C. THEORETICAL MODELS FOR STELLAR FLUXES

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THE EFFECTIVE TEMPERATURES OF THE O STARS

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Abstract. Effective temperatures of O-type stars imbedded in diffuse nebulae are derived from measurements of Hα and radio fluxes from the nebulae and the apparent magnitudes of the stars. Accurate model atmospheres, with ultraviolet line blanketing where appropriate, are used for the theoretical relation between effective temperature and the ratio of Lyman continuum to visual stellar fluxes. Although there is considerable scatter in the results, an average temperature of 48000 K is found for spectral type O5, 40000 K for O6, and 35000 K for O7.

Two years ago Morton and Adams (1968) proposed a scale of effective temperatures for O and B stars by comparing the observations of the Balmer jump by Chalonge and Divan (1952) with theoretical model atmospheres which included line blanketing in the ultraviolet. For the O stars Morton and Adams adopted the scale in the third column of Table I, but the temperatures were very uncertain for the hottest ones because their Balmer jumps are very small. Also the temperature at O5 was an extrapolation because Chalonge and Divan had no observations earlier than O6 and no weight was given to the ultraviolet fluxes which dominate the emission of these stars.

A better procedure uses the nebula surrounding an O star to count the number of photons emitted in the stellar Lyman continuum, as described by Pottasch (1965) and Hjellming (1968). Each Lyman-continuum photon produces a Balmer photon so that it is possible to obtain for the exciting star the ratio

$$\frac{\text{number of Lyman continuum photons cm}^{-2}\text{ sec}^{-1}}{\text{energy in the } V \text{ magnitude band cm}^{-2}\text{ sec}^{-1}}$$

from the nebular Hα flux and the apparent visual magnitude of the star. This ratio also can be derived from the radio flux by equating the rates of ionizations and recombinations to give an expression for $\int n_e^2/T^{1/2}\,\mathrm{d}V$ over the volume of the nebula and hence the rate of free-free emission. Therefore from observations of either the nebular Hα flux or radio emission it is possible to obtain the above ratio as a function of spectral type of the central star. This ratio then can be compared with theoretical models which include ultraviolet line blanketing, when important, to give a relation between effective temperature T_e and spectral type. A surface gravity of $g = 10^4$ cm sec^{-2} has been adopted in all cases.

This approach has the advantage of comparing fluxes over a very wide spectral range, but there are some difficulties. A few nebulae may be limited by density rather than by ionization so that all the Lyman-continuum photons are not converted to Balmer and radio emission, with the result that the derived temperatures are too low. In other nebulae with considerable obscuration all the exciting stars may not have been found so that the temperatures derived for the identified stars may be too high. In this investigation it has been assumed that these effects cancel on the average.

Houziaux and Butler (eds.), Ultraviolet Stellar Spectra and Ground-Based Observations, 59–63.

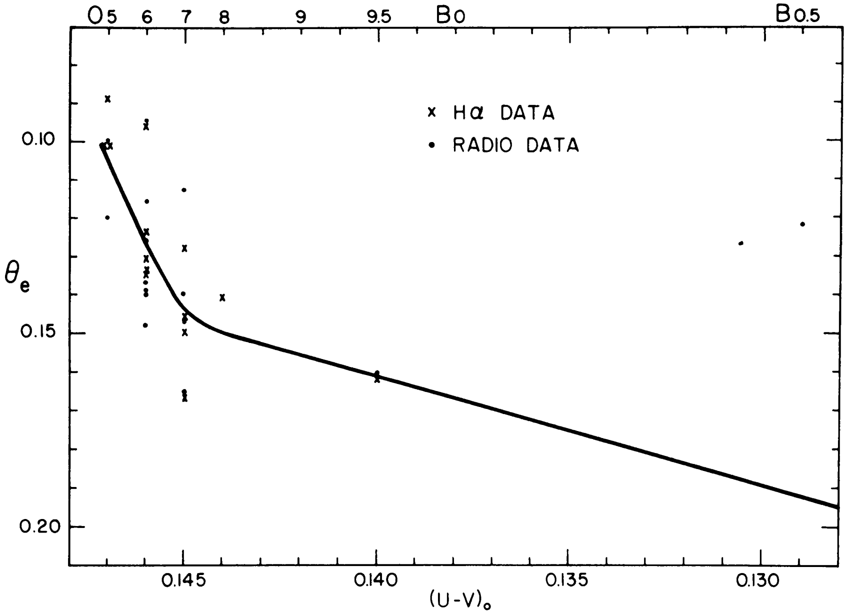

Fig. 1. Reciprocal effective temperatures ($\theta_e = 5040.2/T_e$) of O stars in nebulae.

