ON ULTRAVIOLET FLUXES, BOLOMETRIC CORRECTIONS AND EFFECTIVE TEMPERATURES OF LATE B TO F STARS

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Abstract. Observed ultraviolet fluxes have been compared with the predictions of line blanketed model atmospheres for stars of spectral type later than B5. The comparison reveals significant differences which increase towards later spectral type and which lead to differences between empirical and theoretical bolometric corrections. Empirical bolometric corrections for the spectral range B8–F5 have been computed from a combination of ultraviolet, visual and infrared observational data. These have been used to derive empirically based effective temperatures for five A and F type stars for which angular diameter measurements are available.

1. Introduction

The bolometric correction and effective temperature scales for early type stars have been based on the predictions of theoretical model stellar atmospheres in the past. This is because a large fraction of the emergent flux for hot stars is in the ultraviolet and, without measurements in this region of the spectrum, recourse to theoretical estimates was necessary. Since bolometric corrections and effective temperatures play an essential role in the comparison of observations with the results of stellar-interior calculations it would be desirable to derive them directly from observable quantities wherever possible. The empirical data now available in the form of visual spectral energy distributions, infrared photometry, and ultraviolet flux and angular diameter measurements are adequate for this purpose for main sequence stars in the spectral range B8–F5.

The bolometric corrections and effective temperatures derived from observational data for B8–F5 type stars differ significantly from those based on theoretical models and a comparison of the observed ultraviolet fluxes with the model predictions has revealed the reason for the differences.

2. Ultraviolet Fluxes

A. OBSERVED AND THEORETICAL ULTRAVIOLET FLUXES

Figure 1 shows a comparison of observed ultraviolet fluxes with the predictions of model atmospheres for stars of luminosity classes IV and V and spectral type B5 and later at 2800 Å, 2100 Å and 1376 Å.

In selecting observational data for the comparison, peculiar stars and double and variable stars for which the observed fluxes might be significantly affected by their nature, have been excluded. All the observational data have been converted to fluxes

Houziaux and Butler (eds.), Ultraviolet Stellar Spectra and Ground-Based Observations, 90–99.

per unit frequency interval, reduced to $V=0.00$, and corrected for reddening where necessary.

The theoretical models chosen for comparison with the observations are the Balmer line blanketed models of Mihalas (1966) with $\log g=4$. Before the theoretical fluxes could be plotted in Figure 1 it was necessary to identify the models with real stars and to reduce the predicted emergent fluxes to $V=0.00$. The effective temperature scales of Wolff *et al.* (1968) and Hanbury Brown *et al.* (1967) which were based on the Mihalas Balmer line blanketed models may be regarded as an identification of the models

