PART VII

STELLAR TEMPERATURE SCALE AND BOLOMETRIC CORRECTIONS

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

STELLAR TEMPERATURE SCALE AND BOLOMETRIC CORRECTIONS

J. R. W. HEINTZE

Astronomical Institute Sonnenborgh Observatory, Utrecht, the Netherlands

Abstract. In chapter 1 basic methods are reviewed, and applications and suggestions for future work are presented. In chapter 2 a revision is given of the intrinsic-colour relation in the *U, B, V* system of hot main-sequence stars. Some temperature-colour relations are discussed in chapter 3, where also a correction formula is given for the effects of interstellar reddening on the effective temperatures of hot main-sequence stars. An empirical mass-luminosity relation is given in chapter 4.

1. Basis Methods, Future Work and Applications

1.1. Introduction

Pecker (these proceedings, page 173) has reviewed some problems concerning the determination of effective temperatures. From his paper it will be clear that no new scales of temperatures and of bolometric corrections can be given at this moment. Such scales would not be better than previous ones.

At the moment there is far more sense in trying to reduce some of the disagreements mentioned by Pecker. This can be done by improving the theory as well as the observational accuracy. The latter will be emphasized in this paper.

1.2. Basic formulae

The well known definition formula of the effective temperature, T_{eff}, is

$$\sigma T_{\text{eff}}^4 = \pi \int_0^\infty \mathscr{F}_\lambda \, \mathrm{d}\lambda = \pi \int_0^\infty \mathscr{F}_\nu \, \mathrm{d}\nu , \tag{1}$$

where σ denotes Stefan-Boltzmann's constant and $\mathscr{F}$ is the monochromatic emergent flux at wavelength λ (ergs cm^{-3} s^{-1}) or at frequency ν (ergs cm^{-2} s^{-1} Hz^{-1}).

The absolute bolometric magnitude, M_{bol}, can be written as

$$M_{\text{bol}} = - 5 \log R/R_\odot - 10 \log T_{\text{eff}} + M_{\text{bol}_\odot} + 10 \log T_{\text{eff}_\odot} . \tag{2}$$

Combined with the definition of the bolometric correction, *BC*,

$$M_{\text{bol}} = M_v + BC , \tag{3}$$

one gets the classical expression:

$$BC = - M_v - 5 \log R/R_\odot - 10 \log T_{\text{eff}} + M_{v_\odot} + BC_\odot + 10 \log T_{\text{eff}_\odot} . \tag{4}$$

This formula gives the possibility to determine the *BC* in an empirical way (see

B. Hauck and B. E. Westerlund (eds.), Problems of Calibration of Absolute Magnitudes and Temperature of Stars, 231–271.

Section 1.8). It may already be stated here, that $T_{\text{eff}\odot}$ (= 5800 K, see Code's paper, these proceedings page 131), $BC_\odot$ (see Section 1.8) and $M_{v\odot}$ (= 4.87 mag., Gallouet, 1964) can be assumed to be rather well known at present; that sometimes T_{eff} can be determined from spectral scans and spectra (Sections 1.6 and 1.7); that the radius $R/R_\odot$ sometimes can be found if the star is a component of a well studied eclipsing binary, which has well determined radial velocity curves, or sometimes can be calculated from the parallax and the angular diameter as could be obtained from interferometric measurements or lunar occultations; that M_v sometimes can be found from narrow band photometry, spectroscopic parallaxes or from astrometric parallaxes and V_0, the latter being given by

$$V_0 = V - R \cdot E(B - V). \tag{5}$$

Unfortunately, the colour excess, $E(B-V)$, (see chapter 2) as well as the ratio of the visual interstellar extinction to the colour excess, R, is often rather uncertain.

Other well known expressions for the BC are

$$BC = 2.5 \log \frac{\int_0^\infty S_\lambda \mathscr{F}_\lambda \, \mathrm{d}\lambda}{\int_0^\infty \mathscr{F}_\lambda \, \mathrm{d}\lambda} + c \quad \text{or} \tag{6a}$$

$$= 2.5 \log \frac{\int_0^\infty S_\lambda f_\lambda \, \mathrm{d}\lambda}{\int_0^\infty f_\lambda \, \mathrm{d}\lambda} + c \quad \text{or} \tag{6b}$$

$$= 2.5 \log \frac{\int_0^\infty S_\lambda F_\lambda \, \mathrm{d}\lambda}{\int_0^\infty F_\lambda \, \mathrm{d}\lambda} + c, \tag{6c}$$

where S_λ denotes a normalized photovisual sensitivity function as given by Matthews and Sandage (1963) for example (see the last but one paragraph of Section 2.7);

f_λ the monochromatic stellar flux at the Earth in a relative scale,

F_λ the absolute monochromatic stellar flux measured at the Earth, and

c a constant. For the Sun F_λ is measured over a sufficiently large wavelength region and $BC_\odot$ is known from Equation (3), $M_{v\odot}$ and the adopted zero point of the bolometric scale. So c is known. However, here a hitherto unsolved difficulty arises, which can be shown most easily by combining the Equations (6a) and (1) into:

$$BC = 2.5 \log \int_0^\infty S_\lambda \mathscr{F}_\lambda \, d\lambda - 10 \log T_{\mathrm{eff}} - 2.5 \log \int_0^\infty S_\lambda \mathscr{F}_\lambda(\odot) \, d\lambda + \\ + 10 \log T_{\mathrm{eff}}(\odot) + BC(\odot). \quad (7)$$

Now $\mathscr{F}_\lambda(\odot)$, as obtained from direct measurements or from an *empirical* solar model, is not equal to $\mathscr{F}_\lambda(\odot)$ as obtained from a *stellar* model with $T_{\mathrm{eff}} = 5800\,\mathrm{K}$ and $\log g = 4.44$ (cgs units), calculated in hydrostatic and radiative equilibrium and with constancy of the integrated flux throughout those parts of the model that are important for producing the emergent spectrum $\mathscr{F}_\lambda$. Reference may be made to Weidemann *et al.* (1967) and to the discussion remarks of Weidemann and Popper on page 276 of Gingerich (1969). It may be suggested that in order to determine an usable c the adopted $BC_\odot$ should be used is formula (6a) and that the $\mathscr{F}_\lambda(\odot)$ should be obtained from a stellar model with $T_{\mathrm{eff}} = 5800\,\mathrm{K}$ and $\log g = 4.44$.

1.3. Direct empirical determination of the BC and fundamental determination of T_{eff}

For some unreddened stars F_λ is already known over a sufficiently large wavelength region. In such cases BC can be determined empirically with Equation (6c). In the near future much more complete flux envelopes will be known of stars for which the BC then can be found with Equation (6c). A main problem will be the accurate correction of the observed flux envelope for interstellar and/or circumstellar reddening.

Once a BC is obtained in this way, the T_{eff} of that star can be found from Equation (4) rewritten as:

$$10 \log T_{\mathrm{eff}} = - M_v - BC - 5 \log R/R_\odot + M_{v\odot} + BC_\odot + 10 \log T_{\mathrm{eff}\odot}. \quad (8)$$

1.4. Theoretical determination of the BC

In most cases the BC's have still to be derived from model atmospheres with (6a), where $\mathscr{F}_\lambda$ is the calculated flux. A consistent grid of models should be used and this grid should include a model with $T_{\mathrm{eff}} = 5800\,\mathrm{K}$ and $\log g = 4.44$. It is necessary that the influence of variation of the line strengths is properly taken into account; the calculations have to be performed for a set of $V \sin i$ values. The constant c in Equation (6a) could be determined as suggested at the end of Section 1.2. A possibility of checking these BC's will be indicated in Section 1.8.

1.5. Determination of T_{eff} from theoretical bolometric corrections

The theoretical BC's according to Equation (6a) are a function the line strengths, $V \sin i$, $\log g$ and T_{eff}. These BC's can be plotted against T_{eff} together with (BC, T_{eff}) relations according to Equation (4) for stars for which $R/R_\odot$ and M_v are known. The intersection of the lines representing the Equations (6a) and (4) yields an estimate of the effective temperature. Note that T_{eff} can be estimated even if the star is reddened by interstellar extinction if $E(B-V)$ and R (see Equation (5)) are rather well known. Uncertainties in $BC_\odot$ do not matter too much if the $BC_\odot$ adopted in formula (4) is also used in Equation (6a) to calculate c.

An example of this method is given in Figure 14 in Heintze (1968) from which the effective temperatures of Vega and Sirius are estimated to be 9650 ± 550 K and 10800 ± 150 K respectively. In this Figure Balmer- and metal-line blanketed models of Strom (1968) were used for which $BC_\odot = -0.11$. Models with a 10 times higher metal abundance than the Sun give 10600 ± 150 K for Sirius, whereas Hanbury Brown *et al.* (1967) found 10350 ± 180 K from their interferometric measurements.

This Figure also shows that while for $T_{\text{eff}} < 10000$ K the BC practically does not depend on gravity, it does for $T_{\text{eff}} > 10000$ K. So in applying this method the gravity has to be known for the A and later type stars. Sometimes unexpected differences in gravity can occur. For example from

$$\log g = \log g_\odot + \log M/M_\odot - 2 \log R/R_\odot \tag{9}$$

and the radii found by Hanbury Brown *et al.* (1967) for Sirius and Vega it follows that $\log g_{\text{Sirius}} - \log g_{\text{Vega}} \approx 0.45$ assuming equal masses for both stars. Yet both stars were classified as main sequence stars for a long time (see discussion remark of Miss Divan in these proceedings, page 267).

1.6. The Determination of T_{eff} from Observed Energy Distributions in the Visual Part of the Spectrum

1.6.1. The Paschen Continuum

The observed absolute energy distribution of Vega according to Hayes (1967) and to Oke and Schild (1970) agree very well with each other in the Paschen continuum (see Code's paper in these proceedings, p. 131). With Vega as a standard, the energy distribution in the visual part of the spectrum of all kinds of stars can be determined fairly accurately with photoelectric scanner methods (for a general review article see Oke, 1965). Interstellar reddening changes the slope of the Paschen continuum and corrections have to be made for this. Comparison between the corrected and the theoretical energy distributions yields T_{eff}.

The slope of the Paschen continuum calculated from model atmospheres depends on the line strengths (whatever the cause of differences in the line strengths may be: abundance or NLTE effects, microturbulence influences), $V \sin i$, $\log g$ and T_{eff}. The blocking of the continuous energy flow of a star by lines causes backwarming, which changes the temperature distribution in some parts of the stellar atmosphere and therefore the energy distribution.

Bernacca (these proceedings, page 222) reported UV flux variations of α Scl. It would be of great interest to investigate whether linestrengths variations can be found in α Scl and whether they are correlated with the variations in the continuum flux.

The early grids of models did not include any blanketing effect. Nowadays grids exist of models with Balmer-line blanketing; with H- and He-line blanketing; with

H-, He- and metal-line blanketing and as reported by Schild (communication during the symposium) an extensive grid of models including all known absorbing mechanisms and all possible kinds of blanketing is in preparation at the Harvard-Smithsonian Astrophysical Observatory at Cambridge, Mass. As soon as this grid of models will be available an attempt can be made to revise the temperature scale and the bolometric corrections.

In general the computed slope of the Paschen continuum becomes the steeper the more line blanketing is put into the models. This causes a lowering of the effective temperature of a star of which the observed energy distribution is matched with theoretical energy distributions. At the same time the agreement between observed and calculated UV fluxes is being improved. Figure 8 in Underhill (1972) is an example: the energy distribution of a fully line-blanketed model with $T_{\text{eff}} = 10000$ K and $\log g = 4$ from Maran *et al.* (1968) gives much better agreement with the measured UV fluxes of Sirius between 2000 and 3000 Å than a H-line blanketed model of $T_{\text{eff}} = 9750$ K and $\log g = 4$ from Klinglesmith' (1971) grid.

1.6.2. *The Balmer Jump*

For the hot stars the Balmer jump, BJ, is a rather good temperature indicator. However, apart from the still existing differences in the observed BJ of Vega (see Code's paper, these proceedings page 131) there are some difficulties in the determination of the BJ from the observations and from the models, which should be carried out in the same way. The Balmer and Paschen continua have to be extra-polated to $\lambda 3700$. A rather good procedure is to plot monochromatic magnitudes (fluxes in units of erg cm^{-2} s^{-1} Hz^{-1}; $\mathscr{F}_\nu$) as a function of $1/\lambda$ and to extrapolate linearly from $1/\lambda = 2.2 - 2.4\ \mu^{-1}$ and $1/\lambda > 2.7\ \mu^{-1}$ to $1/\lambda = 2.7\ \mu^{-1}$ and to take the magnitude difference at $1/\lambda = 2.7\ \mu^{-1}$ (see also the answer to Schmidt-Kaler's comment on page 269 of these proceedings and the discussion remark of Miss Divan on page 267). BJ's determined in this way are independent of interstellar reddening, because the extinction (in mag., and flux-decrease in erg cm^{-2} s^{-1} Hz^{-1}) is a linear function of the frequency for $2.2 < 1/\lambda(\mu^{-1}) < 3$.

1.7. The simultaneous determination of T_{eff} and $\log g$

In the (T_{eff}, $\log g$) plane the line representing the possible combinations of T_{eff} and $\log g$ for which the model-Paschen continuum matches the observed one can be drawn as a function of abundance, line strengths etc. The observed H- and He-lines for example can provide other (T_{eff}, $\log g$) relations in the (T_{eff}, $\log g$) plane so that (an) intersection point(s) may be found (see Section 1 of Pecker's paper, in these proceedings page 173). Regarding the H-lines: the position of the line representing the possible combinations of T_{eff} and $\log g$ that can explain the observed hydrogen line profiles (see Figures 1 and 2 of Heintze, 1968) depends on whether the Edmonds *et al.* (1967) broadening function or the Griem (1967) broadening theory is used. Up till now no conclusive observational evidence has been obtained for deciding which broadening function has to be preferred. Moreover, the profiles of the published (observed) H profiles of a star depend on the chosen height of the continuum above the H line and vary greatly from one observer to the other. As soon as these problems are solved one possible cause of discrepancies in determining T_{eff} with (T_{eff}, $\log g$) relations can be removed.

