presence of dust in the nebula (Gillett, Forrest, and Merrill 1973; Moseley 1980; Natta and Panagia 1981*a*). There is no firm evidence that the dust in the nebula causes the ultraviolet extinction for HD 184738 to be anomalous, but this is a possibility which should be kept in mind.

Confirmation that the effective temperatures of Wolf-Rayet stars are like those of early B type stars rather than like those of O stars can be found by plotting v_∞ , the maximum outflow velocity, against $\log T_{\text{eff}}$. The maximum outflow velocity reached will be proportional to the density of continuum radiation available for accelerating material that on the model of Underhill (1983) has been propelled outward to supersonic velocities as the result of the deposition of nonradiative momentum in the mantle. The density of radiation available should be proportional to T_{eff}^4 . These statements are approximate. It would be necessary to study the outflow of gas from a star under the action of all relevant forces if a precise statement based on the results of models were to be made.

The maximum velocity of outflow has been estimated for 10 Wolf-Rayet stars, 13 O stars, 13 B type supergiants, and 2 A0 supergiants from *IUE* high-resolution spectra. These values are shown plotted against $\log T_{\text{eff}}$ in Figure 12. The data used to make Figure 12 are given in Table 3. In the case of the Wolf-Rayet and O stars, the shortward end of the absorption trough is rather rounded, suggesting the presence of "turbulence" of the order of 100 km s^{-1} ; see the analyses by Hamann (1980, 1981) and the C IV profiles presented in Underhill (1983). The best estimate of v_∞ is found by measuring the wavelength where a sharp upturn begins at the end of the saturated, zero-intensity part of the profiles of

strong absorption troughs. The values given in Table 3 for v_∞ for Wolf-Rayet stars are systematically smaller than the values listed by Barlow, Smith, and Willis (1982), no doubt because they have been determined by a different method than adopted by Barlow, Smith, and Willis. In the case of the B type supergiants, the upturn is very steep. For these stars, the listed values of v_∞ correspond to the wavelength where the upturn cuts the level of the continuous spectrum in the neighborhood of the line. An interpretation of the rounded ends of the profiles of the absorption troughs from very strong lines is given in Underhill (1983).

The points in Figure 12 scatter about a straight line. A representative line has been sketched in by eye. Its equation is

$$v_\infty = 4.2 \log T_{\text{eff}} - 16.865. \quad (5)$$

Here v_∞ is in 10^3 km s^{-1} and T_{eff} is in kelvins. The maximum outflow velocities measured for the Wolf-Rayet stars seem to follow the same relation to T_{eff} as do the maximum outflow velocities for O stars and B type supergiants. It is clear that v_∞ varies about as $\log T_{\text{eff}}^4$.

Barlow, Smith, and Willis (1981) have used energy distributions determined from low-resolution *IUE* spectra of Wolf-Rayet stars to find the slope of the continuous spectrum from the neighborhood of 1300 Å to approximately 2500 Å. They have adopted temperatures

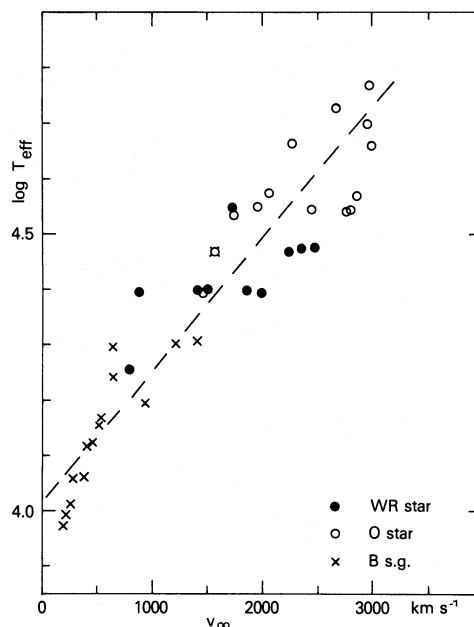


FIG. 12.—The correlation between maximum velocity of outflow, v_∞ , and $\log T_{\text{eff}}$ for Wolf-Rayet stars, O stars, and B type supergiants.