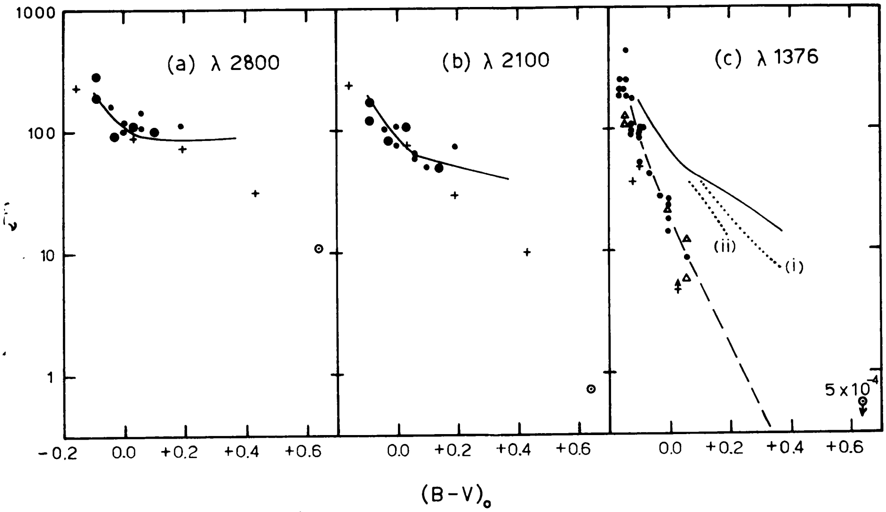

Fig. 1. Ultraviolet fluxes for main sequence stars and model atmospheres for (a) 2800 Å, (b) 2100 Å and (c) 1376 Å. The full curves represent the predicted fluxes for the Balmer line blanketed models of Mihalas. All data have been reduced to $V=0.00$ (3.78×10^{-20} erg cm^{-2} sec^{-1} Hz^{-1} at $1.83\mu^{-1}$). The ordinate is in units of 10^{-22} erg cm^{-2} sec^{-1} Hz^{-1}. – (a) and (b). Large dots: observations by Bless *et al.*; small dots: observations by Bless *et al.* which were followed by a colon; crosses: observations by Stecher. The solar fluxes are those given by Labs and Neckel. – (c) Dots: observations by Smith at 1376 Å; triangles: observations by Chubb and Byram (1963) at 1427 Å; crosses: observations by Chubb and Byram at 1314 Å. The solar flux is by Detwiler *et al.* (1961). The dotted curves represent the predicted fluxes for the convective models of Mihalas. The curve marked (i) is for $1/H=1$ and the curve (ii) is for $1/H=2$. The dashed curve passes through the mean fluxes of Smith at $B-V=-0.09$ and $B-V=0.00$ and is extrapolated to the solar point.

with real stars and these have been used in conjunction with Mihalas' own identification of his models with stars. To normalise the fluxes to $V=0.00$ the flux at the constant energy reciprocal wavelength (Code, 1960) of the V magnitude system ($1.83\mu^{-1}$) was taken to be 3.78×10^{-20} erg cm^{-2} sec^{-1} Hz^{-1}, a value based on the work of Code (1960), Willstrop (1965), and Labs and Neckel (1968) (see Davis and Webb, 1970). In addition to the fluxes for the Balmer line blanketed models, which are represented by the full curves in Figure 1, fluxes for the convective models of Mihalas (1965) with $1/H=1$ and $1/H=2$ are also plotted in Figure 1c for 1376 Å. The fluxes for the convective models do not differ significantly from those for the Balmer line blanketed radiative models at 2800 Å and 2100 Å.

B. DISCUSSION

Figures 1a and 1b show that for 2800 Å and 2100 Å the observations and theoretical predictions are in good agreement for the earlier spectral types considered, but that in passing to later spectral types the observations fall significantly and increasingly below the theoretical curves, the breakaway occurring earlier for the shorter wavelength. The data by Bless *et al.* (1968) and Stecher (1969) at 2500 Å show effects intermediate to those at 2800 Å and 2100 Å. The fact that the observations can be extrapolated smoothly to the solar fluxes confirms that the fall away from the theoretical curves is a real effect.

At 1376 Å the observed fluxes all lie below the theoretical curves and it is noted that even if Smith's absolute calibration of his observational data is wrong, and it appears unlikely that it can be seriously in error, there is a difference in slope between the observations and the theoretical curves. The solar flux falls well below Figure 1c but the dashed curve shows that the observations can be extrapolated smoothly to it. It is concluded that for 1376 Å the fluxes are less than predicted by the Mihalas models and that the discrepancy increases towards later spectral types just as it does at longer ultraviolet wavelengths. The difference between theory and observation is ~ 1.2 mag. at $(B-V)_0 = 0.00$ and the extrapolated curve suggests that it is of the order of 5 mag. at $(B-V)_0 = +0.40$.

The discrepancies between the Mihalas model predictions and the observed ultraviolet fluxes would be greatly reduced by the inclusion in the models of additional sources of ultraviolet opacity such as bound-free absorption by Mg I and Si I (Strom and Strom, 1969) and by C I (Gingerich, 1969), the more important bound-bound metallic and hydrogen absorptions (see for example Mihalas and Morton (1965), Van Citters and Morton (1969)) and, to a lesser extent, by the effects of convection, Mihalas (1965) as shown in Figure 1c. The inclusion of any of these features will affect the relative magnitude of the visual and ultraviolet fluxes. For example, for a given effective temperature the visual fluxes would be expected to increase relative to those predicted by the Mihalas models if the ultraviolet spectrum is depressed. Alternatively, for a given visual flux, the inclusion of additional ultraviolet opacities will lead to a model of lower effective temperature. It is important to take this into account in considering bolometric correction and effective temperature scales based on the identification of observable parameters with model predictions.

