COMMENTS ON THE SIGNIFICANCE OF THE POSITIONS OF POPULATION I WOLF-RAYET STARS IN THE HR DIAGRAM

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ABSTRACT

The size of typical errors in log $L/L_\odot$ and log T_{eff} is investigated for WR stars, and it is found that typically Δ log $L/L_\odot = \pm(0.25 \pm 0.03)$, and Δ log $T_{eff} = \pm(0.05 \pm 0.02)$. The major sources of error are the uncertainties in the distance modulus of the star and the integrated continuous flux from about 1400 Å to 1 μm or so. The same is true for O and early B stars. With uncertainties of these sizes in log $L/L_\odot$ and log T_{eff}, it is unreliable to estimate the mass of an early-type star from its observed position in the HR diagram. The WN7/8 stars lie with the O9/B0 Ia stars, the other WR stars with the B0/B1 III stars.

I. CONCEPTS USED

In order to determine the position of a star in the HR diagram and to establish the significance of that position, one must find log $L/L_\odot$ and log T_{eff} for the star, as well as the typical errors in these quantities.

The quantities log $L/L_\odot$ and log T_{eff} can be found from knowledge of the distance modulus for the star, Mod(*), from the integrated energy received from the star over a wavelength range λ_1 to λ_2, (the observed fluxes having been corrected for interstellar extinction), from the observed flux, f_λ, at a wavelength in the visible range, corrected for interstellar extinction, and from two quantities which may be found from model atmosphere. These quantities are $F_\lambda(T_{eff})$, the predicted monochro-

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matic flux at the typical wavelength which is used with f_λ to find the angular diameter of the star, and

$$G(T_{eff}) = 1 + \left(\int_o^{\lambda_1} F_\lambda d\lambda + \int_{\lambda_2}^{\infty} F_\lambda d\lambda\right) / \int_{\lambda_1}^{\lambda_2} F_\lambda d\lambda \quad . \tag{1}$$

It is necessary to assume a value for T_{eff} and log g in order to specify the model atmosphere which is selected to represent the photosphere of the star. In what follows, log g is an insensitive parameter, and the possible errors arising from error in the choice of this parameter will be ignored. Results found in this way about log T_{eff} and log $L/L_\odot$ for some early-type stars have been presented by Underhill et al. (1979), and by Underhill (1980, 1981).

We have

$$\log L/L_\odot = \log F_{obs} + 0.4Mod(*) + \log \mathcal{G}(T_{eff}) + const., \tag{2}$$

and

$$\log T_{eff} = \frac{1}{4}\left[\log F_{obs} - \log f_\lambda + \log \mathcal{G}(T_{eff}) + \log F_\lambda(T_{eff})\right] + const. \tag{3}$$

Here

$$F_{obs} = \int_{\lambda_1}^{\lambda_2} f_\lambda d\lambda, \tag{4}$$

and T_{eff} is the selected effective temperature for the model. Usually λ_1 is of the order of 1400 Å and λ_2 is of the order of 0.6 to 1 μm.

There are errors in each of the observed quantities and there is an error in the choice of T_{eff}. Let us denote the errors by ΔF_{obs}, Δf_λ, and $\Delta T = T_{eff}(*) - T_{eff}(\text{model})$. Typical fractional errors in F_{obs} and f_λ fall in the ranges 10 to 20 percent, and 5 to 10 percent, respectively. The error ΔT may lie in the range of 1000 to 2000 K. Outside information, such as the shape of the spectrum over a long wavelength range or the spectral type, must be used to find T_{eff}(model).

If it is assumed that all the errors add quadratically, then

$$\langle\Delta \log L/L_\odot\rangle = \left[\left(\frac{\Delta F_{obs}}{F_{obs}}\right)^2 + (0.4\ \Delta Mod(*))^2 + \Delta T^2\left(\frac{1}{G}\frac{\partial G}{\partial T}\right)^2\right]^{\frac{1}{2}} \qquad (5)$$

and

$$\langle\Delta \log T_{eff}\rangle = \frac{1}{4}\left[\left(\frac{\Delta F_{obs}}{F_{obs}}\right)^2 + \left(\frac{\Delta f_\lambda}{f_\lambda}\right)^2 + \Delta T^2\left(\frac{1}{G}\frac{\partial G}{\partial T}\right)^2 + \Delta T^2\left(\frac{1}{F_\lambda}\frac{\partial F_\lambda}{\partial T}\right)^2\right]^{\frac{1}{2}} . \qquad (6)$$

II. TYPICAL ERRORS IN log $L/L_\odot$ and log T_{eff} FOR WR STARS

If one assumes that $|\Delta F_{obs}/F_{obs}|$ lies in the range 0.10 to 0.20, that $|\Delta f_\lambda/f_\lambda|$ in the visible spectral range lies in the range 0.05 to 0.10, that $|\Delta Mod(*)|$ is 0.5 mag, and that $|\Delta T|$ is 1000 to 2000 K, then application of eqts. (5) and (6) for the case that T_{eff}(model) lies in the range 25000 to 35000 K, shows that

$$\langle\Delta \log L/L_\odot\rangle = \pm\ (0.25 \pm 0.03),$$
$$\langle\Delta \log T_{eff}\rangle = \pm\ (0.05 \pm 0.02).$$