TABLE 3
MAXIMUM OUTFLOW VELOCITIES AND LOG T_{eff} FOR W-R, O, AND B STARS

HD	Name	Spectral Type	v_{∞} (km s ⁻¹)	log T_{eff}	Reference for T_{eff}
50896.....	...	WN5	2370	4.476	1
92740.....	...	WN7	1850	4.400	1
93131.....	...	WN7	2240	4.473	1
96548.....	...	WN8	870	4.396	1
151932.....	...	WN7	1510	4.398	1
165763.....	...	WC5	2470	4.477	1
184738.....	...	WC9	780	4.255	1
191765.....	...	WN6	1990	4.394	1
192103.....	...	WC8	1410	4.401	1
192163.....	...	WN6	1720	4.601	1
15558.....	...	O5 III	2260	4.665	2
30614.....	α Cam	O9.5 Ia	1450	4.398	3
46150.....	...	O5 V	2800	4.544	2
46223.....	...	O4 V	2770	4.542	2
47839.....	S Mon	O7 V	1950	4.549	3
48099.....	...	O6.5 V	2850	4.571	3
66811.....	ξ Pup	O4 If	2450	4.544	3
93129A	...	O3f	2990	4.663	2
303308.....	...	O3 V	2950	4.700	2
93205.....	...	O3 V	2980	4.771	2
164794.....	9 Sgr	O4 V	2670	4.732	2
188001.....	9 Sge	O8 I	1740	4.538	3
210839.....	λ Cep	O6ef	2060	4.576	3
2905.....	κ Cas	B1 Ia	1220	4.303	3
12301.....	53 Cas	B8 Ib	400	4.064	4
21291.....	...	B9 Ia	260	4.013	4
21389.....	...	A0 Ia	230	3.995	4
34085.....	β Ori	B8 Ia	270	4.057	3
41117.....	χ^2 Ori	B2 Ia	660	4.243	3
53138.....	σ^2 CMa	B3 Ia	530	4.170	3
58350.....	η CMa	B5 Ia	410	4.114	3
87737.....	η Leo	A0 Ib	200	3.973	4
91316.....	ρ Leo	B1 Ib	1420	4.307	3
164353.....	67 Oph	B5 Ib	440	4.121	3
167264.....	15 Sgr	B0 Ia	1570	4.473	4
190603.....	...	B1 Ia ⁺	640	4.294	4
198478.....	55 Cyg	B3 Ia	570	4.155	3
206165.....	9 Cep	B2 Ib	950	4.196	3

REFERENCES.—(1) This paper. (2) Underhill 1982. (3) Underhill *et al.* 1979. (4) Underhill and Doazan (1982), chap. 4.

for the stars, T_{BB} , which correspond to the temperatures of blackbodies having the slopes which they determine. They then use blackbody energy distributions corresponding to the T_{BB} to estimate the amount of continuum energy radiated by Wolf-Rayet stars shortward of 1300 Å. This procedure leads to very uncertain estimates for the amount of energy radiated by Wolf-Rayet stars shortward of 1300 Å. Furthermore, these estimates will tend to be high.