3. Bolometric Corrections

A. DEFINITION

The bolometric correction (BC) is, conventionally, the correction required to reduce visual magnitudes to bolometric magnitudes and is defined by

$$\mathrm{BC} = m_{\mathrm{bol}} - V \tag{1}$$

https://doi.org/10.1017/S0074180900101895 Published online by Cambridge University Press

which is equivalent to writing

$$\mathrm{BC} = 2.5 \log \frac{\int_0^\infty f_\nu S_V \, \mathrm{d}\nu}{\int_0^\infty f_\nu \, \mathrm{d}\nu} + \text{constant} \tag{2}$$

where f_ν is the flux per unit bandwidth received outside the atmosphere from a star at frequency ν, and S_V is the sensitivity function of the V magnitude system.

The constant in Equation (2) is uniquely defined if we adopt a value for the bolometric correction for a specified spectral distribution of f_ν. In practice the Sun is the only star for which f_ν is sufficiently well known to define the zero point of the bolometric correction scale. For a star of spectral type G2 V a value of BC $= -0.07$ has been adopted by Popper (1959), Harris (1963) and many others. We therefore adopt -0.07 for the bolometric correction for the Sun together with the solar spectral energy distribution tabulated by Labs and Neckel (1968) and the sensitivity function S_V, outside the atmosphere, tabulated by Matthews and Sandage (1963) (their v_0).

Equation (2) can now be written

$$\mathrm{BC} = 2.5 \log \frac{\int_0^\infty f_\nu S_V \, \mathrm{d}\nu}{\int_0^\infty f_\nu \, \mathrm{d}\nu} + \left\{ -0.07 - 2.5 \log \frac{\int_0^\infty f_{\nu\odot} S_V \, \mathrm{d}\nu}{\int_0^\infty f_{\nu\odot} \, \mathrm{d}\nu} \right\}, \tag{3}$$

where $f_{\nu\odot}$ is the solar flux per unit bandwidth from Labs and Neckel (1968) (from their $H(\lambda)$).

In the case of a model stellar atmosphere the bolometric correction is given by Equation (3) if f_ν is replaced by πF_ν.

B. BOLOMETRIC CORRECTIONS FROM OBSERVATIONAL DATA

Bolometric corrections for stars of spectral type later than about F5 can be derived from ground-based observations alone as has been done by Kuiper (1938) and Popper (1959) using radiometric magnitudes, and by Johnson (1966) using multicolour photometry. For earlier type stars a large fraction of the flux is in the ultraviolet region of the spectrum and a reliable bolometric correction can only be derived if the absolute flux in the ultraviolet has been measured with reasonable precision. Because of the present uncertainty in the absolute calibration of observations for $1/\lambda \gtrsim 7.6\mu^{-1}$ it is not possible to derive accurate bolometric corrections for stars of spectral type earlier than about B8.

Empirical bolometric corrections have been computed for the four cases listed in Table I using Equation (3). Ultraviolet fluxes (Smith, 1967, 1969; Bless *et al.*, 1968;

and Stecher, 1969), visual energy distributions (Bahner, 1963; Hayes, 1967; and Wolff *et al.*, 1968) and absolute infrared photometry (Johnson *et al.*, 1966, and Johnson, 1966) were combined to obtain the absolute energy distributions (i.e. the energy distributions in flux units) for the four cases by reducing all absolute fluxes to $V=0.00$ and normalising the visual energy distributions to $V=0.00$ by making $f(1/\lambda=1.83)=3.78\times10^{-20}$ erg cm^{-2} sec^{-1} Hz^{-1}.