The dominant source of error in log $L/L_\odot$ is $\Delta Mod(*)$, followed by $\Delta F_{obs}/F_{obs}$. The dominant source of error in log T_{eff} is $\Delta F_{obs}/F_{obs}$. Neither of these observational errors can be reduced from the assumed ranges without an improved knowledge of the distances of the WR stars and of the amount of interstellar extinction which WR stars experience at all wavelengths.

Comparison of the shape of the ultraviolet to visible energy curves of Wolf-Rayet stars with those of the Kurucz (1979) model atmospheres (Willis and Wilson 1978, Underhill 1981) shows that the assumed range for T_{eff}(model) is acceptable. The errors in log $L/L_\odot$ and log T_{eff} for O and early B stars are not much less than those for WR stars because $\Delta Mod(*)$ and $\Delta F_{obs}/F_{obs}$ have almost the same values for O and early B stars as for WR stars.

III. DISCUSSION

Figure 7 of Underhill (1981) shows the positions in the HR diagram of some B and O stars, and of 9 WR stars. If one superimposes on this diagram crosses to show the typical ranges found in this study for the uncertainties in log $L/L_{\odot}$ and log T_{eff} for stars with log $T_{eff} > 4.30$, it is seen tnat the uncertainties in log $L/L_{\odot}$ embrace evolutionary tracks for model stars differing by a factor 2 in mass. Because of the size of the uncertainties in the positions of O, WR, and early B stars in the HR diagram, and because of the uncertainties in the positions of evolutionary tracks owing to uncertainties in the choice of composition, opacity tables, and the manner in which convection and mass loss are handled, see Stothers and Chin (1980), no secure estimate can be made of the mass of a Population I O, WR, or early B star from its position in the HR diagram. Similarly it is impossible to relate any single star surely to any particular evolutionary track.

The WN7/8 stars fall in the same part of the diagram as the O9/B0 Ia supergiants 15 Sgr, α Cam, and ε Ori, while the other WR stars, (2 of type WC, 3 of type WN) fall in the region of the B0 and B1 stars of luminosity class III (Underhill 1981). This result demonstrates that two significantly different spectral types are to be found in the same area of the HR diagram. What differs is the physical state of the outer atmosphere or mantle. The photospheres of the stars in each of these two groups are similar because the stars of each group have the same T_{eff} and $R/R_{\odot}$, so far as can be determined. Information available about the masses of these stars, determined from spectroscopic binaries, suggests that the masses are comparable in each group.

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DISCUSSION FOLLOWING UNDERHILL

Schmutz: 1) A method to estimate the errors in the determinations of the effective temperature and luminosity is to compare the results of two groups. Nussbaumer et al. (1981) found stars to be located to the left of the ZAMS. Therefore the error bars you showed in your viewgraphs should at least be doubled.

2) I do not believe that plane-parallel models are appropriate for WR stars, because only about 1/3 of the WR stars have a continuum energy distribution that is similar to the model calculations. The other ones have a black-body like energy distribution indicating that a black-body is still the best model for the WR stars, which do not show effects of an extended continuum emitting region.

Underhill: 1) Comparing the results of two groups means little when the two groups determine different quantities. The T_{BB} of Nussbaumer et al. (1981) is not an effective temperature according to the definition of effective temperature. It is merely that temperature which defines a black-body energy distribution, having a slope like that of a hot model atmosphere. The theory of stellar atmospheres shows that T_{BB} will be systematically higher than T_{eff} when T_{eff} is in the range 20000 to 60000 K and the fit is done between about 1300 and 6000 Å. The error in log T_{eff} is probably not larger than 1.5 times my estimate; the error in log $L/L_{\odot}$ may be larger by a factor 2 if the uncertainty in the distance modulus for the star is 0.8 mag or so.

2) Similarity in shape to a black-body energy distribution over the wavelength range from 1300 to 6000 Å is no proof that a stellar atmosphere radiates like a black-body. In fact a stellar atmosphere cannot do so over all wavelengths because radiation escapes from a star; it does not escape from a black-body, by definition. You must use the physics of gas and radiation to find the energy distribution of a star.

Conti: I am concerned with some of the conclusions you have made on the basis of these continua. In particular, the step in going from an interior physics model to a comparison with the observed integrated flux requires a knowledge of the physics. Your procedure is as fraught with uncertainties as your previous criticisms of others during this symposium. The theoretical tracks are plotted with non-LTE, zero turbulence, line blanketed plane parallel atmospheres. These do seem far from real WR stars.