A nice example of the use of the (T_{eff}, $\log g$) plane is given in Figure 2 in Klinglesmith (1972). (T_{eff}, $\log g$) relations as derived from the Paschen continuum, the H-lines and the He I-lines of 29 Psc (rather B6 V than B8 III) are given as functions of the He content using the model grid of Klinglesmith (1971). The results are $T_{\text{eff}} = 15150 \pm 700$ K, $\log g = 4.08 \pm 0.15$ and $n(\text{He})/n(\text{H}) = 0.027$ assuming the star to be unreddened. In Section 3.2 it will be shown that 29 Psc is slightly reddened. Correction for it results in $T_{\text{eff}} = 15400$ K and $\log g = 4.14$.

1.8. Indirect empirical determination of the *BC*

Kuiper's (1938) scale of *BC*'s was scaled to radiometric magnitudes of F2V and later type stars. Popper (1959) has improved this scale using the same radiometric magnitudes of Pettit and Nicholson (1928). Morton and Adams (1968) adopted Popper's (1959) scale for the stars cooler than F2, in which $BC_{\odot} = -0.07$ mag. According to Aller (1963, p. 293) $BC_{\odot} = -0.11$ mag. In this paper $BC_{\odot} = -0.09$ is adopted as a reasonable compromise.

For the hotter stars Morton and Adams scaled their published (theoretical) *BC*'s to Popper's (1959) value of the *BC* at F0 V. They stress, that if one uses formula (7) with $\mathscr{F}_{\lambda}(\odot)$ as given by Allen (1963) and $BC_{\odot} = -0.07$ mag., their published *BC*'s have to be corrected by -0.29. According to Hyland (1969) this has indeed to be done (see Section 1.10).

In the future, *BC*'s calculated from models can possibly be scaled and checked with observed *BC*'s as indicated in Section 1.3. There the old radiometric measurements are replaced by complete flux envelopes F_{λ}. Another possibility is that as soon as T_{eff} and $\log g$ are known fairly well for a star the models and the method to obtain c (see last paragraph of Section 1.2) can be tested by equating the result of formula (6a) with to that of formula (4). Whenever the radius of a star is not known, Equation (4) can be combined with Equation (9) giving:

$$BC = -2.5 \log \mathfrak{z}/\mathfrak{z}_{\odot} - (M_v + 10 \log T_{\text{eff}} - 2.5 \log g) + \\ + (M_{v\odot} + BC_{\odot} + 10 \log T_{\text{eff}\odot} - 2.5 \log g_{\odot}). \tag{10}$$

From this formula it is clear that components of binaries of which the distance and the individual masses are known and for which T_{eff} and $\log g$ can be determined from scans and spectra could be suitable objects for this purpose. In this way a rather reliable empirical mass-luminosity relation (see chapter 4) might be constructed.

Formula (10) can be used in an attempt to find in an empirical way the influence of the line strength on the *BC*. For, it can be used for stars with strong as well as weak metallic lines of which the $R-I$ colors are the same and the H-line profiles are identical. Possibly in this way the *BC* can be found empirically as a function of T_{eff}, $\log g$, $\delta(U-B)$ and $V \sin i$.

Strom (1968) tried to calculate *BC*'s for models with different line strengths due to changes in the metal abundance. In Figure 1 some preliminary results are shown. Note that the absolute value of the *BC* decreases with increasing line strengths.

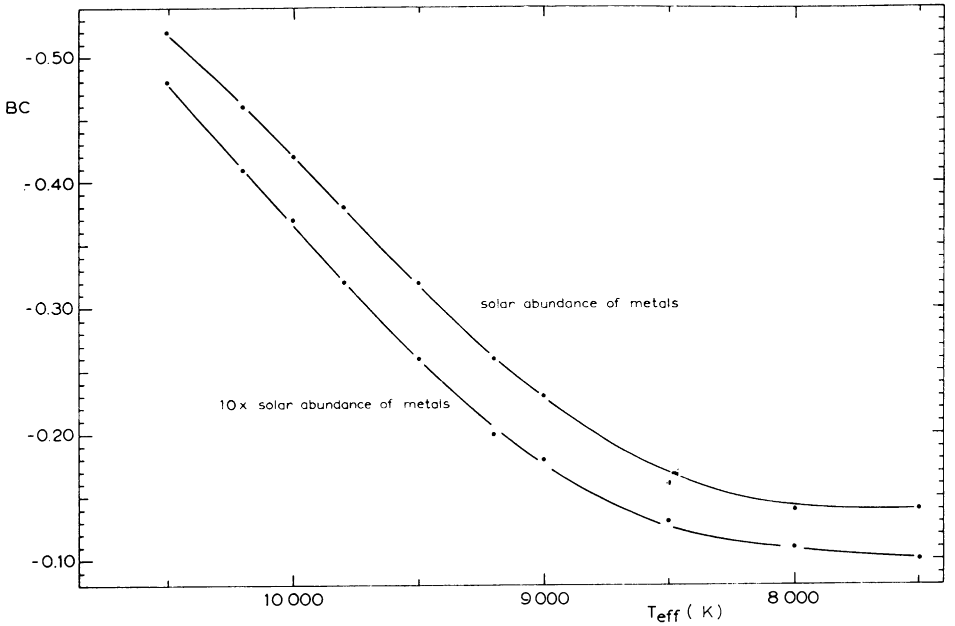

Fig. 1. Bolometric correction as a function of the effective temperature according to Strom's (1968) models.

1.9. The Hyades' problem

A decrease of the absolute value of the *BC* could help to solve the Hyades' problem. The Hyades are known to be metal rich (see Parker *et al.* (1961) and Wallerstein *et al.* (1965) for example). It is quite well possible that when the influence of the metal-line strengths, $V \sin i$ and gravity on the *BC* will be known better, that the resulting absolute bolometric magnitude of the Hyades will decrease in such a way that they will conform to the mass-luminosity relation of the field stars without changing their masses and thus their distance (Hodge and Wallerstein (1966) and Wallerstein and Hodge (1967)).

This idea is supported by Eggen's (1969) measurements of M_I and $R-I$ for 24 M type main sequence members of the Hyades cluster and for 25 field stars of large parallax and in the same colour range as the cluster stars. The (M_I, $R-I$) relation of both groups of stars are the same to within less than 0.1 mag. if the distances of the Hyades stars as obtained by Wayman *et al.* (1965) with the convergent-point method are used. Theoretically it is conceivable that the absolute I magnitude is much less, if any, affected by blanketing. With respect to the field stars the absolute visual magnitude of the Hyades is too bright. If the absolute values of the *BC*'s of the Hyades indeed have to be smaller (see end of Section 1.8) the difference in M_{bol} between field stars and Hyades becomes smaller than the difference in M_v.

It is interesting to note that according to Figure 2 of Schild's paper (these proceedings, page 31) the $U_2 - V$ colours of the Hyades behave much more similar to those of the field stars than the $U_2 - V$ colours of the Pleiades do. The peculiar behaviour of the Pleiades can probably be explained by the presence of circumstellar shells (Jones, 1972b; Hobbs, 1972).

It may be remembered that at any case the mild subdwarfs have moved to the Hyades-man sequence in the (M_v, $B-V$ plane as well as in the (M_{bol}, $\log T_{eff}$) plane by correcting the magnitudes and the colours of the subdwarfs for the weakness of the metal lines in their spectra (Sandage and Eggen, 1959; Wildey *et al.*, 1962).

1.10. Determination of stellar radii

Formula (4) can be written as:

$$\log R/R_\odot = -0.2\,(M_v + BC + 10\log T_{eff}) + + 0.2\,(M_{v\odot} + BC_\odot + 10\log T_{eff\odot}). \quad (11)$$

Hyland (1969) has shown that at least for the hot stars the BC's published by Morton and Adams (1968) give erroneous results. Application of a correction of -0.29 mag. (see Section 1.8) gives much better results.

Underhill (1966) has stressed, that although the introduction of blanketing in the models causes rather large changes in the BC the quantity (BC + $10\log T_{eff}$) does not change much. (The T_{eff} of a blanketed model is less than the T_{eff} of an unblanketed model of which the Paschen continua match an observed energy distribution, see last paragraph of section 1.6.1.) Therefore according to Equation (11) $R/R_\odot$ does not depend much on the grid of models used. Moreover the exact zero point of the BC scale does not have to be known if $BC_\odot$ is taken from a suitable model of the grid. Underhill did not investigate the dependence of ($BC + 10\log T_{eff}$) on $\log g$. If there is any, the gravity of the star to be studied should be determined first.

1.11. Mass determination

The gravity and the radius provide the mass of a star. Formula (10) can be rewritten as

$$\log \mathscr{M}/\mathscr{M}_\odot = -0.4\,(M_v + BC + 10\log T_{eff} - 2.5\log g) + + 0.4\,(M_{v\odot} + BC_\odot + 10\log T_{eff\odot} - 2.5\log g_\odot). \quad (12)$$

The same remarks can be made as in Section 1.10.

For the blue horizontal branch stars in M67 Sargent (1968) found in this way $\mathscr{M} = (0.7 \pm 0.2)\,\mathscr{M}_\odot$. Sargent did not mention whether the BC's were derived from the models used or were taken from a list.

Possibly Equation (12) can be used to determine masses of Cepheids. There is still a discrepancy between the masses of Cepheids as derived from stellar pulsation theory and those derived from stellar evolution computations, which are 1.5–2 times larger

(Fricke *et al.*, 1971). M_v can be found from the empirical period-colour-luminosity (Sandage and Tamman, 1969); T_{eff} and $\log g$ can be determined in the same way as done by Oke (1961); the models used provide the *BC*. As soon as observed radii of Cepheids become available from interferometric measurements for example, this method can be tested. For then the observed radii can be compared with calculated ones according to Equation (11). At the same time, however, the search for and the astrometric study of Cepheids in binary systems should not be neglected.

2. Intrinsic Colours

2.1. Introduction

Quite a number of astronomers still use the Johnson and Morgan (1953) intrinsic-colour relation. However, in 1963 at least three authors (Crawford, Serkowski and Westerlund) suggested that the 1953 intrinsic-colour relation is not blue enough for the late B-type stars. Moreover, α Vir, the hottest apparently unreddened star Johnson and Morgan could use in 1953 had at that time a published $(B-V)=-0.26$, whereas it now is -0.23 (being the mean of the values given in the catalogue of Blanco *et al.* (1972), hereafter called BDDF catalogue). For this reason I decided to reinvestigate the $[(U-B)_0, (B-V)_0]$ relation of the hot main sequence stars, unaware of the fact that Schmidt-Kaler (1965) had already revised it (see his comment on page 269 of these proceedings).

In this paper not only stars listed by Johnson and Morgan, but also stars listed by Serkowski (1963) and Westerlund (1963) are used. For the colours mean values determined from the BDDF catalogue are taken. Moreover all the O5–B1 stars of the BDDF catalogue and the stars of three young clusters (see Section 2.3) are used.

2.2. Reddening lines

2.2.1. *Basic Formulae*

The interstellar reddening for stars of the same spectral type can be represented (see Fitzgerald (1970) for example) by

$$\frac{E(U-B)}{E(B-V)} = a_1 + a_2 \cdot E(B-V). \tag{13a}$$

Assuming $(B-V)_0$ to be the intrinsic $(B-V)$ colour of stars of a certain spectral type, $(U-B)_0$ can be found by first adopting an $(U-B)_0'$ and then solving the equation

$$(U-B)-(U-B)_0' = a_0 + a_1[(B-V)-(B-V)_0] + \\ + a_2[(B-V)-(B-V)_0]^2 \tag{13b}$$

for the constants a_0, a_1 and a_2 by the method of least-squares. Then

$$(U-B)_0 = (U-B)_0' + a_0. \tag{14}$$

In this way a set of possible combinations of $(B-V)_0$ and $(U-B)_0$ can be found

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

for each spectral type. This was carried out for the O5–B1 main sequence stars of the BDDF catalogue. Table I shows some results. It turns out that a_2 does not change if $(B-V)_0$ changes from -0.24 to -0.34. However, a_1 does depend on $(B-V)_0$. Sometimes a_2 is put equal to zero. This is necessary if only a few stars are available (see Figure 2). From Equation (13a) it follows that possible combinations of $(B-V)_0$ and $(U-B)_0$ can be found in this case from

$$U - B = Q + a_1 (B - V), \tag{15a}$$

where $Q = (U-B)_0 - a_1(B-V)_0$. This quantity can be determined directly from the observations without knowing $(B-V)_0$ and $(U-B)_0$.

Once $(B-V)_0$ and $(U-B)_0$ are known the quadratic form (13b) can be written as

$$U - B = Q + A_1 (B - V) + a_2 (B - V)^2, \tag{15b}$$

where

$$\left.\begin{aligned} Q &= (U - B)_0 - a_1 (B - V)_0 + a_2 (B - V)_0^2 \\ &\text{and} \\ A_1 &= a_1 - 2a_2 (B - V)_0 . \end{aligned}\right\} \tag{16}$$

a_1 or A_1 is the slope of the reddening line. The final choice will be represented by S (see Figure 8). a_2 is the curvature of the reddening line and the term $a_2(B-V)^2$ can be omitted if $|(B-V)| > 0.25$.

In Section 2.7 the final values of $(B-V)_0$ and $(U-B)_0$ will be determined.