As an example the normalised empirical fluxes for α CMi are plotted in Figure 2. The continuum flux distribution for a Balmer line blanketed model with $\theta_e=0.75$ and $\log g=4$, obtained by extrapolating the data for the Mihalas (1966) grid of models, has been included in the diagram for comparison with the empirical data. When corrections for line absorption effects between $2.75\mu^{-1}$ and $1.57\mu^{-1}$ (Oke and Conti, 1966) are made to the theoretical continuum fluxes, as shown by the dotted curve, the

TABLE I

Computed empirical bolometric corrections

Spectral type	$B-V$	Empirical BC
B8 V[a]	-0.09	-0.55 ± 0.10
A0 V[b]	0.00	-0.21 ± 0.08
A7 IV, V[c]	$+0.22$	$+0.01\pm0.06$
F5 IV–V[d]	$+0.42$	-0.04 ± 0.04

[a] Mean flux data for B8 V used for BC
[b] Mean flux data for A0 V used for BC
[c] Flux data for α Aql used for BC
[d] Flux data for α CMi used for BC

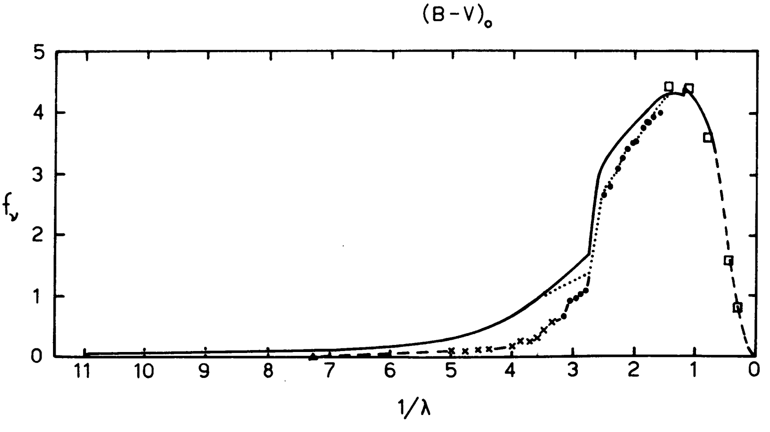

Fig. 2. Empirical absolute flux distribution for α CMi (F5 IV–V) normalised to $V=0.00$. The data are represented by squares: Johnson (1966); dots: Bahner (1963); crosses: Stecher (1969); triangle: from Figure 1c. Full curve: continuum flux distribution for model with $\theta_e=0.75$ and $\log g=4$ (extrapolated from Mihalas, 1966) normalised to $V=0.00$; dotted curve: model corrected for line absorption; dashed curve: drawn through empirical points. Ordinate: in units of 10^{-20} erg cm^{-2} sec^{-1} Hz^{-1}; abscissa: in μ^{-1}.

agreement with the observational points is reasonably good on the long wavelength side of the Balmer jump. The differences between theory and observation in the ultraviolet are obvious. The empirical absolute energy curve has been completed by taking a linear interpolation between Stecher's point at $5.88\mu^{-1}$ and the point derived from Figure 1 at $7.27\mu^{-1}$.

Since the bandpasses for the observational data avoid the inclusion of Balmer lines, small corrections ($\leqslant 0.04$) have been made to the bolometric corrections derived from the empirical absolute energy curves. The uncertainties in the final values for the empirical bolometric corrections are set primarily by the uncertainties in the absolute calibration of the ultraviolet fluxes and in the far ultraviolet extrapolation, the latter dominating for the B8 V and A0 V cases.

C. DISCUSSION

The empirical bolometric corrections have been plotted in Figure 3 and a curve drawn through them to join smoothly to the point representing the Sun. For comparison, bolometric corrections for the Mihalas Balmer line blanketed models computed from the equivalent of Equation (3) (Davis and Webb, 1970*) are also shown. The empirical values fall below the curve through the theoretical points as would be expected from the differences in the ultraviolet fluxes.

The empirical bolometric corrections tabulated by Popper (1959), which give BC = -0.07 for a star of the same colour as the Sun, are also plotted in Figure 3 and the

