EFFECTIVE TEMPERATURES OF WOLF-RAYET STARS

DONALD C. MORTON
Princeton University Observatory, Princeton, N.Y., U.S.A.

We have learned from Lindsey Smith's talk how useful it would be for our understanding of Wolf-Rayet stars to have reliable effective temperatures and bolometric corrections. The ring nebulae surrounding a few WN stars provide one method for estimating the stellar temperatures. I have assumed each nebula is a normal H II region excited primarily by the Lyman continuum radiation of the central star. Then, if the nebula is optically thick shortward of 912 Å, each stellar photon with more energy than 13.6 eV is absorbed by the nebula and re-radiated in a predictable way as hydrogen lines and free-free radio emission. Consequently, nebular radio measures such as those recently obtained by Hugh Johnson (1971) provide a direct indication of the number of Lyman-continuum photons emitted by the central star. The exact equations have been described in the *Astrophysical Journal* (Morton, 1969; Morton, 1970).

For the exciting stars a measure of the visual flux in the continuum is available from Lindsey Smith's UBV photometry of narrow bands between the emission lines. I have used the relation

$$V^* = v - 0.02 - 0.36\,(\mathrm{b}-\mathrm{v})$$

to convert each v magnitude to an equivalent one on the Johnson UBV system such that V^* represents the visual magnitude the WR star would have if there were no emission lines. This transformation is necessary to convert the observed magnitudes to absolute visual fluxes incident at the Earth, since the calibration factor is not known for v. I adopted a flux of 3.8×10^{-9} erg s^{-1} cm^{-2} Å^{-1} at 5460 Å for a star with $V = 0.0$. A recent measurement by Oke and Schild (1970) was 3% lower. The total visual extinction was derived from the observed colour excess by the formula

$$A_V = 3.0\,\mathrm{E}(\mathrm{B}-\mathrm{V}) = 3.6\,\mathrm{E}(\mathrm{b}-\mathrm{v}).$$

Fortunately there is no interstellar absorption of the radio emission.

Table I lists the photometric data on the central stars and Table II gives the nebular radio fluxes, the derived effective temperatures, and the bolometric corrections. The first six entries of Table II are reproduced from Morton (1970) and depend on radio measurements by Johnson and Hogg (1965), Gebel (1968), and Smith and Batchelor (1970) while the last three rows are based on the new data by Johnson (1971). The Gaunt factor is accounted for through the term

$$g(T, \nu) = 1 + 0.13 \log\left(T^{3/2}/\nu\right),$$

where ν is the frequency in Hertz and $T = 10^4$ K.

The observational data provided $N_L/\pi F_V$, the ratio of the number of Lyman continuum photons to the energy flux in the V bandpass. It was assumed that the relation

M. K. V. Bappu and J. Sahade (eds.), Wolf-Rayet and High-Temperature Stars, 54–56. All Rights Reserved.

TABLE I

Photometry of Wolf-Rayet stars in nebulae

Nebula	Star	Spectrum	v	b − v	E(b − v)	V^*	A_V
NGC 2359	HD 56925	WN 5	11.74	+0.33	0.47	11.60	1.69
NGC 3199	HD 89358	WN 5	11.20	+0.54	0.68	10.99	2.45
RCW 58	HD 96548	WN 8	7.85	+0.11	0.26	7.79	0.94
RCW 104	HD 147419	WN 6	11.42	+0.63	0.80	11.17	2.88
NGC 6888	HD 192163	WN 6	7.73	+0.25	0.42	7.62	1.51
S157	HD 219460	WN 4.5 + B0	10.03	+0.52	0.71	9.82	2.56
S308	HD 50896	WN 5	6.94	−0.07	0.07	6.95	0.25
	HD 211853	WN 6 + B0:I:	9.20	+0.32	0.49	9.06	1.76

TABLE II

Effective temperatures of Wolf-Rayet stars in nebulae

Nebula	Spectrum	f_ν (flux units)	ν (Hz)	log $f_\nu/g(T, \nu)$	log $N_L/\pi F_V$	θ_e	T_e(K)	B.C.
NGC 2359	WN 5	5.9	1400	+1.00	12.50	0.094	53600	−4.7
NGC 3199	WN 5	20	2650	+1.56	12.52	0.093	54200	−4.7
RCW 58	WN 8	0.2	2650	−0.44	9.84	0.20	25000	−2.5
RCW 104	WN 6	8.6	2650	+1.19	12.04	0.120	42000	−3.9
NGC 6888	WN 6	4.7	1400	+0.90	10.88	0.164	30700	−3.0
S157	WN 4.5 + B0	40	2650	+1.86	12.30	0.105	48000	−4.3
S308	WN 5	1.3	5010	+0.40	10.62	0.171	29500	−2.9
NGC 6888	WN 6	4.0	7795	+0.91	10.89	0.164	30800	−3.0
HD 211853	WN 6 + B0:I:	0.46	7795	−0.03	10.43	0.176	28600	−2.8