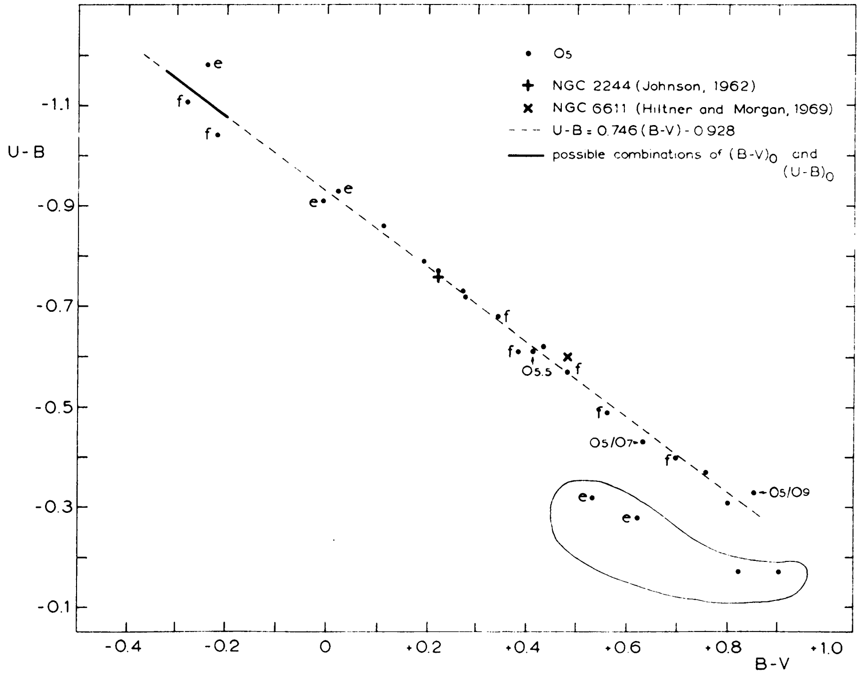

Fig. 2. Two colour diagram of the O5 stars of the BDDGF catalogue. Encircled stars are omitted for the determination of the reddening line.

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

2.2.2. *Application to the O5–B1 V Stars*

2.2.2.1. *The O5 stars.* In Figure 2 the $[(U-B), (B-V)]$ diagram of the O5 stars of the BDDF catalogue is given. The 4 encircled fairly reddened stars in the lower part of Figure 2 are not included for the determination of Q and a_1 in Equation (15a).

2.2.2.2. *The O6, O7 and O8 V stars.* The two-colour diagram of these stars of the BDDF catalogue is given in Figure 3. The linear expression (15a) and the quadratic

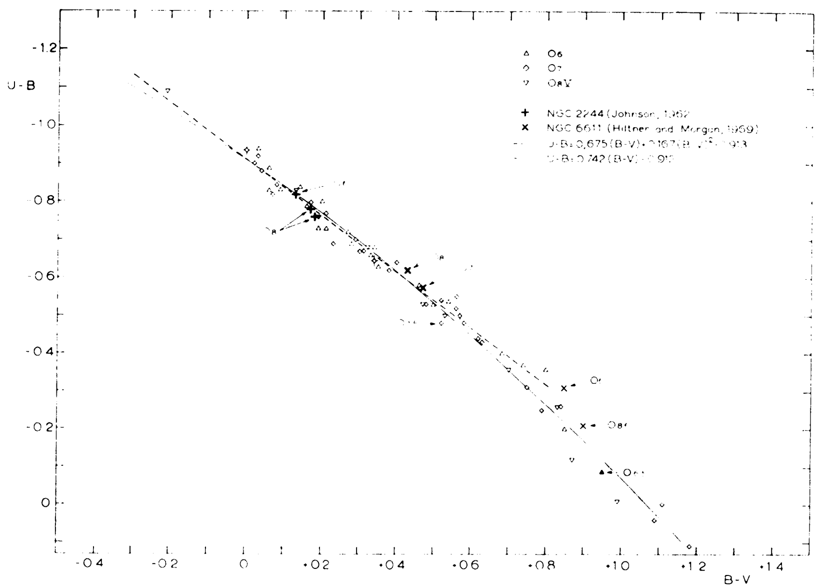

Fig. 3. Two colour diagram of the O6, O7 and O8 V stars of the BDDF catalogue.

expression (13b) of the reddening line give quite different sets of possible combinations of $(B-V)_0$ and $(U-B)_0$. This is not the case for the O8 V stars alone as can be seen from Table I.

2.2.2.3. *The O9/O9.5 IV/V stars.* An interesting result obtained for these stars is that the possible combinations of $(B-V)_0$ and $(U-B)_0$ are nearly identical whether or not the Cygnus stars are left out, included or partly included (see Table I). So mean values could be used to represent the line of possible combinations of $(B-V)_0$ and $(U-B)_0$ of the *O*9/9.5 IV/V stars in the two-colour diagram (heavy short line in the left top part of Figure 4).

Note that υ Ori, classified as B0 V, apparently is an O9 V or an O9.5 V star according to the Figures 4 and 5.

2.2.2.4. *The B0/0.5 IV/V stars.* Becanse of their large deviations from the mean the

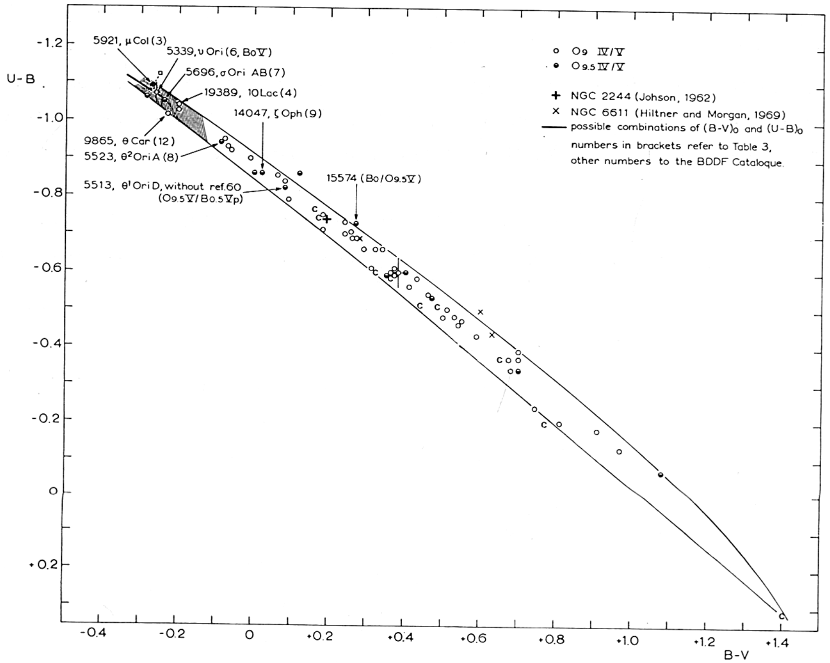

Fig. 4. Two colour diagram of the O9/9.5 IV/V stars of the BDDF catalogue. Cygnus stars are indicated by C.

encircled stars of Figure 5 are not used for the determination of the linear or quadratic relation between $(U-B)$ and $(B-V)$, which give nearly the same set of possible combinations of $(B-V)_0$ and $(U-B)_0$ (see Table I).

μ Col is rather an O9.5 V star than a B0 V star. If the classification of γ Cas and o Pup is correct then these stars are either peculiar or doubles.

2.2.2.5. *The B1 IV/V stars.* The two-colour diagram of these stars is shown in Figure 6. Encircled stars are omitted for the determination of the $[(U-B), (B-V)]$ relations.

2.3. Intrinsic colours from clusters

2.3.1. *A Preliminary $(B-V)_0$-Spectral Type Relation*

Three young clusters [NGC 2244 (O5–B1 V) (Johnson, 1962); NGC 6611 (O5–B2 V) (Hiltner and Morgan, 1969) and NGC 2232 (B2 V–A0) (Claria, 1972)] were chosen in order to determine a preliminary $[(U-B)_0, (B-V)_0]$ relation. Figure 2 of Johnson's paper shows that NGC 2244 must be very young, so does Figure 1 of Hiltner and Morgan's paper for NGC 6611. The $(B-V)_0$ spectral type relation of the first two clusters was hand-drawn, that for NGC 2232 is represented by a straight line obtained by means of least-squares. The three groups were shifted together by eye to one graph, going through λ Lep (B0.5 V) which is assumed to be unreddened (see Figure 5). The

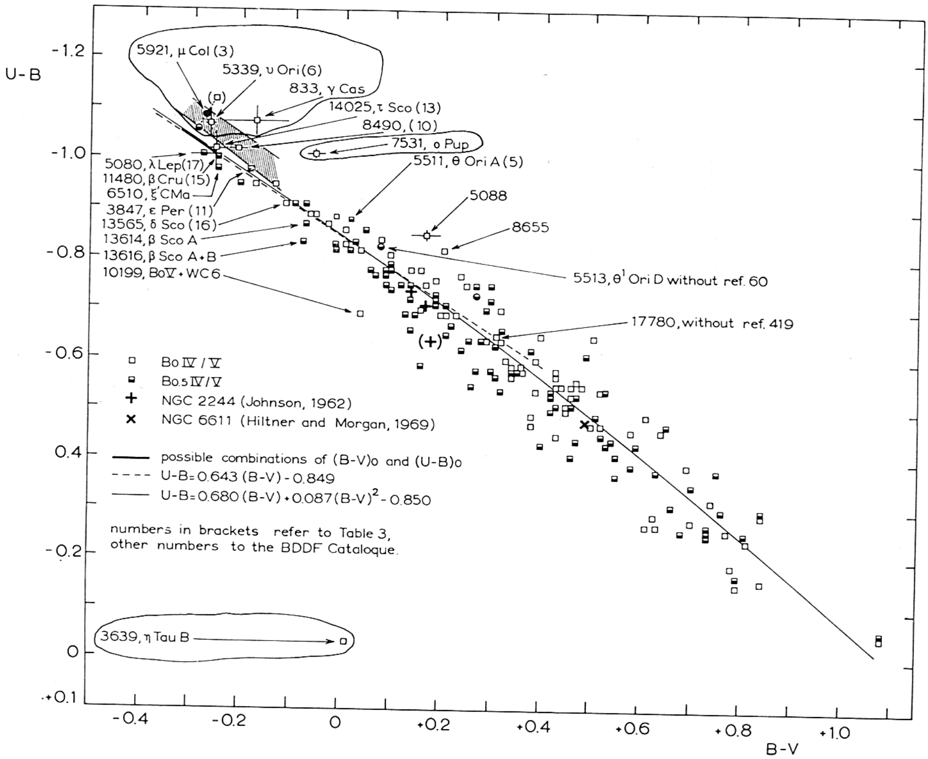

Fig. 5. Two colour diagram of the B0/0.5 IV/V stars of the BDDF catalogue. Encircled stars are omitted for the determination of the reddening line.

result is shown in Figure 7a. The thin crosses in this figure have not been used as these stars probably are not members of NGC 6611. $E(B-V)$ as determined from Figure 7a is 0.45 mag. for NGC 2244 (0.46 mag. according to Johnson), 0.74 mag. for NGC 6611 (0.80 mag. acc. to Hiltner and Morgan) and 0.05 mag. for NGC 2232 (0.01 mag. acc. to Claria).

2.3.2. *A Preliminary $(U-B)_0$-Spectral Type Relation*

Preliminary values of $E(U-B)$ were obtained with Equation (13a) by taking a_1 values from Table I for which determination the just derived $(B-V)_0$ values were used. For NGC 2232 a_2 is taken equal to zero and $a_1=0.645$ (see Section 2.4). The results are shown in Figure 7b.

In Figure 7 the position of the hot subdwarf HD 49798 (Jaschek and Jaschek, 1963) is indicated. Figure 7 suggests that HD 49798 could quite well be regarded as a normal O6 star.

2.3.3. *A Preliminary Intrinsic-Colour Relation*

From Figures 7a and 7b an $[(U-B)_0, (B-V)_0]$ relation can be determined and

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

TABLE I

Some data of the main-sequence stars used to determine reddening functions in the two-colour diagram and some results (see Section 2.2.1)

	B1 IV/V		B0/0.5 IV/V		O9/9.5 IV/V: All stars	O9/9.5 IV/V: Without most red (Cygnus) stars	O9/9.5 IV/V: Without Cygnus stars	O8 V		O8 V/O7/O6		O5/O5e/O5f
Number of stars available	118	86	164	83	67	66	59	11	6	65	53	23
range of $B-V$	-0.25_5 $+0.88$	-0.25_5 $+0.48$	-0.26 $+1.08$	-0.26 $+0.36$	-0.27_5 $+1.40_5$	-0.27_5 $+1.08$	-0.27_5 $+1.08$	-0.21 $+1.22_5$	-0.21 $+0.53$	-0.21 $+1.22_5$	-0.21 $+0.80$	-0.24 $+0.80$
a_2	0.036	0	0.087	0	0.078	0.046	0.048	0.101	0	0.167	0	0
						$(U-B)_0$						
$(B-V)_0 = -0.34$								-1.18_5	-1.20	-1.12	-1.16_5	-1.18
-0.32			-1.05	-1.05_5	-1.10_5	-1.11_5	-1.11	-1.16_5	-1.18	-1.11	-1.15	-1.16_5
-0.30	-0.96	-0.97	-1.04	-1.04	-1.09	-1.10	-1.10	-1.16	-1.16_5	-1.10	-1.13_5	-1.15
-0.28	-0.95_5	-0.95_5	-1.03_5	-1.03	-1.08	-1.08_5	-1.08_5	-1.14_5	-1.15	-1.09	-1.10_5	-1.13_5
-0.26	-0.95	-0.94_5	-1.01	-1.01_5	-1.06_5	-1.07	-1.07					
-0.24	-0.94_5	-0.93	-1.00	-1.00								
						a_1						
$(B-V)_0 = -0.34$								0.714		0.561		
-0.32			0.623		0.672	0.721	0.704	0.718		0.568		
-0.30	0.688		0.627		0.675	0.713	0.706	0.722		0.575		
-0.28	0.689		0.630		0.678	0.715	0.708	0.726		0.582		
-0.26	0.690		0.633		0.681	0.717	0.710					
-0.24	0.692		0.637									
		0.674		0.643					0.808		0.742	0.746
						A_1						
	0.710		0.680		0.721	0.740	0.740	0.782		0.675		
						Q						
	-0.763	-0.768	-0.850	-0.849	-0.890	-0.880	-0.885	-0.934	$--0.924$	-0.913	-0.912	-0.928
adopted Q-values	-0.765		-0.850		-0.885			-0.930				
adopted values of $(B-V)_0$	-0.26		-0.27_5			-0.29_5		-0.34	$--0.28$	results do not change whether the first or the second set is used		
$(U-B)_0$	-0.94_5		-1.03			-1.09_5		-1.18_5	-1.14_5			