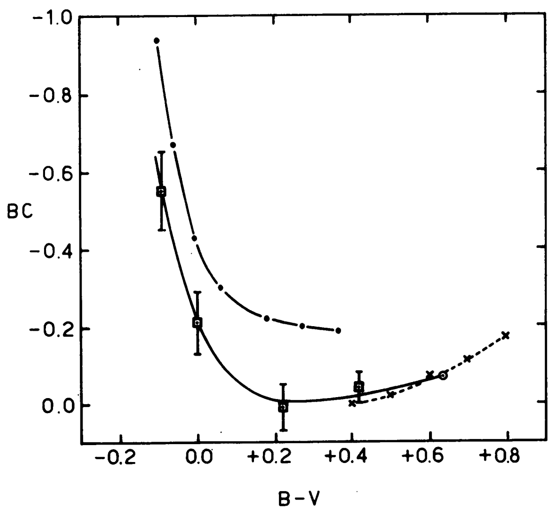

Fig. 3. Bolometric corrections for main sequence stars. Dots: Mihalas Balmer line blanketed model values from Davis and Webb (1970); crosses: mean empirical values (Popper, 1959, his Table II); squares: empirical values from Table I. The curves have been fitted to the points by eye in each case.

* This reference contains a detailed discussion of bolometric corrections derived for model atmospheres.

https://doi.org/10.1017/S0074180900101895 Published online by Cambridge University Press

new results show good agreement with them. The small difference in slope in the overlapping region which is suggested by the curves drawn through the data can be explained by the fact that Popper's bolometric corrections do not include corrections for the ultraviolet flux for $1/\lambda > 3.3\mu^{-1}$.

Johnson (1966) has given empirical bolometric corrections which are appreciably greater than the values presented in Table I. This is expected since Johnson based his calculations for stars hotter than the Sun on estimates of the ultraviolet flux made from the data available at the end of 1965. These data were generally lower than the more recent data, on which the present values are based, and therefore led to less negative values for the bolometric corrections.

4. Effective Temperatures of A and F Type Stars

The new empirical bolometric corrections can be combined with measurements of stellar angular diameters to give empirical effective temperatures. Table II lists five stars in the spectral range A–F whose angular diameters have been measured by Hanbury Brown *et al.* (1967). The bolometric corrections given in Table II are, for α Aql and α CMi, the values derived for these stars; for α Lyr and α CMa, the value derived for $B-V=0.00$; and for α PsA, the interpolated value given by the empirical curve in Figure 3 for $B-V=+0.09$. In addition to the photometric data for these stars (Johnson *et al.*, 1966) and their angular diameters (Hanbury Brown *et al.*, 1967), the angular diameter (1919″), the V magnitude (-26.74 from Johnson (1965)), the effective temperature (5780 K from Labs and Neckel (1968)), and the bolometric correction (-0.07 by definition, Section 3a) of the Sun have been used to obtain the effective temperatures in column 5 of Table II. These effective temperatures are based entirely on observational data and in the cases of α Aql and α CMi (except for the ultraviolet flux at 1376 Å which is almost negligible) on data from observations of these stars, as opposed to averaged data for stars of the same spectral type. It follows that the effective temperatures for α Aql and α CMi are the best values that can be determined specifically for them.

TABLE II

Effective temperatures for 5 stars of spectral type A–F

BS	Star	Spectral type	BC	T_e(K)[a] (BC)	T_e(K)[b] (M)	T_e(K)[c] (HB)
7001	α Lyr	A0 V	-0.21	9330	9700	9500
2491	α CMa	A1 V	-0.21	9910	10750	10380
8728	α PsA	A3 V	-0.07	8970	9550	9300
7557	α Aql	A7 IV, V	$+0.01$	8110	8600	8250
2943	α CMi	F5 IV–V	-0.04	6470	–	–

[a] Effective temperature from empirical bolometric correction.
[b] Effective temperature from theoretical model bolometric correction.
[c] Effective temperature given by Hanbury Brown *et al.* (1967).

We note that the empirical effective temperatures could have been obtained directly from the absolute flux distributions by using

$$\sigma T_e^4 = \int_0^\infty \pi F_\nu \, d\nu = \frac{4}{\theta_{LD}^2} \int_0^\infty f_\nu \, d\nu , \tag{4}$$

where f_ν is the flux per unit bandwidth received outside the Earth's atmosphere and θ_{LD} is the angular diameter of the star. This is completely equivalent to using the bolometric correction since the solar data enter only because the Sun is used to fix the arbitrary constant in the definition of the bolometric correction (Section 3a).