Figure 1 is a plot of the effective temperatures expressed as $\theta_e = 5040.2/T_e$ for nebulae where only one exciting star has been found. The line has been drawn through the average for each spectral type and fitted to the Morton-Adams scale for the B stars, since this agrees reasonably well with that proposed by Brown *et al.* (1967) from measurements with the intensity interferometer. The fourth column in Table I lists the adopted mean temperatures. The curve shows a sharp rise beginning at O7, and consequently the new temperatures for O5 and O6 are much hotter than the old scale. Full details of this research have been described elsewhere by Morton (1969).

The data on two nebulae with Wolf-Rayet stars suggest that HD 219460 (WN4.5+BO) has a temperature around 50000°K, while HD 168206 (WC8+BO:) cannot be much hotter than 35000°K.

TABLE I

Effective temperatures and bolometric corrections for O stars

Spectrum	$(U-V)_0$	T_e(K) Morton-Adams	T_e(K) from nebulae (adopted here)	B.C.
O5	−1.47	37500	48000	−4.32
O6	−1.46	36500	40000	−3.70
O7	−1.45	35700	35000	−3.27
O8	−1.44	35000	33500	−3.15
O9	−1.42	34300	32000	−3.06
O9.5	−1.40	32100	31000	−2.98

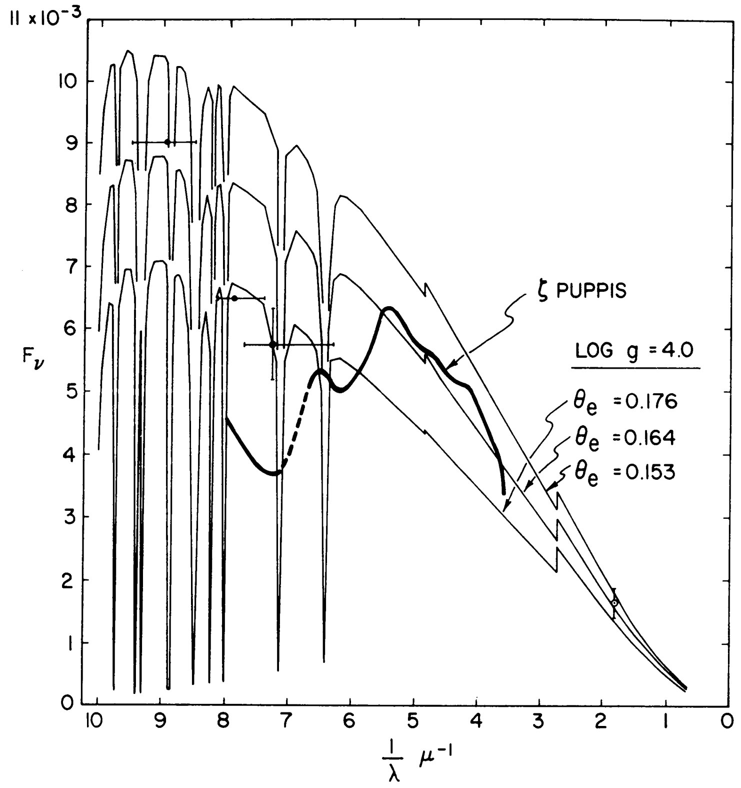

Fig. 2. Absolute surface fluxes of ζ Puppis in units of erg cm^{-2} sec^{-1} Hz^{-1} vs. reciprocal wavelengths in μ^{-1}. Here F_ν must be multiplied by π to obtain the physical flux. The heavy line is from Stecher's ultraviolet scan while the light lines represent three blanketed models. Broad-band measures by Carruthers and Smith are indicated by dots with horizontal lines to show the band widths. The point marked ○ was derived from the visual flux.

In the table, bolometric corrections calculated from the theoretical models are given for the new temperatures derived from the nebulae. These bolometric corrections have a zero point tied directly to the Sun as described by Bradley and Morton (1969). This procedure is to be preferred over the indirect method adopted by Morton and Adams who used the F-type models of Mihalas (1966) which may have serious errors in their ultraviolet fluxes, as will be described later in this symposium by Davis and Webb.

It is of interest to compare the new temperature scale with what we know about one hot O star, ζ Puppis, which is classed O5f. This star probably contributes to the ionization of the great Gum nebula, but unfortunately no Hα or radio measures are readily available for the integrated emission. However, the existing ultraviolet and visual data for the star seem to suggest that it is an exceptional case.