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

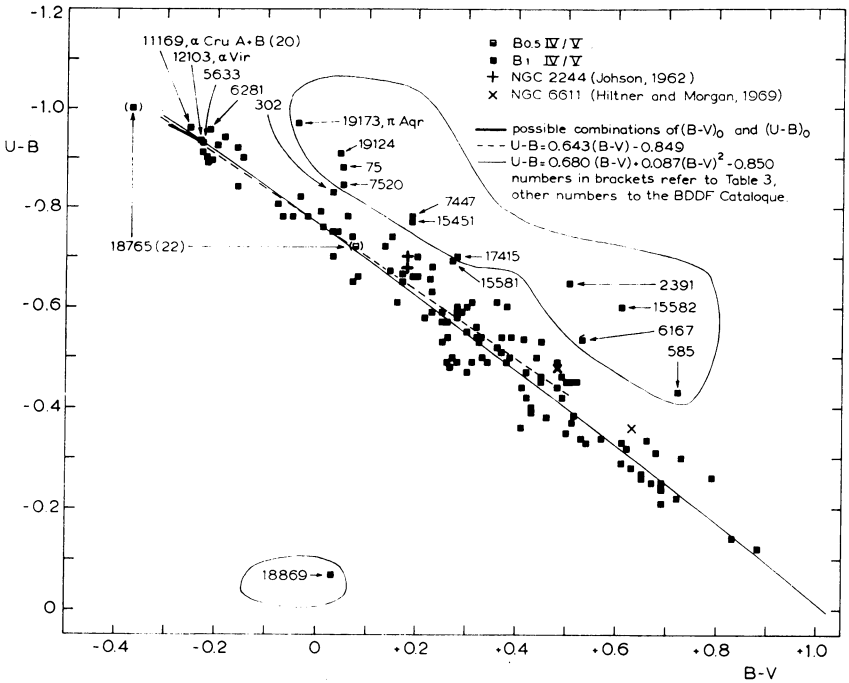

Fig. 6. Two colour diagram of the B1 IV/V stars of the BDDF catalogue. Encircled stars are omitted for the determination of the reddening line.

drawn in a two-colour diagram in which also the lines of possible combinations of $(B-V)_0$ and $(U-B)_0$ for each spectral type between O5–B1 stars (see Section 2.2) can be drawn (see the four short heavy lines in the top part of Figure 10). So preliminary values of $(B-V)_0$ and $(U-B)_0$ could be obtained for the stars of the Figures 2, 3, 4, 5 and 6 and by substituting into Equation (16) also Q and A_1 values of formula (15b)

2.4. The slope of the reddening line

Values of the slope of the reddening line, S, as derived by Johnson (1958), Serkowski (1963), and Fitzgerald (1970) for hot main sequence stars are plotted in Figure 8. In the same figure values of A_1 and $a_1 (a_2 = 0)$ as obtained for the stars of the Figures 2–6 (see Section 2.2.1) are plotted. For the O8 V, B0/0.5 IV/V and the B1 IV/V stars the A_1 and a_1 values are connected with each other by vertical lines. The vertical line at O9/9.5 represents the spread in the A_1 values of the different groups of O9/9.5 IV/V stars (see Table I).

The heavy line in Figure 8 can be regarded as a reasonable compromise and is a proposal for S values to be used in the future. Numerical values are given in Table II.

This proposal includes that the Q value of not too much reddened stars of spectral type B1 V–A1 V should be calculated with

$$Q = (U - B) - 0.645\,(B - V) \tag{17}$$

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

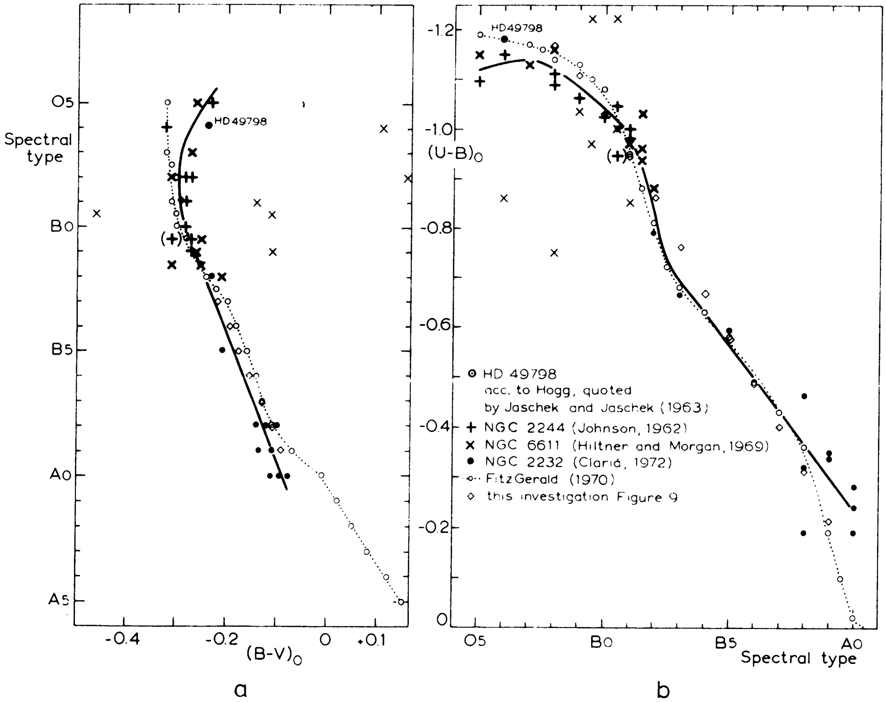

Fig. 7. $(B-V)_0$ (Figure a) and $(U-B)_0$ (Figure b) as a function of spectral type for the stars of the clusters NGC 2244, NGC 6611 and NGC 2232. The adopted $E(B-V)$ values are 0.45 mag., 0.74 mag. and 0.05 mag. respectively. See Section 2.31.

and not with Johnson and Morgan's (1953) formula:

$$Q = (U - B) - 0.72(B - V). \tag{18}$$

For some 80 B2V–A1V stars Q values were calculated with Equation (17). These values are plotted against spectral type in Figure 9a. The stars are listed in Table III. Among these stars are the apparently unreddened ones used by Johnson and Morgan (1953), Morgan *et al.* (1953) and the bluest stars listed by Serkowski (1963) and Westerlund (1963). The Q values of the O5, the O5/O7/O8 V, the O8 V, the O9/9.5 IV/V, the B0/0.5 IV/V and the B1 IV/V stars were taken from Table I. By least-squares straight line was fitted through these points, represented by

$$Q = -1.24 + 0.08\,n \quad \text{for} \quad 5 \leqslant n < 15, \tag{19}$$

where the spectral type indicator n is equal to 5 for B0/V and increases to $n = 15$ for A0 V.

2.5. The $[Q, (B-V)_0]$ and $[Q, (U-B)_0]$ relations

In Figure 9b the Q values of the B2 V–A1 V stars of Table III according to Equation (17) are plotted against $(B-V)$. No $(B-V)_0$ values are assigned to the Q values of the

O8 V and O9/9.5 IV/V stars of Table I whereas for the B0/0.5 IV/V and B1 IV/V stars the Q values are plotted against the $(B-V)_0$ values of section 2.3.3 from which the Q values were calculated with Equation (16) (filled squares in Figure 9b). By least-squares a straight line was fitted through these two filled squares and the bluest stars,

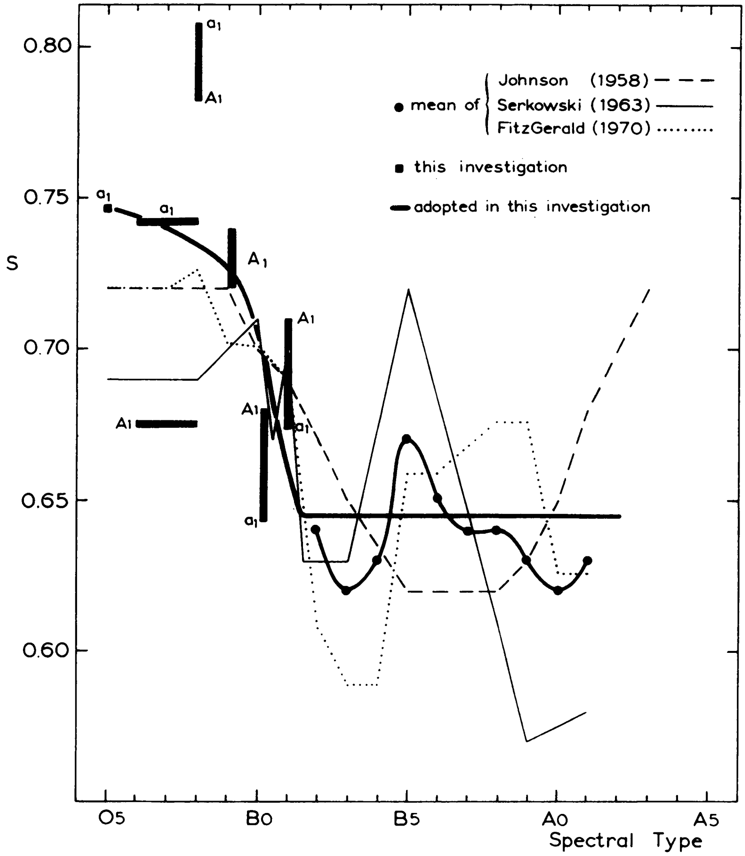

Fig. 8. The slope of the reddening line as a function of spectral type.

TABLE II

Proposed S values for hot main-sequence stars

Spectral type	S
O5/O6/O7	0.74
O8 V	0.73_5
O9 V	0.72_5
O9.5 V	0.72
B0 V	0.70_5
B0.5 V	0.68
B1 V–A0 V	0.64_5

TABLE III

Hot main sequence stars used to determine the final intrinsic-colour relation

The $(B-V)$, $(U-B)$ and V values are mean values from the BDDF catalogue. Q values are calculated from these values with formula (17). Underlined stars (large symbols in Figure 9) are in first approximation assumed to be unreddened

Name	No. This paper	No. BDDFcat	Spectral type	Q	$B-V$	$(B-V)_0$	$U-B$	$(U-B)_0$	V
λ Cep	1	18994	O6 f	−0.92	+0.25	−0.30	−0.74	−1.15	5.04
–	2	2451	O8/O8 V	-0.93_5	−0.21	-0.30_5	−1.09	−1.16	7.46
μ Col	3	5921	B0 V	-0.94_5	−0.25	-0.30_5	−1.12	−1.16	5.17
			O9.5 V	-0.85_5	-0.28_5	−0.28	−1.06	-1.05_5	
10 Lac	4	19389	O9 V	-0.89_5	−0.20	-0.29_5	−1.04	-1.10_5	4.88
θ^1 Ori A	5	5511	B0.5 V	-0.89_5	+0.02	-0.29_5	−0.88	-1.09_5	6.72
υOri	6	5339	B0 V	-0.88_5	−0.26	−0.29	−1.07	−1.09	4.62
σ Ori AB	7	5696	O9.5 V	-0.87_5	−0.24	-0.28_5	−1.05	-1.08_5	3.73
θ^2 Ori A	8	5523	O9.5 V	-0.87_5	−0.09	-0.28_5	−0.94	−1.08	5.08
ζ Oph	9	14047	O9.5 V	-0.87_5	+0.02	-0.28_5	−0.86	−1.08	2.57
–	10	8490	B0 Vn	-0.87_5	-0.20_5	-0.28_5	−1.02	−1.08	5.15
ε Per	11	3847	B0.5 IV	−0.86	−0.18	−0.28	−0.98	−1.05	2.89
θ Cas	12	9865	O9.5 V	−0.85	−0.23	−0.28	-1.01_5	−1.05	2.76
τ Sco	13	14025	B0 V	-0.84_5	−0.25	−0.28	−1.02	−1.04	2.83
–	14	5488	B0 V(p)/B0.5 V	−0.84	−0.25	−0.28	−1.01	−1.03	4.78
β Cru	15	11480	B0 III/B0.5 V	-0.83_5	-0.24_5	-0.27_5	-1.00_5	-1.02_5	1.26
δ Sco	16	13563	B0 IV/B0 V	−0.83	−0.11	-0.27_5	−0.91	-1.02_5	2.30
λ Lep	17	5080	B0.5 IV	−0.82	-0.27_5	−0.27	−1.01	−1.01	4.29
–	18	5366	B1 V	−0.82	-0.18_5	-0.27_5	−0.94	-0.99_5	5.34
–	19	6281	B1 V	-0.81_5	-0.21_5	−0.27	-0.95_5	−0.99	5.91
α Cru A+B	20	11169	B1/B1 V	−0.79	-0.25_5	-0.26_5	−0.96	-0.96_5	0.79
–	21	5633	B1 V	−0.78	−0.23	−0.26	−0.93	−0.95	6.03
–	22	18765	B1 V	−0.77	$+0.07_5$	−0.26	−0.72	−0.94	6.66
				-0.75_5	−0.37	-0.25_5	−1.00	-0.92_5	
κ Sco	23	15027	B2 IV	-0.74_5	-0.21_5	−0.25	-0.88_5	−0.91	2.41
–	24	5132	B1 V/B5 V/B2 V	-0.74_5	-0.21_5	−0.25	−0.88	−0.90	5.69
α Lup	25	12788	B2/B1 V	−0.74	−0.21	−0.25	−0.88	-0.90_5	2.30
δ Cet	26	2626	B2 V/B2 IV	−0.72	-0.21_5	-0.24_5	−0.86	−0.88	4.05
ν Cen	27	12315	B2 IV/B2 V	−0.71	−0.23	−0.24	−0.86	−0.87	3.41
γ Peg	28	128	B2/B2 V/B2 IV	−0.71	−0.22	−0.24	−0.85	-0.86_5	2.86