In the first place, because it is impossible to resolve the continuous spectrum of a Wolf-Rayet star on SWP low-resolution spectra from the many emission lines which occur shortward of 1900 Å, the apparent energies at wavelengths shortward of 1900 Å will be overesti-

mated. This will lead to the determination of slopes between the SWP and LWR wavelength ranges which are systematically too large. Second, the slope of the spectrum between, say 1300 Å and 2500 Å, from a model atmosphere of normal composition, or from one largely composed of helium, and having a temperature in the O and B star range is much steeper than that from a blackbody which has a temperature equal to the effective temperature of the model atmosphere. This can be seen from the illustrations published by Underhill (1951, 1957), and it can be verified using the model-atmosphere continuous spectra published by Mihalas (1972) and Kurucz (1979). Third, although the bolometric correction for radiation shortward of about

4000 Å determined from a blackbody curve having a temperature equal to the effective temperature of a hot model atmosphere is roughly equal to the bolometric correction determined from the continuous spectrum from the model atmosphere (McDonald and Underhill 1952; Underhill 1966), the same is not true for an ultraviolet bolometric correction which is designed to take account of only the energy radiated in the wavelength range from 0 Å to 1300 Å. Consideration of the energy distributions published by Underhill (1950, 1951, 1957) or of those published by Mihalas (1972) or Kurucz (1979) readily shows that the far-ultraviolet bolometric correction determined for a blackbody having a temperature equal to the effective temperature of an O or B type model atmosphere will be larger than that from the model atmosphere. If the effective temperature of the equivalent model atmosphere representing the photosphere of a star is overestimated by taking a temperature equal to the T_{BB} of Barlow, Smith, and Willis (1982), then the value for the far-ultraviolet bolometric correction will be further overestimated.

For all of these reasons, the bolometric corrections estimated by Barlow, Smith, and Willis for Wolf-Rayet stars are too large. Consequently, the typical luminosities for the various Wolf-Rayet subtypes deduced by these authors are too high. The luminosities listed in Table 2 for 10 Wolf-Rayet stars are the best estimates that can be made at this time. We have seen that they have an uncertainty of about 90%, typically. In most cases these luminosities are lower than those suggested by Barlow, Smith, and Willis. Because there is little evidence that the photospheres of the Wolf-Rayet stars of a given subtype are indeed closely similar to each other or that subtype among the Wolf-Rayet classes relates unambiguously and monotonically with effective temperature, there is little value in attempting to assign representative luminosities to the various Wolf-Rayet subtypes and expecting these to differ systematically, the one from the other.

A Wolf-Rayet spectral type manifestly represents the physical conditions in the mantle of the star. According to Underhill (1983), these conditions are determined far more by the amount of nonradiative energy and momentum deposited in the mantle than by the effective temperature and $\log g$ value of the star. Consequently, a

Wolf-Rayet subtype is no sure guide to the position of the star in the H-R diagram. It offers only an ambiguous means of tying to the predictions of the theory of stellar evolution, that is, to T_{eff} and $\log L/L_{\odot}$. These predictions give the effective temperature and radius expected for a model star of a given mass as a function of time elapsed since the star reached the zero-age main sequence. Until it is possible to relate conditions in the mantle of the star uniquely and unambiguously to information derived from the theory of stellar evolution, it will be impossible to use a Wolf-Rayet subtype as an index to the stage of evolution of the star.

VII. SUMMARY

Effective temperatures have been determined for 10 Wolf-Rayet stars by means of ultraviolet energies determined from high-resolution *IUE* spectra and energies determined from observations made in the visible range. It is essential to use high-resolution *IUE* spectra in order to resolve the continuum from the many emission lines which are present, particularly shortward of 1900 Å. The results confirm what was found earlier, namely that the effective temperatures of Wolf-Rayet stars are similar to those of early B stars. The effective temperature of the central star of the planetary nebula BD 30°3639, HD 184738, is found to be 18,000 K. Maximum outflow velocities are given for 10 Wolf-Rayet stars, 13 O stars, 13 B type supergiants, and 2 A0 supergiants. It is demonstrated that v_{∞} varies about as $\log T_{\text{eff}}^4$. Arguments are given indicating that it will be impossible to use a Wolf-Rayet subtype as an index to the stage of evolution of a Wolf-Rayet star until it is possible to relate conditions in the mantle of a Wolf-Rayet star uniquely and unambiguously to information furnished by the theory of stellar evolution.

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