TEMPERATURES AND RADII OF O STARS

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ABSTRACT

Angular diameters have been estimated for 18 O and 142 B stars using absolute intermediate-band photometry in the near infrared and they have been combined with integrated fluxes to yield effective temperatures. The effective temperatures of the O stars lie in the range 30000 K to about 47000 K. For a given subtype, the luminosity class I stars have lower effective temperatures than the main-sequence stars by about 1000 K. The absorption-line spectral types of the supergiants of types O and B reflect electron temperatures which are higher than can be maintained by the integrated flux which flows through the stellar atmosphere. Distances have been estimated for all the stars and linear diameters found. The average radius for an O8 to O9.5 supergiant is about 23.3 $R_\odot$; the radii for luminosity class III and Class V O stars lie in the range 6.8 to 10.7 $R_\odot$.

METHOD

The flux effective temperature of a star is defined by the relation

$$T_{eff}(\mathrm{flux}) = (4f/\sigma_R)^{\frac{1}{4}}\,\theta^{-\frac{1}{4}}, \qquad (1)$$

where f is the integrated flux from the star over the full extent of the spectrum, σ_R is the Stefan-Boltzmann constant and θ is the angular diameter. We find f over the range 1380 to 11084 Å using the S2/68 absolute ultraviolet spectrophotometry (Jamar et al. 1976) and the absolute-energy 13-colour photometry of Johnson and Mitchell (1975). We correct for interstellar extinction using the reddening law of Nandy et al. (1975, 1976). The parts of f shortward of 1380 Å and longward of 11084 Å are estimated using the predicted continuum fluxes from the adopted model atmospheres with the derived angular diameters.

The angular diameters for our stars are found from the relation

P. S. Conti and C. W. H. de Loore (eds.), Mass Loss and Evolution of O-Type Stars, 103–108.

$$\theta_{\lambda} = 2(f_{\lambda} / \mathcal{F}_{S,\lambda})^{\frac{1}{2}}, \tag{2}$$

where f_{λ} is the absolute flux in a Johnson and Mitchell intermediate-width passband having an effective wavelength in the range 6356 to 11084 Å. We usually found a mean value from the results from the 6 longest passbands. If an infrared excess seemed to be present, we omitted the results from the longest wavelength band. Here $\mathcal{F}_{S,\lambda}$ is the monochromatic flux emitted in wavelength λ at the star. It is approximated by the monochromatic flux from a model atmosphere. We adopted the LTE, classical model atmospheres of Kurucz (1977) and their continuum fluxes in 25-angstrom-wide bands. We found that the predicted continuous spectra from these models at the wavelengths we needed were essentially the same as those of the NLTE models of Mihalas (1972), and that they were more consistent and given in greater detail than the Mihalas results. To select a representative model for each star, we adopted the effective temperature scale of Conti (1975) for the O stars, which is based on an interpretation of the strengths of the He I and He II lines using the NLTE calculations of Auer and Mihalas (1972). We assigned log g equal 4.5 for main-sequence stars and 4.0 or 3.5 for giants and supergiants.

If the angular diameters are to be correct, the monochromatic fluxes used in eqt. (2) must refer to single stars. For those of our stars for which the spectrophotometry refers to two or more stars, we made a correction, representing the light from the companion(s) by photometry from a single B star of the same spectral type scaled to allow for the difference in magnitude and interstellar extinction between it and the companion.

STARS STUDIED

The O stars which we have studied are α Cam O9.5Ia, δ Ori A O9.5II, ν Ori O9V, λ Ori A O8III((f)), σ Ori AB O9.5V, ζ Ori A O9.5Ib, S Mon A O8III((f)), HD 48099 O6.5V, UW CMa O8.5If, τ CMa O9I, ζ Pup O4ef, ζ Oph O9Ve, HD 151804 O8Ifp, 9 Sge O8If, HD 188209 O9.5Ib, HD 193322A O8.5III, λ Cep O6ef and 10 Lac O8III. We also studied 142 B stars.

RESULTS

We have 14 stars in common with Hanbury Brown et al. (1974). Fig. 1 shows that we can systematically reproduce the angular diameters measured by the intensity interferometer provided that for the B-type supergiants and giants we use a representative model atmosphere with an effective temperature corresponding to the $(B-V)_0$ colour. The one widely divergent point, at $\theta_{LD} = 19.2 \times 10^{-4}$ arc sec, is α Eri. We do not know the reason for this discrepancy. Usually the agreement between our angular diameters and those of Hanbury Brown et al. is excellent.