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

Table III (Continued)

Name	No. This paper	No. BDDFcat	Spectral type	Q	$B-V$	$(B-V)_0$	$U-B$	$(U-B)_0$	V
μ^2 Sco	29	14254	B2 IV	-0.69	-0.21_5	-0.23_5	-0.83_5	-0.85	3.56
γ Lup	30	13314	B2n/B2 Vn	-0.68_5	-0.20_5	-0.23_5	-0.81_5	-0.83_5	2.77
χ Cen	31	13000	B3/B2 V	-0.64_5	-0.21_5	-0.22_5	-0.78_5	-0.79	3.13
–	32	5673	B3 V	-0.64_5	-0.15_5	-0.22_5	-0.74_5	-0.79	6.84
η Hya	33	8422	B3/B3 V	-0.61_5	-0.19_5	-0.21_5	-0.74	-0.75_5	4.29
σ Sgr	34	16048	B3/B3 V/B2 V	-0.61	-0.21	-0.21_5	-0.74_5	-0.74_5	2.05
α Pav	35	17659	B3 IV	-0.58_5	-0.20	-0.20_5	-0.71_5	-0.72	1.93
ι Her	36	15035	B3/B3 V	-0.57_5	-0.18	-0.20_5	-0.69	-0.70_5	3.80
τ Lib	37	13346	B2 V/B2.5 V	-0.56	-0.17_5	-0.20	-0.67_5	-0.69	3.65
η UMa	38	12316	B3 V	-0.55_5	-0.18_5	-0.20	-0.67_5	-0.68_5	1.88
η Aur	39	4878	B3 V	-0.55_5	-0.18	-0.20	-0.67	-0.68	3.18
–	40	8467	B4 IV	-0.55_5	-0.17_5	-0.20	-0.66_5	-0.68	4.86
–	41	287	B3/B5 IV	-0.51_5	-0.12	-0.19	-0.59_5	-0.64	5.58
–	42	11156	B6/B7 V	-0.51	-0.14_5	-0.18_5	-0.60	-0.62_5	10.65
ν And	43	672	B5 V	-0.48	-0.15	-0.18	-0.57_5	-0.59_5	4.52
κ Hya	44	9190	B3/B5 V	-0.47	-0.15_5	-0.17_5	-0.57	-0.58	5.05
τ Her	45	13871	B5 V	-0.46	-0.15_5	-0.17	-0.56	-0.57	3.89
α Scl	46	907	B8 III(p)/B5	-0.44_5	-0.16_5	-0.17	-0.55	-0.55	4.30
α Gru	47	18893	B2 V/B5 V	-0.44_5	-0.15	-0.17	-0.54	-0.55	1.74
ψ^2 Aqr	48	19937	B3 V/B5 V	-0.44_5	-0.15	-0.17	-0.54	-0.55	4.40
β Sex	49	9684	B6 V	-0.43	-0.13_5	-0.16_5	-0.52	-0.54	5.07
29 Psc	49–50	20638	B8 III/B6 V	-0.41_5	-0.13_5	-0.16	-0.50	-0.52	5.10
19 Tau	50	3570	B6 V	-0.39_5	-0.10_5	-0.15_5	-0.46	-0.49	4.30
23 Tau	51	3607	B6e/B6 IVnn	-0.38	-0.06	-0.15	-0.42	-0.48	4.18
π Cet	52	2717	B5 V/B7 V	-0.35	-0.14	-0.14	-0.44	-0.44	4.24
18 Tau	53	3565	B8 V	-0.31	-0.07_5	-0.13	-0.36	-0.39_5	5.65
β Lib	54	13171	B8 V	-0.30	-0.11	-0.13	-0.37	-0.38	2.61
–	55	11355	A0/B7 V	-0.29_5	-0.13_5	-0.13	-0.38_5	-0.38	8.76
α Leo	56	9452	B8 V/B7 V	-0.29	-0.11_5	-0.12_5	-0.36_5	-0.37	1.35
φ Eri	57	2360	B8 V	-0.28	-0.12_5	-0.12_5	-0.36	-0.36	3.55
β CMi	58	7201	B7 V/B8 V	-0.23	-0.10	-0.11	-0.29_5	-0.30	2.90
53 Tau	59	4169	B9 V	-0.21_5	-0.10	-0.10_5	-0.28	-0.28_5	5.35

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

Table III (Continued)

Name	No. This paper	No. BDDFcat	Spectral type	Q	$B-V$	$(B-V)_0$	$U-B$	$(U-B)_0$	V
ζ Peg	60	19416	B8.5 V/B8 V	-0.21	-0.08_5	-0.10_5	-0.26_5	-0.27_5	3.30
21 Tau	61	3586	B8 V	-0.20_5	-0.04	-0.10	-0.23	-0.27	5.76
η Aqr	62	19306	B8 V	-0.20	-0.09	-0.10	-0.26	-0.26_5	4.02
α Del	63	17924	B9 V	-0.17	-0.05_5	-0.09	-0.20_5	-0.23	3.77
–	64	11825	B9 V	-0.15	-0.08_5	-0.08_5	-0.20_5	-0.20_5	5.20
22 Tau	65	3595	B9.5 V	-0.13_5	-0.02	-0.08_5	-0.15	-0.19	6.43
134 Tau	66	5940	B9 V	-0.13	-0.07	-0.08	-0.17_5	-0.18	4.89
θ Crt	67	10459	B9 V	-0.12	-0.08	-0.08	-0.17	-0.17	4.75
ε Sgr	68	15626	A0 V/B9 IV	-0.09_5	-0.02_5	-0.07	-0.11	-0.14	1.84
ω^2 Aqr	69	20387	B9 V/A0/B9.5 V	-0.09	-0.04	-0.07	-0.11_5	-0.13_5	4.47
μ Ser	70	13452	A0 V	-0.08_5	-0.04	-0.07	-0.11	-0.13	3.54
58 Aql	71	16962	A0 n	-0.08_5	$+0.10$	-0.07	-0.02	-0.13	5.61
θ Hya	72	8842	B9.5 V/A0 p	-0.07_5	-0.07	-0.06_5	-0.12	-0.12	3.88
–	73	11442	A0 V	-0.06	-0.04	-0.06	-0.08_5	-0.10	8.29
α CMa	74	6709	A0 V/A1 V	-0.04_5	0.00	-0.06	-0.04_5	-0.08	-1.46
–	75	11319	A1 V	-0.04_5	-0.04	-0.06	-0.07	-0.08	8.88
–	76	11314	A1 V	-0.03	-0.05_5	-0.05_5	-0.06_5	-0.06_5	1.31
α Peg	77	19775	B9 V	-0.02_5	-0.04	-0.05	-0.05	-0.06	2.49
109 Vir	78	12888	A0 V	-0.02_5	-0.01	-0.05	-0.03	-0.06	3.72
o Peg	79	19425	A1 V	-0.02	$+0.00_5$	-0.05	-0.01_5	-0.05	4.81
ϱ Peg	80	19647	A1 V	-0.01_5	$+0.00_5$	-0.05	-0.01	-0.04_5	4.90
β UMa	81	10075	A1 V	-0.00	-0.01	-0.04_5	-0.01_5	-0.04	2.38
ε Aqr	82	17998	A1 V	$+0.02$	$+0.00_5$	-0.04_5	$+0.02_5$	-0.00_5	3.77
θ Vir	83	11889	A1 V	$+0.00_5$	-0.01	-0.04_5	$+0.00$	-0.02	4.37
α Lyr	84	15842	A1 V	$+0.00_5$	-0.00_5	-0.04_5	-0.00_5	-0.02	0.03

which are indicated by large filled symbols in Figure 9b. The thus obtained $[Q, (B-V)_0]$ relation is

$$(B - V)_0 = 0.277\,Q - 0.045 \tag{20}$$

and might replace Johnson's (1958) formula

$$(B - V)_0 = 0.332\,Q\,. \tag{21}$$

For each of the stars of Table III, $(B-V)_0$ was calculated with Equation (20) and $E(B-V)$was determined. $E(U-B)$ was found from

$$E(U - B) = S \cdot E(B - V), \tag{22a}$$

where S is taken from Table II. For fairly reddened stars $E(U-B)$ was calculated with

$$E(U - B) = [S + 0.06\,E(B - V)]\,E(B - V), \tag{22b}$$

where the value 0.06 is the mean of the a_2 values of Table I for the O9–B1 stars. In this way $(U-B)_0=(U-B)-E(U-B)$ is known. Q values of stars of Table III were plotted against these $(U-B)_0$ values in Figure 9c. For the B0/0.5 IV and the B1 IV/V stars the Q values of Table I and the $(U-B)_0$ values of Section 2.3.3 were used. For the O8 V and O9/9.5 IV/V stars no $(U-B)_0$ values are plotted, because the uncertainties in them were regarded too large. By least-squares the following relation was obtained:

$$(U - B)_0 = 1.242\,Q + 0.013 \quad \text{for} \quad Q < -\,0.6 \tag{23a}$$
$$(U - B)_0 = 1.175\,Q - 0.030 \quad \text{for} \quad Q > -\,0.6\,. \tag{23b}$$

A less accurate expression for the entire spectral range under consideration is given by

$$(U - B)_0 = 1.200\,Q - 0.021\,. \tag{23c}$$

The differences in $(U-B)_0$ with (23a) and (23b) are of the order of 0.005 mag. and never exceed 0.009 mag.

2.6. α Virginis

It is worthwhile to note that the BDDF value of $(B-V)$ of α Vir (indicated in Figure 9 by 1972) does not correspond to the above mentioned $[Q, (B-V)_0]$ relation. The 1953 value of $(B-V)$, used by Johnson and Morgan (1953), lies nearly on the $[Q, (B-V)_0]$ relation of Figure 9b. However, the most recent value of $(B-V)$ has to be regarded as the better one. The colour excess $E(B-V)=0.03$ is most probably due to the binary nature of α Vir.

2.7. The final intrinsic-colour relation

A plot similar to Figure 10 was made of $(U-B)_0$ and $(B-V)_0$ values of the stars of Table III (not shown here). For the O8 V to A0 V stars the intrinsic-colour relation

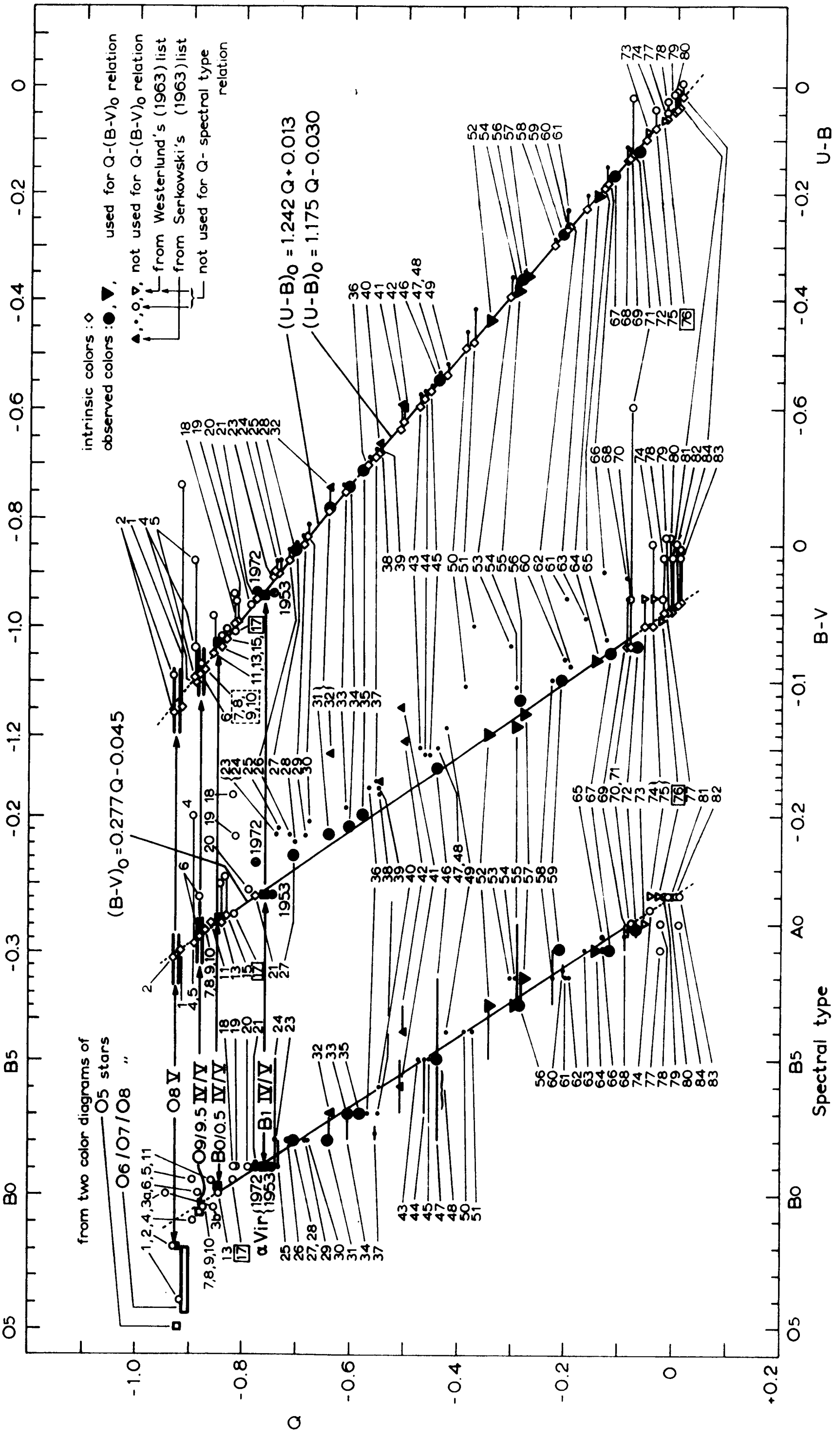

Fig. 9. Q as a function of (a) spectral type, (b) $(B-V)$ and (c) $(U-B)_0$.

as found by least-squares can be expressed by

$$(U - B)_0 = 4.636\,(B - V)_0 + 0.252 \quad \text{for} \quad -0.32 < (B - V)_0 < -0.18 \tag{24a}$$
$$(U - B)_0 = 3.971\,(B - V)_0 + 0.130 \quad \text{for} \quad -0.18 < (B - V)_0 < -0.05 \tag{24b}$$

or less accurately for the entire spectral range under consideration by

$$(U - B)_0 = 4.246\,(B - V)_0 + 0.161\,. \tag{24c}$$

The latter formula differs at maximum by 0.02 mag. in $(U-B)_0$ from Equations (24a) and (24b).