between this ratio and the effective temperatures of WN stars is given by the theoretical relation derived from a series of model atmospheres with gravity $g = 10^4$ cm s^{-2} representing hot main-sequence stars. The models were derived under the usual simplyfying conditions of hydrostatic equilibrium, radiative equilibrium, and local thermodynamic equilibrium (LTE). Auer and Mihalas (1972) have shown that the continuum energy distribution for O type models is little changed by consideration of the effects of non-LTE and a similar situation may hold for the WN stars. I am less confident about the conditions of hydrostatic and thermal equilibrium which are likely to fail in the region of the emission lines. However the models may not be so bad for relating the effective temperature to the energy distribution in the continuum. Until we have self-consistent models for WN atmospheres there is nothing better to do. The last column in Table II gives the bolometric correction based on the T_e in the previous column and the B.C.–T_e relation derived from the model atmospheres of O and B stars by Bradley and Morton (1969) and Van Citters and Morton (1970).

For the first six stars in Table II, there is the expected trend of decreasing temperature from WN 4.5 to WN 8, though the two WN 6 stars give considerably different values. The new measurement on NGC 6888 nicely confirms the earlier result for HD 192163. An effective temperature of 30800 K is reasonably consistent with the far-ultraviolet energy distribution obtained from OAO-2 just described by Hugh

Johnson. However, the two new values for HD 50896 (WN5) and HD 211853 (WN6) seem a little cooler compared with the earlier estimates, especially the WN5 star. In that case I wonder if the nebula is optically thin or if the radio telescope missed some of the nebular emission. If any of the photons escape either the nebula or the telescope, the effective temperature will be underestimated.

References

Auer, L. and Mihalas, D.: 1972, *Astrophys. J. Suppl.* **24**, 193.
Bradley, P. T. and Morton, D. C.: 1969, *Astrophys. J.* **156**, 687.
Gebel, W. L.: 1968, *Astrophys. J.* **153**, 743.
Johnson, H. M. and Hogg, D. E.: 1965, *Astrophys. J.* **142**, 1033.
Johnson, H. M.: 1971, *Astrophys. J.* **167**, 491.
Morton, D. C.: 1969, *Astrophys. J.* **158**, 629.
Morton, D. C.: 1970, *Astrophys. J.* **160**, 215.
Oke, J. B. and Schild, R. E.: 1970, *Astrophys. J.* **161**, 1015.
Smith, L. F. and Batchelor, R. A.: 1970, *Australian J. Phys.* **23**, 203.
Smith, L. F.: 1968a, *Monthly Notices Roy. Astron. Soc.* **138**, 109.
Smith, L. F.: 1968b, *Monthly Notices Roy. Astron. Soc.* **140**, 409.
Smith, L. F.: 1968c, *Monthly Notices Roy. Astron. Soc.* **141**, 317.
Van Citters, G. W. and Morton, D. C.: 1970, *Astrophys. J.* **161**, 695.

DISCUSSION

Smith: HD 211853 is a binary. And the ring around HD 50896 is very faint and incomplete.

Thomas: Do you really mean it when you say that there are no non-LTE effects in your calculations?

Morton: Of course there are always non-LTE effects, but in these models they are not serious as they might be with a middle B star.

Thomas: Auer and Mihalas calculations are all for radiative equilibrium; if there is any kind of mechanical energy transport, their calculations go out the window. That is a major objection. My second is what does one get for the ratio of the Lyman continuum to the visible if one uses their hottest model? What is the difference in the ratio of the Lyman continuum to the visible when one considers LTE and non-LTE effects?

Morton: It is not very big, at most a factor two at 25000° and less at higher temperatures.

Thomas: What does it do to the temperature distribution in the model?

Underhill: It does affect the line strengths quite seriously. However, we try to identify the models via the continuum and you identify the model with a star using parts of the Paschen continuum which is almost insensitive to anything.

Thomas: I just do not see how you can get away with it unless you have mechanical heating.

Morton: Since we have only models in radiative equilibrium, it is the best we can do at present.

Thomas: The best you can do in a sophisticated way, but I am not sure that in a fairly rough way you cannot do better.

Conti: If a Wolf-Rayet star is a star that has lost its hydrogen into the interstellar medium by one way or another, the density around the star may be very large and that may be one reason why the Strömgren sphere is not very large, because the density of this sphere is much larger than normal.

Thomas: I personally like better the response having to do with the lack of nebular shells. I am getting more intrigued with the idea of the environment being fixed by previous stages.

Smith: There may be a systematic error in Morton's temperatures because of his assumption that the stars radiate like models; however, the difference between his temperatures for different subclasses may have some validity. It certainly provides a beautiful explanation for the surprising anticorrelation between excitation class and visual magnitude.

Thomas: I just do not believe it, not only out of prejudice, but also from the standpoint of your own arguments this morning when you were asking for much differential mechanical heating between WN6 and WN3.