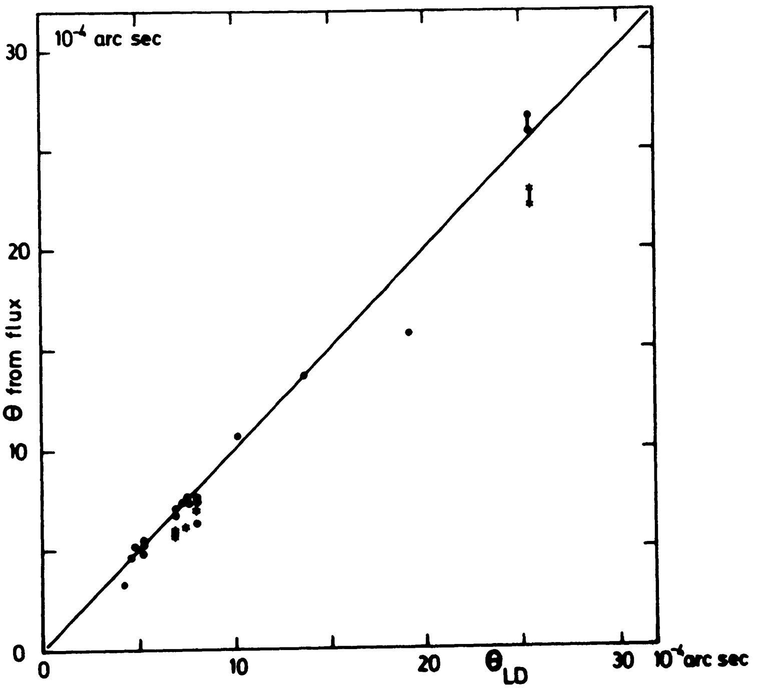

Fig. 1. The relation between angular diameters found from long-wavelength fluxes and the angular diameters measured by Hanbury Brown _et al_. (1974) for 14 stars. Points using the same model fluxes but different values of E(B-V) are joined by a vertical line. The angular diameters of ϵ Ori, B0Ia, η CMa, B5Ia, β Ori, B8Ia and ϵ CMa, B2II are plotted with filled circles when a model effective temperature correspon-ing to the $(B-V)_0$ is used, and by a star when a model effective temperature like that suggested by the line spectrum is used. The other stars, α Eri, γ Ori, ζ Ori A, β CMa, ζ Pup, α Leo, δ Sco A, ζ Oph, α Pav and α Gru are represented by filled circles.

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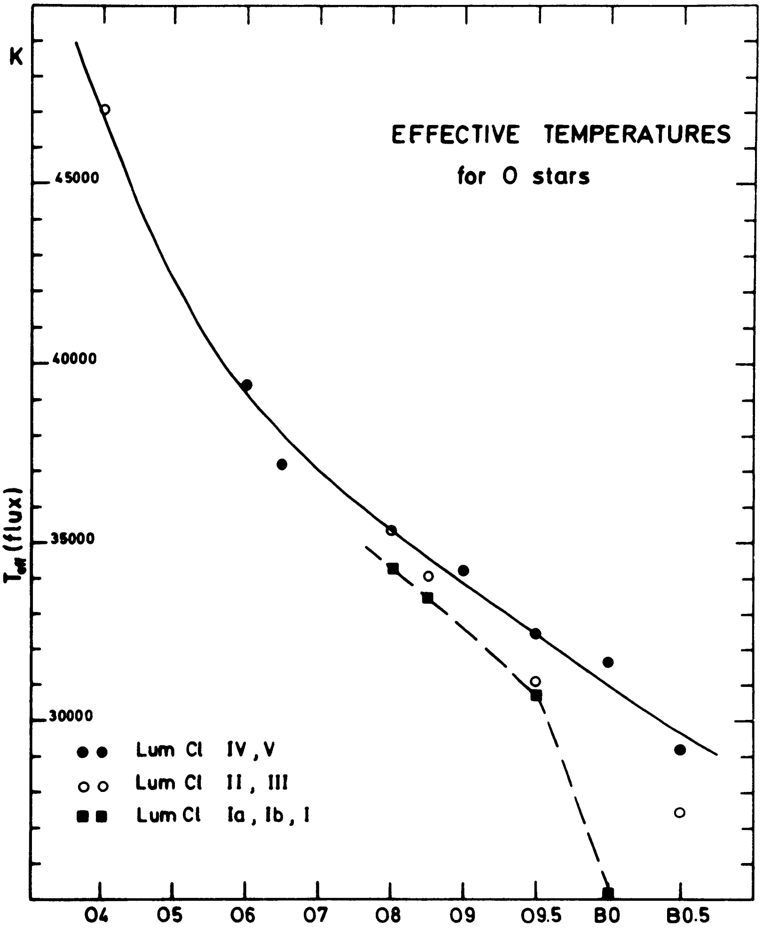