In Figure 10 the intrinsic-colour relation according to the Equations (24a) and (24b) is shown together with the results from the three young clusters (open squares in Figure 10, see Section 2.3). It turns out that the observed colours of λ Lep, star No. 17 of Table III and star No. 76 of Table III, which both can be assumed to be unreddened according to Figure 9, are nearly exact solutions of formula (24c) (differences in $U-B$ less than 0.005 mag.). This is not the case with the Equations (24a) and (24b). Perhaps formula (24c) has to be regarded as a better representation of the intrinsic-colour relation for the B type main-sequence stars than formulae (24a) and (24b). In that case the S values of Table II used to obtain $(U-B)_0$ (according to Equation (22a)) need some correction. Here still some work has to be done. However, Johnson's (1966) relation (dashed line in Figure 10) provides at any case too red $(U-B)_0$ values for given $(B-V)_0$ values in the region $-1.10<(U-B)_0<-0.90$. The open squares in Figure 10 give an indication that for $(U-B)_0 < -1.10$ the intrinsic-colour relation bends back again. It is conceivable that this part of the relation is going through HD 49798 (see Section 2.3 and Figure 7).

In Table IV the proposed intrinsic-colour relation for the B type stars is given. Although no unique relation with spectral type exists, tentative spectral types are given in the last column of Table IV. These were obtained from Figure 9 and should be used only as a rough estimate.

It should be remarked that for $-0.40<(B-V)_0<-0.05$ the proposed intrinsic-colour relation agrees very well with curve B of Figure 1 of the paper by Rufener and Maeder (these proceedings page 156). For $-0.05\leqslant(B-V)_0< +0.05$ curve B of Rufener and Maeder lies slightly higher than the proposed $[(U-B)_0, (B-V)_0]$ relation.

For $-0.05<(B-V)_0< +0.3$ the intrinsic-color relation of Figure 10 was drawn by eye through the lowest points such that it merges better into the relation for the Hyades main-sequence (Eggen, 1962) than Johnson's (1966) relation.

In Figure 10 the observed colours of the faint blue stars HZ 22 (Kowal, quoted by Young *et al.*, 1972) and of HZ 29 (Ostriker and Hesser, 1968) are also plotted. The observed colours of HZ 22 are a solution of Equation (24c). Assuming HZ 22 indeed to be unreddened, this supports the idea that the atmosphere of HZ 22 could be quite similar to that of normal B-type stars. From the hydrogen-line profiles Greenstein (1969) found the surface gravity to be $\log g = 3.9$. Young *et al.* however found for

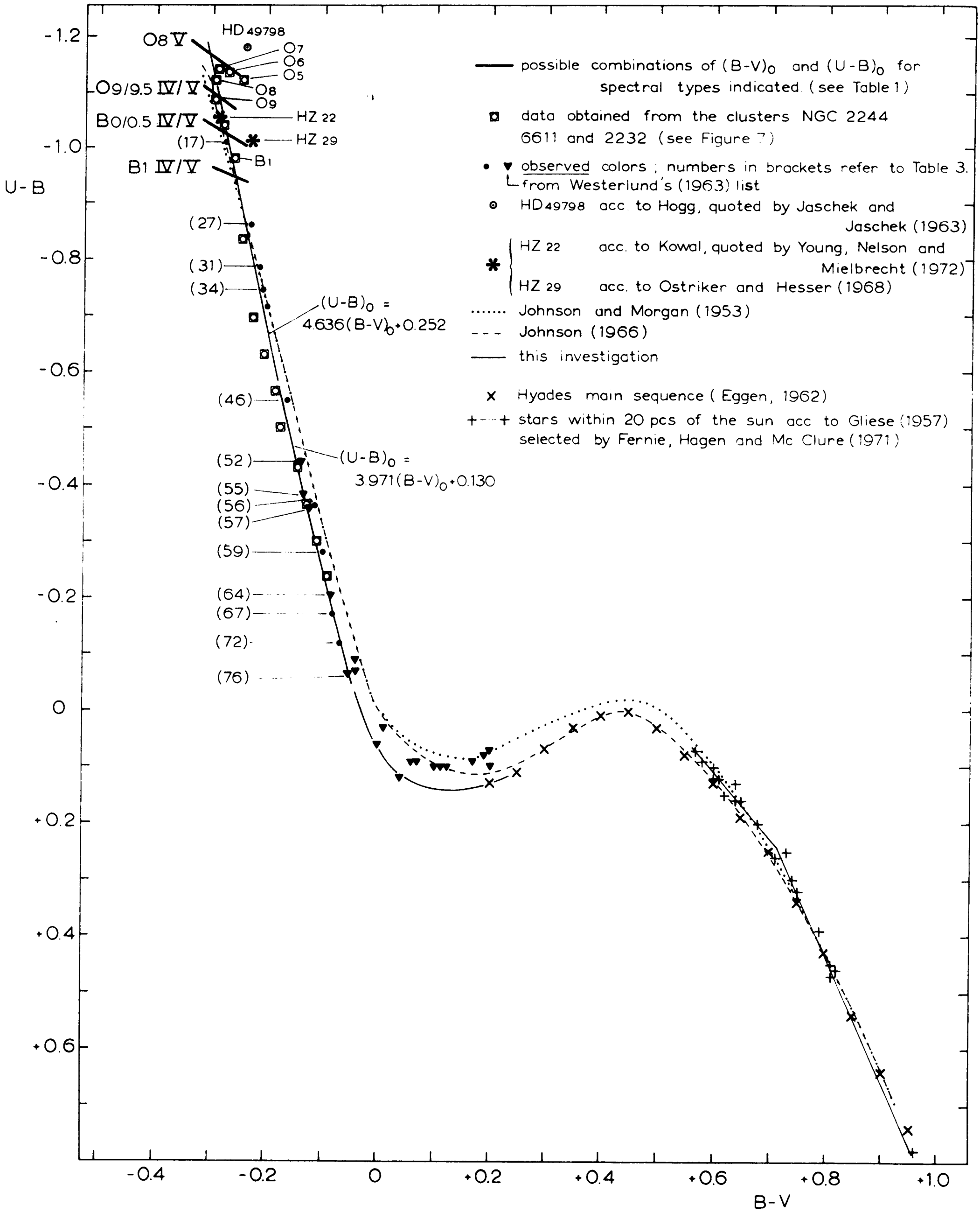

Fig. 10. Proposed intrinsic colour relation (full-drawn line) compared with some other intrinsic-colour relations.

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

the mass of the only visible primary component of this binary system ($P = 0\overset{d}{.}573703$) = $= 0.2 < \mathcal{M}/\mathcal{M}_\odot < 0.7$.

The nature of HZ 29 ($P = 1051.118 \pm 0.015$ s) is not yet known. According to Ostriker and Hesser it could be a hot subdwarf undergoing radial pulsations, a magnetic variable or a typical member of a new class of variable stars. If not reddened its position in the two-colour diagram is of importance for a better understanding of this class of stars.

TABLE IV

The intrinsic-colour relation according to formula (24c) for hot main-sequence stars

$(B-V)_0$	$(U-B)_0$	Q	Spectral type
-0.29_5	-1.09	-0.90	O9
-0.29	-1.07	-0.87_5	O9.5
-0.28	-1.03	-0.85	B0
-0.27	-0.98_5	-0.81	B0.5
-0.26	-0.94_5	-0.77_5	B1
-0.24	-0.86	-0.70	B2
-0.22	-0.76_5	-0.62	B3
-0.19_5	-0.67	-0.54_5	B4
-0.17_5	-0.58	-0.46_5	B5
-0.15_5	-0.49_5	-0.39	B6
-0.13	-0.39_5	-0.31_5	B7
-0.11	-0.30_5	-0.23_5	B8
-0.09	-0.22	-0.16	B9
-0.08	-0.18	-0.12	B9.5

Q values are obtained from Equation (20) and spectral types from Figure 9a.

2.8. Comparison with Crawford's (1963) Work

Crawford (1963) has measured $(B-V)$ and $(U-B)$ colours of 501 B8 and B9 stars brighter than 6.5 mag. and has compared the results with the intrinsic-colour relation of Johnson and Morgan (1953). From his table it follows that 12% of the stars have an $E(U-B) \approx 0$ and that 20% are definitely too blue in $(B-V)$ with respect to Johnson and Morgan's relation. (The $E(U-B)$ values of these stars are: -0.01 mag. for 11%; -0.02 mag. for 5%; -0.03 mag. for 1.8%; -0.04 mag. for 0.8%; -0.05, -0.06, -0.08 and -0.12 mag. each for 0.2%.)

With the proposed intrinsic-colour relation it is found that

for 13 stars (2.6%) $\quad |E(B-V)| \leqslant 0.005$

for 3 stars (1.6%, together with the next 5) $\quad -0.01 < E(B-V) < -0.005$

for 5 stars $\quad \begin{cases} -0.03 < E(B-V) < -0.01 \\ -0.017 \leqslant E(U-B) \leqslant -0.008 \end{cases}$

Of the latter 5 stars (BS 1638, 2033, 4082, 3059, 7911) the first three are peculiar stars (11 Ori, A0 Si; 137 Tau, Ap; 25 Sex, Ap).

3. Effective Temperatures as a Function of $(U-B)$ for B Type Stars

3.1. The observations

It has been known for a long time that $[T_{eff}, (U-B)]$ relations of B type stars are very smooth if T_{eff} is determined from a comparison of observed energy distributions with theoretical ones of a grid of models (see Figure 3 in Heintze (1969) for example). This is true even if no corrections for reddening are applied. Clearly the apparent lower effective temperature determined from the reddened energy distribution is with the reddened $(U-B)$ colour still a point of the $[T_{eff}, (U-B)]$ relation for unreddened stars. The same seems to be true for the influence of rotation.

Hyland (1969) found a rather linear $[\theta_{eff}=5040/T_{eff}, Q]$ relation for B type stars. Also Schild *et al.* (1971) found a fairly linear relation between θ_{eff} and Q for $\theta_{eff} < 0.46 (Q < -0.1)$.

It turns out that different published temperature relations can nicely be expressed as a linear relation between θ_{eff} and $(U-B)$. The following expressions could be derived by means of least-squares, for Hyland's (1969) results:

$$\theta_{eff} = 0.314_5 (U - B) + 0.513 \tag{25a}$$

for Heintze's (1969) results:

$$\theta_{eff} = 0.306 (U - B) + 0.507 \tag{25b}$$

for the results of Schild *et al.* (1971)

$$\theta_{eff} = 0.304_5 (U - B) + 0.502 . \tag{25c}$$

3.2. Temperature corrections for interstellar reddening and rotation

From Equations (25a, b, c) it follows that

$$\Delta\theta_{eff} = - 0.31 \times E(U - B) \tag{26a}$$

or

$$\Delta\theta_{eff} = - 0.31 \times S \times E(B - V) . \tag{26b}$$

According to Johnson and Morgan's (1953) intrinsic-colour relation, 29 Psc (B6 V rather than B8 III, see last paragraph of Section 1.7) is unreddened. However, according to the proposed intrinsic-colour relation $E(B-V)=0.03$, so $\Delta\theta_{eff}=-0.006$. This means that $T_{eff}=15400$ K rather than 15150 K and $\log g=4.14$ rather than 4.08.

Theoretical work has shown the dependence of Mv, M_{bol}, $(U-B)$, $(B-V)$ etc. on $v_R \sin i$ or v_R, where v_R denotes the equatorial rotational velocity (see Collins (1970) for a recent review article). The effective temperature of a rotating star is lower than the effective temperature of the same star in case it would not be rotating. Here just as in the case of reddening the observed effective temperature obtained by fitting the observed energy distribution of the rotating star to a theoretical energy distribution of a non rotating star provides together with the observed $(U-B)$ value a point on the $[T_{eff}, (U-B)]$ relation of unreddened stars (see Figure 3 in Heintze, 1969).

From Equation (26a) it follows that

$$\Delta\theta_{\text{eff}} = -\, 0.31 \times \Delta\,(U - B),$$

where in this case $\Delta(U-B)$ denotes the changes in $(U-B)$ due to the rotational velocity. From Figure 15 in Collins and Harrington (1966), Figure 10 of this paper and formula (24c) it is possible to derive for the hot main-sequence stars the following relation between the changes in $(U-B)$ and $(B-V)$ due to rotation

$$\Delta\,(U - B) = 4.246\,\Delta\,(B - V).$$

Model calculations of Maeder and Peytremann (1970) show that

$$\Delta\,(B - V) = k_\theta\,(v_R \sin i)^2,$$

where k_θ is a constant.