Effective temperatures based on the theoretical bolometric corrections in Figure 3 will be systematically higher than those based entirely on empirical data as a consequence of the excess ultraviolet flux predicted by the Mihalas models. Although they have no real significance, effective temperatures from the theoretical bolometric corrections have been included in column 6 of Table II for comparison purposes.

Column 7 of Table II contains the effective temperatures assigned to the stars on the basis of a comparison of the empirical and theoretical model fluxes at 4425 Å by Hanbury Brown *et al.* (1967). It is to be expected that temperatures based on a comparison of observed fluxes in the visual region of the spectrum with those predicted by the Mihalas models should be higher than those based on empirical flux distributions and this is borne out by a comparison of the figures in Table II.

It is clear that effective temperatures based on the Mihalas models should be treated as upper limits to the interpretation of the observations. We believe that effective temperatures based on the empirical bolometric corrections are to be preferred but since additional angular diameter measurements should be available in the near future we have refrained from tabulating an empirically based effective temperature scale.

5. Conclusions

It has been demonstrated that empirical bolometric corrections and effective temperatures can be determined for main sequence stars in the spectral range B8 to F5 from the available data. These empirical results are preferred to results based on present model atmosphere predictions because of large differences between the predicted and observed ultraviolet fluxes.

The Mihalas (1966) Balmer line blanketed models predict ultraviolet fluxes significantly greater than are observed and this points to the need for new models for late B and A type stars which take into account additional sources of continuous and line absorption and which include the effects of convective energy transport for the cooler models.

Although it does not follow from the present discussion that the predictions of the hotter ultraviolet line blanketed models are incorrect, it is of great importance to have reliable far ultraviolet fluxes in order to test them. The availability of such measurements would allow empirical bolometric corrections and effective temperatures to be obtained for stars of spectral types earlier than B8.

The time is approaching when the combination of ultraviolet flux data and visual and infrared observations with angular diameter measurements will allow the effective temperature scale for early type stars to be put on a sound observational basis.

Acknowledgements

We are grateful to Drs. Daniel M. Popper and Donald C. Morton for their interest in this work and for valuable discussions. We are also indebted to Drs. O. Gingerich, D. C. Morton and T. P. Stecher for making available results in advance of publication, to Drs. D. Mihalas and A. M. Smith for supplementary data, and to Professor R. Hanbury Brown for his interest and support. This investigation formed part of the programme of the Stellar Intensity Interferometer group which is supported by the Air Force Office of Scientific Research (Office of Aerospace Research) of the United States Air Force under grant (AFOSR-68-1560), the Australian Research Grants Committee, the Research Grants Committee of the University of Sydney and the Science Foundation for Physics within the University of Sydney. One of us (R. J. W.) gratefully acknowledges the tenure of a Commonwealth Scholarship.

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Discussion

Heintze: You are using the solar energy distribution as measured by Labs and Neckel to determine the constant in the formula for the bolometric correction. In spite of the fact that Labs and Neckel's measurements agree with the observed value of the solar constant I am more inclined to trust Peyturaux's (1968) measurements of the solar energy distribution. According to these observations the slope of the continuum from 7000 to 4500 Å is steeper than that according to Labs and Neckel and the difference between them is equal to the difference in slope between Hayes (1967) and the 1964 adoption of the energy distribution of α Lyr (Oke, 1964). According to me (Heintze, 1969; see also Aller *et al.*, 1966) Willstrop's (1965) observations are in agreement with the 1964 adoption of the energy distribution of α Lyr. Labs and Neckel show that their energy distribution of the Sun agrees very well with Willstrop's measurements of a G2 V star. Applying corrections Oke-Hayes on the energy distribution of this G2 V star it is in agreement with Peyturaux's observations. I wonder whether the discrepancies you mentioned will disappear when Peyturaux's measurements are used.

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Davis: I disagree with you concerning the intercomparison of the relative photometry. I find that Willstrop's relative photometry is in good agreement with Hayes' calibration but is not in such good agreement with the calibration adopted by Oke in 1964. Hayes may care to comment?

Hayes: With respect to the comparison of my calibration and Willstrop's, the difficulty is that there are few stars in common. I have used my own and other reliable spectrophotometry reduced to my system to make this comparison, and I find that Willstrop's calibration agrees well with mine.