First Smith (1967) measured fluxes in a broad band around 1376 Å and found that the ratio $f_\lambda(1376)/f_\lambda(5475)$, corrected for interstellar extinction, was smaller for ζ Pup than for the O7 stars 15 Mon and ξ Per and the O9.5V star ζ Oph. Secondly, the

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angular diameter of ζ Pup measured with the intensity interferometer by Davis *et al.* (1969) gives an effective temperature of only 31000 K for the sequence of model atmospheres used for the nebular temperature scale. Finally, Stecher's (1968) observed ultraviolet flux distribution from 1800 to 2200 Å, when placed on an absolute scale at the stellar surface by the angular diameter, corresponds to a model around 31000°K.

These absolute fluxes are shown in Figure 2, where F_ν must be multiplied by π to obtain the physical flux. The visual point derived from the apparent magnitude shows the error bars for the angular diameter, but the uncertainties from the absolute calibration of the V magnitude scale are of the same order. The ultraviolet part of the curve is Stecher's spectral scan with the strong emission and absorption lines smoothed from 1350 to 1750 Å. Also plotted in Figure 2 are blanketed models from Hickok and Morton (1968), and Bradley and Morton (1969) with $\log g = 4.0$ and $\theta_e = 0.153$, 0.164, 0.176, corresponding respectively to $T_e = 32940$, 30730 and 28640 K. (The model for $\theta_e = 0.153$, $\log g = 3.5$ lies between the curves for $\theta_e = 0.164$, $\log g = 4.0$ and $\theta_e = 0.153$ $\log g = 4.0$, so that a slightly hotter temperature would be needed to fit the data to a model with lower surface gravity.) The visual point and the UV flux longward of 1800 Å are reasonably consistent, but at shorter wavelengths there is a major decrease in flux. A check on Stecher's measures is provided by the broad-band observations of Smith (1967) at $1/\lambda = 7.3\mu^{-1}$ and Carruthers (1968, 1969) at 7.9 and $9.0\mu^{-1}$ which give $F_\nu = 5.7 \pm 0.6 \times 10^{-3}$, 6.5×10^{-3} and 9.0×10^{-3} erg cm^{-2} sec^{-1} Hz^{-1} respectively. The values at 7.3 and $7.9\mu^{-1}$ appear to confirm that there is a flux deficiency in ζ Pup below the blanketed model with $\theta_e = 0.164$, but the third point suggests the effect does not extend to $1/\lambda = 9.0\mu^{-1}$. However, the more important result is that for ζ Pup, $T_e \approx 31000$ K, which is much cooler than the temperatures derived from the Hα and radio observations of O5 and even O6 stars imbedded in nebulae.

Acknowledgement

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Discussion

Stecher: You have left out the emission lines in this consideration. When you add them in, the situation is somewhat improved.

Morton: For simplicity I have smoothed over both emission and absorption lines and they cancel each other to some extent so that the basic discrepancy remains.

Underhill: The O spectral types are assigned according to line ratios, chiefly HeI/HeII. The apparent strengths of these lines are not sensitively affected by T_{eff} and the continuous spectrum of the model. Thus any correlation between models and stars (types) based on identifying stars with models *via* the continuous spectrum will be very uncertain at type O.

Martynov: The temperature for W-R stars given in the paper is much too high: in the eclipsing binary V444 Cygni the surface brightness (in the optical part of spectrum) of the W-R component is much smaller than that of the O-component.

Morton: The Wolf-Rayet temperatures are not very accurate because they depend on only one star each, but a large range of temperatures is indicated. In a more recent investigation of these stars in nebulae I have found one at 31000 K and another possibly as cool as 25000 K.

Sunayev: I think the main contribution to the heating of gas in nebulae near hot stars may come from the stellar wind connected with mass loss from the stars. Dr. Tscheglov (Sternberg Astronomical Institute) has found from Hα observations regions in nebulae, with very high velocities ($\sim$ 100 km sec^{-1}). Prof. Pikelner has calculated the interaction of a stellar wind with the interstellar medium and showed that in some nebulae there must exist shock waves, which obviously must heat the interstellar gas. The energy in the stellar wind is very high in the case of O and B stars and it may be that its interaction with gas gives the main contribution to heating, and the photon flux in the Lyman continuum region may be not so high.

Morton: Certainly the wind from some O stars will have an important effect on the surrounding interstellar gas, but it is not certain that all stars in my list have significant mass loss.