Combination of these three equations yields:

$$\Delta\theta_{\text{eff}} = -\, 1.32\, k_\theta\,(v_R \sin i)^2. \tag{27}$$

For comparison, Roxburgh and Strittmatter (1966) found in a theoretical approach as a first approximation

$$\Delta \log T_{\text{eff}} = k_T v_R^2$$

and

$$\Delta M_{\text{bol}} = k_{Mb} v_R^2,$$

where k_T and k_{Mb} depend on the type of the star. Some dependence on $\sin i$ is present but very little. Strittmatter (1966) found from a study of the Praesepe cluster that

$$\Delta M_v = b_{Mv}\,(v_R \sin i)^2$$

at a given colour.

3.3. Temperature Relations from Model Predictions

In Figure 11 the $[\theta_{\text{eff}}, (U-B)]$ relations (25a, b and c) are shown together with some results of model-calculations. For Mihalas' (1965) unblanketed models one finds

$$\theta_{\text{eff}} = 0.303\,(U - B) + 0.513 \quad \text{for} \quad 0.18 \leqslant \theta_{\text{eff}} \leqslant 0.28. \tag{28a}$$

For $\theta_{\text{eff}} \geqslant 0.28$ the Mihalas' (1965) results are nearly identical to those of Klinglesmith (1971), which are hydrogen-line blanketed models. However, the results of Klinglesmith do not agree with the results of the Balmer-line blanketed models of Mihalas (1966). For $\theta_{\text{eff}} \geqslant 0.40$ the results of the latter models practically coincide with the temperature relation of Schild *et al.* (1971) (see Figure 11). Moreover if the $(U-B)$ values of Mihalas (1965) are corrected by $+0.03$ mag the extension of the linear $[\theta_{\text{eff}}, (U-B)_{\text{corr}}]$ relation between $0.18 \leqslant \theta_{\text{eff}} \leqslant 0.28$ to greater values of θ_{eff} fits nicely into Mihalas' (1966) results. Heintze (1968) found that Mihalas' 1965 $(U-B)$ values have to be corrected by $+0.02$ mag. A correction of $(U-B)$ by $+0.025$ mag. causes

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

a correction of -0.08 in the constant c of formula (28a), giving

$$\theta_{\text{eff}} = 0.303\,(U - B) + 0.505 \quad \text{for} \quad 0.18 \leqslant \theta_{\text{eff}} \leqslant 0.40\,. \tag{28b}$$

This formula is in very good agreement with the Equations (25b) and (25c).

3.4. Uncertainties in the $[\theta_{\text{eff}}, (U-B)]$ relation

3.4.1. *The Main-Sequence Stars Used by Schild et al. (1971)*

In Figure 11 also θ_{eff} values as found by Schild *et al.* (1971) for the eight main-sequence B type stars studied by them are plotted against $(U-B)$ values as derived from the BDDF catalogue for these stars. In this case the relation between θ_{eff} and $(U-B)$ turns out to be

$$\theta_{\text{eff}} = 0.326\,(U - B) + 0.509\,. \tag{29a}$$

It has to be investigated whether or not the $(U-B)$ values used by Schild *et al.* are the correct ones because these stars were also used for the determination of the intrinsic-colour relation proposed here (see Table III and Section 2.5).

3.4.2. *Effective Temperatures Derived by Auer and Mihalas (1972)*

In Figure 11 also the effective temperatures of three hot stars (10 Lac, υ Ori and τ Sco) as determined by Auer and Mihalas (1972) are plotted against their $(U-B)_0$ values given in Table 3. These points seem to support formula (29a) as adding of these three stars to the eight main sequence stars of Schild *et al.* results in a least-squares solution

$$\theta_{\text{eff}} = 0.329\,(U - B) + 0.511\,, \tag{29b}$$

which is nearly identical to Equation (29a).

Auer and Mihalas included in their models a complete NLTE treatment of the H, He I and He II lines (departures from LTE for the first five levels of a 15-level hydrogen atom, allowing explicitly for six line transitions, and for departures from LTE in the groundstate continua of He I and He II; N(He)/N(H) is assumed to be 0.10). They did not compare theoretical with observed energy distributions. Therefore their results are independent of interstellar reddening.

Auer and Mihalas did not give a final T_{eff} of υ Ori as they did not have reliable observations of the He II line profiles of this star and just these lines are very sensitive to T_{eff} in this temperature range. However, they mention that a model of $T_{\text{eff}} = 30000$ K and $\log g = 4.0$ (assuming υ Ori to be a B0 V star!, see section 2.2.4) gives a better fit for the He I line profiles (especially $\lambda\lambda$5015, 5048 and 6678) than in the case of τ Sco ('another' B0 V star) for which they publish $T_{\text{eff}} = 31\,500$ K and $\log g = 4.15$. If 30000 K is indeed a fairly representative effective temperature for υ Ori, which according to Section 2.2.4 is rather an O9.5 V than a B0 V star, then υ Ori fits nicely to the temperature-relations of Hyland (Equation (25a): 29600 K); Heintze (Equation (25b): 30400 K) and Schild *et al.* (Equation (25c): 29600 K). So τ Sco, which indeed is a B0 V star according to Figure 5, should have a lower effective temperature than

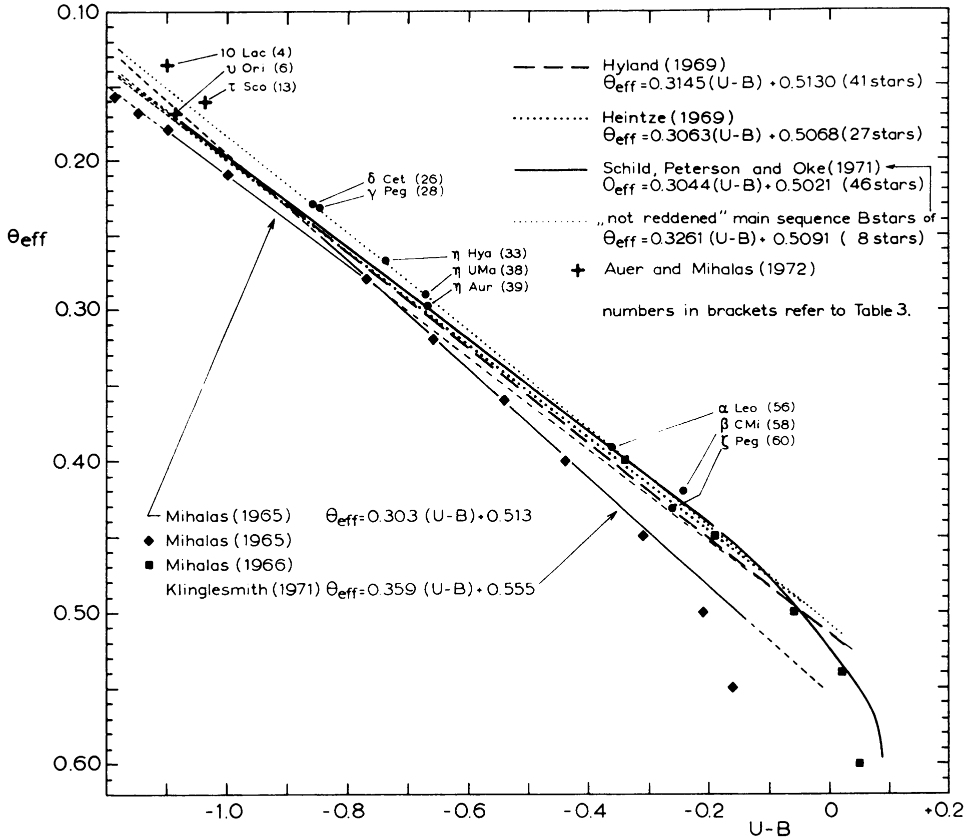

Fig. 11. θ_{eff} as a function of $U-B$ according to some grids of models (Section 3.3) and according to some observational results (Section 3.1 and 3.4)

30000 K in the order of 26900 K, being the mean of the values obtained from the Equations (25a, b and c).

A final remark: Auer and Mihalas' (1972) models do not include any line blanketing. It is possible that UV-line blanketing once included into these models, will slightly lower the effective temperatures of the stars studied by them.

4. The Mass-Luminosity Relation

In Table V the most modern determinations of masses and radii of 70 components of eclipsing binaries, of 48 components of reliable astrometric binaries and available data of α Leo, α PsA, α Aql and the Sun are compiled.

Effective temperatures were assigned to these stars according to the published spectral types. For the B type stars formula (19) is combined with formula (23c) and with the formulas (25c) or (29b) giving

$$\theta_{\text{eff}} = 0.028\, n + 0.043 \tag{30a}$$

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

TABLE V

Most recent masses and/or radii, M_v and M_{bol} (if published) of 70 components of eclipsing binaries, 48 components of astrometric binaries and 5 single stars

In column 10: M_{bol} calculated from $R/R_{\odot}$ and an adopted temperature scale (see Section 4) are given and in column 11: M_{bol} from a mass-luminosity relation derived from the data of column 5 and 10

No.	Name	Main ref.	Spectral type	$\mathcal{M}/\mathcal{M}_{\odot}$	$R/R_{\odot}$	$\log g$	M_v published	M_{bol} published	M_{bol} acc. to(2)	M_{bol} acc. to mass-lum.rel. (31b)	(31a)
1	V444 Cyg B	[6]	O6	29.6	9.8	3.93				−7.85	−7.25
2	UW CMa A	[6]	O7f	19.0	18.6	3.18				−6.75	−6.28
3	UW CMa B	[6]	O7f	23.0	14.8	3.46				−7.25	−6.72
4	AO Cas A	[6]	O9 III	19.0	13.9	3.43				−6.75	−6.28
5	AO Cas B	[6]	O9 III	23.0	8.9	3.90				−7.25	−6.72
6	γ Cyg A	[9]	O9.5 V	17.4±0.8	5.9	4.13±0.03			−6.7 −6.2	−6.50±0.13	−6.07±0.11
7	γ Cyg B	[9]	O9.5 V	17.2±0.8	5.9	4.13±0.03			−6.7 −6.2	−6.47±0.13	−6.05±0.11
8	AH Cep A	[6]	B0 Vn	16.5	6.1	4.09			−6.4 −6.0	−6.36	−5.94
9	AH Cep B	[6]	B0 Vn	14.2	6.1	4.02			−6.4 −6.0	−5.93	−5.57
10	μ_1 Sco A	[5]	B1.5 V	14.1	5.25	4.15		−4.9 [5]	−5.0 −4.7	−5.91	−5.55
11	μ_2 Sco B	[5]	(B3)	9.3	5.75	3.89		−4.2 [5]	−4.3 −4.2	−4.63	−4.39
12	32 Cyg B	[6]	B3 V	8.1	3.9	4.17		3.4 [5]	−3.45 −3.3	−4.18	−3.97
13	σ Aql A	[6]	B3 V	6.9	4.3	4.02			−3.6 −3.5	−3.63	−3.46
14	σ Aql B	[6]	B3 V	5.5	3.4	4.12			−3.2 −3.0	−2.81	−2.68
15	V539 Ara A	[24]	B3 V [1]	6.8	4.45	3.97			−3.8 −3.6	−3.57	−3.40
16	V539 Ara B	[24]	B5 V [1]	5.8	3.73	4.06			−3.4 −3.2	−3.00	−2.87
17	31 Cyg B	–	B4 V [12]	6.6±0.9 [9]	4.7 [6]	3.91±0.06		{−4.1 [12]; −3.8 [5]}	−3.4 −3.3	−3.4±0.5	−3.3±0.5
18	Z Vul A	[9]	B4 V [4]	5.4±0.3	4.7	3.82±0.03			−3.4 −3.3	−2.75±0.2	−2.6±0.2
19	U Oph A	[13]–[9]	B4 V [12]	5.30±0.36	3.4	4.10±0.03		−2.6 [12]	−2.7 −2.6	−2.65±0.25	−2.5±0.25
20	U Oph B	[13]–[9]	B5 V [12]	4.65±0.34	3.1	4.12±0.03		−2.4 [12]	−2.1 −2.0	−2.2±0.25	−2.1±0.25
21	ζ Phe A	[26]	B6 V	3.85±0.2	2.96±0.05	4.08±0.04		−1.3 [12]	{−1.55 −1.53; ±0.05 ±0.03}	−1.45±0.2	−1.44±0.2
22	ζ Aur B	–	B7 V [9]	5.6±0.6 [9]	7.0 [6]	3.49±0.05			−3.09	−2.85±0.4	−2.7±0.35
23	α Leo	[7]	B7 V	–	3.8±1.0				−1.68±0.58	–	–
24	ζ Phe B	[26]	B8	2.5±0.1	1.96±0.06	4.28±0.03		+0.5 [12]	+0.02±0.07	+0.31±0.17	+0.31±0.17
25	AR Aur A	[13]	B9 V [12]	2.55±0.19	1.9	4.28±0.03		+0.6 [12]	+0.38	+0.24±0.32	+0.26±0.31
26	AR Aur B	[13]	B9 V [12]	2.30±0.19	1.7	4.34±0.04		+0.9 [12]	+0.61	+0.74±0.41	+0.76±0.35
27	TW Cas A	[21]	B9 V	1.84/2.4	2.40/259	4.06/3.88			−0.295/—0.13	+1.65/+0.49	+1.65/+0.50
28	RX Her A	[9]	B9.5 V [12]	2.75±0.06	2.4	4.12±0.01		+0.6 [12]	+0.03	−0.09±0.09	−0.07±0.09
29	RX Her B	[9]	B9.5 V [12]	2.33±0.03	2.0	420±0.005		+1.0 [12]	+0.42	+0.61±0.06	+0.62±0.05
30	V 451 Oph A	[22]	A0	2.78±0.06	2.6±0.1	4.10			+0.35±0.08	−0.14±0.09	−0.11±0.08