Fig. 2. Flux effective temperatures for the O stars as a function of spectral type.

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The average flux effective temperatures for each O subtype represented in our data are shown in Fig. 2 as a function of spectral type. The effective temperatures of the main-sequence stars are the largest at each subtype. Those of the giants and the supergiants are smaller. The result for ζ Pup, 47120 K, is significantly higher than that of Code et al. (1976), 32510 K, and it is reasonable for the assigned spectral type. We find a high effective temperature for ζ Pup because we find θ = 3.27 x 10^{-4} arc sec in place of 4.2 x 10^{-4} arc sec as found by Hanbury Brown et al. No reasonable change in our choice of representative model atmosphere or of reddening correction permits us to reproduce the result of Hanbury Brown et al. It is unlikely that the discrepancy is due to our use of planar geometry to calculate the continuous spectrum.

The flux effective temperatures of the O-type supergiants are about 1000 K lower than those of main-sequence stars of the same subtype. This systematic trend becomes marked in the B supergiants. The discrepancy is more than 6000 K at type BO. We think that the assigned absorption-line spectral types of O and B supergiants correspond to higher temperatures than the integrated flux can support because the strengths of the lines selected as spectral-type criteria reflect conditions in a superheated chromospheric layer rather than conditions in the photosphere.

The linear radii of the class I stars on our list average 23.3 $R_\odot$. The linear radius for δ Ori A is 15.8 $R_\odot$; for ζ Pup it is 15.1 $R_\odot$ while for λ Cep it is 13.9 $R_\odot$. The linear radii for the other stars of luminosity classes V and III range from 6.8 to 10.7 $R_\odot$.

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DISCUSSION FOLLOWING UNDERHILL et al.

Morton: The problem with ζ Pup is not likely an underestimate in the error on the measured angular diameter; it seems that for ζ Pup, which has a large mass outflow, the intensity interferometer is measuring a larger diameter than the photosphere.

Underhill: The 13-color photometry yields the same angular diameter from 4000 to 8600 Å, so I have some confidence in our result.

R. E. Wilson: A check on radii and luminosities such as those you have found can be provided by eclipsing binaries with good velocity data. The problem is that suitable examples are hard to find, especially on the ZAMS. I (Wilson and Rafert, in preparation) have some results of this kind for δ Pictoris, which you may want to compare with your work. Both components are on the ZAMS within the observational uncertainties.

Lamers: The situation on the effective temperatures of B-supergiants is very confusing. The detailed studies of the visual spectra by model atmosphere techniques (e.g., Lamers, 1974, Astron. Astrophys. 37, 237) clearly indicate much larger temperatures than those derived from absolute integrated fluxes. This might indicate that the model atmospheres are not adequate. Would the choice of wrong models for deriving the angular diameter and for extrapolating the flux to wavelength shortward of 1200 Å affect the resulting values of T_{eff} for early-B supergiants?

Underhill: The choice of T_{eff} for the model to predict the continuous spectrum is closely constrained by the requirement that the shape be correct from 6356 to 11084 Å and that the Hanbury-Brown et al. angular diameters be found for the supergiants which he observed (types B0 Ia, B5 Ia, B8 Ia). We tried low and high effective temperatures for the supergiants. Only low effective temperatures corresponding to $(B-V)_0$ reproduce the measured angular diameters and have the correct shape. The "absorption-line" effective temperatures are clearly too high. This point will be discussed fully in the paper which Divan, Doazan, Prévot-Burnichon and I will be submitting to Astron. Astrophys.