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

31	α Lyr	[7]	A0 V	–	3.03±0.19	<3.9 [8]	0.45		−0.14±0.02	–
32	XZ Pup A	[23]	A0	2.6	3.5	3.76			−0.30	+0.15
33	AS Eri A	[13]	A0 V [12]	1.6	1.6	4.25			+1.42	+2.22
34a	Sirius A		A1 V	2.2 [19]	1.76±0.04 [7]	4.29±0.02	1.4		+1.05	+0.87
34b				1.6 [8]		4.15±0.02			+1.05	+2.91
35	β Aur A	[25]	A2 IV [11]	2.3 [13]	2.49±0.12	4.00±0.04		+0.4 [5]	+0.69±0.11	+0.67
36	β Aur B	[25]	A2 IV [11]	2.3 [13]	2.50±0.12	4.00±0.04		+0.6 [5]	+0.68±0.10	+0.67
37	CM Lac A	[9]	A2 V [13]	1.88±0.09	1.6	4.30±0.02		+1.7 [12]	+1.65	+1.56±0.21
38	Z Vul B	[9]	A2–3 III [4]	2.3±0.1	2.0	4.20±0.02			+1.24	+0.68±0.20
39	V477 Cyg A	[13]	A3 V [12]	1.78	1.5	4.33		+2.3 [12]	+1.93	+1.80
40	α PsA	[7]	A3 V	–	1.56±0.15	–			+1.86±0.21	–
41	V451 Oph B	[22]	A5? [12]	2.36±0.05	2.1±0.1	4.17±0.05		+1.7 [12]	+1.48±0.10	+0.56±0.09
42	α Aql	[7]	A7 IV/V	–	1.65±0.10	–			+2.24±0−13	–
43	WW Aur A	[13]	A7 V [12]	1.8	1.95	4.12		+1.8 [12]	+1.87	+1.70
44	WW Aur B	[13]	A7 V [12]	1.7	1.90	4.12		+1.8 [12]	+1.93	+1.91
45	TX Her A	[13]	A7 V [12]	1.6	1.5	4.28		+2.6 [12]	+2.44	+2.33
46	TX Her B	[13]	A7 V [12]	1.4	1.4	4.31		+3.2 [12]	+2.59	+2.86
47	RU UMi A	[18]	F0 V	1.7±0.2	1.7±0.1	4.2±0.1			+2.54±0.13	+2.04±0.54
48	EI Cep A	[22]	F0	1.68±0.03	2.3±0.2	3.94±0.09			+1.88±0.19	+2.06±0.09
49	EI Cep B	[22]	F0	1.78±0.03	3.0±0.3	3.74±0.09			+1.31±0.22	+1.80±0.08
50	τ Cyg A	[5]	F0 IV	1.23	–	–	2.29	+2.25	–	+3.53
51	γ Vir A	[5]	F0 V	1.18	–	–	3.50	+3.46	–	+3.75
52	γ Vir B	[5]	F0 V	1.12	–	–	3.52	+3.48	–	+3.98
53	ZZ Boo A	[16]	F2 IV–V	1.75	1.75	4.19			+2.21	+1.88
54	ZZ Boo B	[16]	F2 IV–V	1.68	1.70	4.20			+2.78	+2.06
55	TV Cet A	[9]	F2	1.5	–	–			–	+2.58
56	CM Lac B	[13]–[9]	F2?	1.47±0.04	1.4	4.31±0.01		+3.0	+3.20	+2.68±0.13
57	Ψ Vel A	[5]	F2 IV	1.29	–	–	+3.1	+3.1	–	+3.30
58	RS CVn A	[13]	F4 (12)	1.35	1.7	4.09		+2.8 [12]	+3.00	+3.08
59	Z Her A	[13]–[9]	F4 (12)	1.22±0.06	1.6	4.12±0.02		+2.9 [12]	+3.13	+3.58±0.24
60	Procyon A	–	F5 IV–V	1.78 [19]	2.17±0.15 [7]	4.02±0.06		+3.8 [12]	+2.61±0.15	+1.80
61	α Com A	[5]	F5 V	1.4	–	–	+3.70	{+3.66, +3.70 [10]}	–	+2.86
62	α Com B	[5]	F5 V	1.45	–	–	+3.73	+3.69	–	+2.76
63	CD Tau A	[13]–[9]	F5 V	1.33±0.05	–	–			–	+3.15
64	CD Tau B	[13]–[9]	F5 V	1.40±0.05	–	–			–	+2.91
65	V 477 Cyg B	[13]	F5(?) (12)	1.35	1.2	4.41		+3.18 [12]	+8.89	+3.09
66	HR 7484 A	[13]	F5 V (12)	1.3	1.3	4.32		+3.4 [12]	+3.71	+3.20
67	HR 7484 B	[13]	F5 V (12)	1.3	1.3	4.32		+3.7 [12]	+3.71	+3.20
68	VZ Hya A	[13]–[9]	F5 V	1.23±0.03	1.25	4.33±0.01		+3.6 [12]	+3.80	+3.53
69	VZ Hya B	[13]–[9]	F5 V	1.12±0.03	1.05	4.34±0.02		+4.1 [12]	+4.18	+3.99±0.13
70	42° 1956 A	[5]	F5 V	0.65	–	–	+3.51	+3.47	–	+6.80
71, 72	{δ Equ A, B}	[17]	F7 V	1.23±0.08	{1.26±0.1 (estim.)}	4.32±0.04	+4.0±0.1	–	+3.92±0.02	+3.54±0.31

Table V (Continued)

No.	Name	Main ref.	Spectral type	$\mathcal{M}/\mathcal{M}_\odot$	$R/R_\odot$	$\log g$	M_v (published)	M_{bol} (published)	M_{bol} acc. to(2)	M_{bol} acc. to mass-lum.rel. (31b) (31a)
73	99 Her A	[5]	F7 V	1.18	–	–	+4.04	{+3.99 +4.02 [10]}	–	+3.75
74	WZ Oph A	[13]–[9]	F8 V	1.13±0.04	1.33	4.24±0.02		+3.8	+3.87	+3.95±0.17
75	WZ Oph B	[13]–[9]	F8 V	1.11±0.04	1.36	4.21±0.02		+3.7	+3.82	+4.03
76	ξ Cnc A	[5]	F8 V	1.00	–	–	+4.51	+4.46	–	+4.54
77	β 648 A	[5]	G0 V	1.95	–	–	+3.97		–	+1.40
78	ζ Her A	[20]	G0 IV	1.22	–	–			+3.64	+3.53
79	η Cas A	[5]	G0 V	0.87	–	–	+4.67	+4.61 [10]	–	+5.24
80	9 Pup A	[5]	G0 V	0.56	–	–	+4.8		–	+7.68
81	26 Dra A	[5]	G1 V	1.1	–	–	+4.49	+4.42 [10]	–	+4.20
82	α Cen A	[19]	G2 V	1.06	–	–	{+4.5 +4.36 [10]}	+4.29 [10]	–	+4.26
83	UV Leo A	[9]	G2 V	1.02±0.04	1.09	4.36±0.02			+4.57	+4.45±0.2
84	Sun		G2 V	1.00	1.00	4.44	+4.87		+4.79	+4.54
85	UV Leo B	[9]	G2	0.95±0.04	1.05	4.37±0.02			+4.65	+4.81±0.2
86	η CrB A	[5]	G2 V	0.66	–	–	+4.69	+4.62 [10]	–	+6.68
87	85 Peg A	[20]	G3 V	0.87	–	–			–	+5.24
88	Σ 3062 A	[5]	G4	1.3	–	–	+4.69	+4.60	–	+3.20
89	TW Cas B	[21]	G5 IV	0.96/1.1	1.85/2.00	3.94/3.82			+3.39/3.56	+4.75/+4.08
90	Σ 3062 B	[5]	G8	1.9	–	–	+5.47	+5.33	–	+1.50
91	MM Her A	[24]	G8 V	1.22	2.8	3.63			+2.82	+3.57
92	MM Her B	[24]	G8 V	1.19	1.5	4.16			+4.18	+3.70
93	Σ 2173 A	[15]	G8 IV–V	1.14	–	–	+4.55 [5]	+4.48 [5]		+3.90
94	Σ 2173 B	[15]	G8 IV–V	1.08	–	–	+4.66 [5]	+4.58 [5]		+4.17
95	AR Lac B	[9]	K0	1.31±0.07	3.0	3.60±0.02			+2.84	+3.23±0.25
96	Z Her B	[9]	K0	1.10±0.03	2.6	3.65±0.01			+3.14	+4.07±0.13
97	85 Peg B	[20]	–	0.69	–	–			–	+6.4
98	ζ Her B	[20]	d K0	0.66	–	–			–	+6.5
99	70 Oph A	[19]	K1	0.95	–	–	+5.70	+5.54 [5]	–	+4.8
100	ξ Boo B	[5]	K4 V	0.72	–	–	+7.64	+6.89	–	+6.2
101	Σ 3121 A	[5]	d K4	0.62	–	–	+6.7	+6.3	–	+7.0
102	−34. 11626 A	[5]	d K5	0.78	–	–	+7.0	+6.5	–	+5.8
103	RU UMi B	[18]	K5 V	0.6±0.1	0.9±0.1	4.31±0.18			+6.24	+7.25±0.9
104	61 Cyg A	[19]	K5	0.58	–	–	+7.5		–	+7.4
105	α Cen B	[19]	K6	0.87	–	–	+5.9		–	+5.2
106	70 Oph B	[19]	K6	0.69	–	–	+7.5		–	+6.4
107	61 Cyg B	[19]	K7	0.57	–	–	+8.3		–	+7.5
108	η Cas B	[5]	d MO	0.54	–	–	+8.42	+7.35	–	+7.8
109	−34° 11626 B	[5]	–	0.54	–	–	+7.9	+7.1	–	+7.8

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

110	Hu 575 A	[5]	–	0.62	–	–	+7.9	+7.1	–	+7.0	
111	YY Gem A	[9]	M1	0.58±0.02	0.60	4.64±0.02		+7.7 [12]	+7.92	7.4±0.2	
112	YY Gem B	[9]	M1	0.58±0.02	0.60	4.64±0.02		+7.7 [12]	+7.92	7.4±0.2	
113	Hu 575 B	[5]	–	0.47	–	–	+ 8.2	+7.2	–	+ 8.5	+ 8.6
114	Σ 2398 A	[19]	M4	0.41	–	–	+11.2		–	+ 9.3	+ 9.4
115	Fu 46 A	[2]	M4	0.31	–	–	+10.96	+8.72	–	+10.9	+11.0
116	Krü 60 A	[19]	M4	0.27	–	–	{+11.7 +11.84 [2]	+9.60 [2]}	–	+11.7	+11.9
117	Fu 46 B	[2]	M4	0.25	–	–	+11.34	+9.10		+12.2	+12.3
118	40 Eri C	[19]	M4e	{0.20 0.21 [2]}	–	–	{+12.8 +12.62 [2]	+10.10 [2]}	–	+13.6	+13.8
119	Σ 2398 B	[19]	M5	0.41	–	–	+12.0		–	+ 9.3	+ 9.4
120	Ross 614 A	[19]	M5e	0.12 [27]	–	–	+13.3 [5]	+11.1 [5]	–	+16.8	+17.2
121	Krü 60 B	[19]	M6	0.16	–	–	{+13.2 +13.39 [2]	+10.58 [2]}	–	+15.0	+15.2
122	L 726–8AB	[19]	M6e	0.15	–	–	{A +15.3 B +15.8 +15.35 [2]	+12.68 [2]		+15.4	+15.7
123	Ross 614 B	[19]	–	0.06 [27]	–	–	+16.8 [5]	+13.0 [5]	–	+21.6	+22.2

References to Table V

[1] Sahade, J. and Dessey, J. L.: 1952, *Astrophys. J.* **115**, 53.
[2] Van de Kamp, P.: 1959, *Astron. J.* **64**, 236.
[3] Popper, D. M.: 1959, *Astrophys. J.* **129**, 647.
[4] Harris III, D. L.: 1963, *Stars and Stellar Systems* **3**, 267.
[5] Harris III, D. L., Strand, K. Aa. and Worley, C. E.: 1963, *Stars and Stellar Systems* **3**, 273.
[6] Wood, F. B.: 1963, *Stars and Stellar Systems* **3**, 377.
[7] Hanbury Brown, R. and Davis, J., Allen, L. R.: 1967, *Monthly Notices Roy. Astron. Soc.* **137**, 393.
[8] Heintze, J. R. W.: 1968, *Bull. Astron. Inst. Neth.* **20**, 1.
[9] Popper, D. M.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 85.
[10] Morton, D. C. and Adams, T. F.: 1968, *Astrophys. J.* **151**, 611.
[11] Toy, L. G. S.: 1969, *Astrophys. J.* **158**, 1099.
[12] Koch, R. H.: 1970, in K. Gyldenkerne and R. M. West (eds.), *IAU Colloquium No. 6*, Copenhagen University Publication Fund, p. 65.
[13] Popper, D. M.: 1970, in K. Gyldenkerne and R. M. West (eds.), *IAU Colloquium No. 6*, Copenhagen University Publication Fund, p. 1.
[14] Popper, D. M.: 1970, *Astrophys. J.* **162**, 925.
[15] Batten, A. H., Fletcher, J. M., and West, R. M.: 1971, *Publ. Astron. Soc. Pacific* **83**, 149.
[16] McNamara, D. H., Hansen, L., and Wilcken, S. K.: 1971, *Publ. Astron. Soc. Pacific* **83**, 192.
[17] Dworetsky, M. M., Popper, D. M., and Dearborn, D. S.: 1971, *Publ. Astron. Soc. Pacific* **83**, 207.
[18] Wood, F. B.: 1971, *Publ. Astron. Soc. Pacific* **83**, 286.
[19] Van de Kamp, P.: 1971, *Ann. Rev. Astron. Astrophys.* **9**, 103.
[20] Feierman, B. H.: 1971, *Astron. J.* **76**, 73.
[21] Cook, G. P.: 1971, *Astron. J.* **76**, 449.
[22] Popper, D. M.: 1971, *Astrophys. J.* **166**, 361.
[23] Johansen, K. T., Jørgensen, H. E., and Behr, V.: 1971, *Astron. Astrophys.* **11**, 20.
[24] Imbert, M.: 1971, *Astron. Astrophys.* **12**, 155.
[25] Johansen, K. T.: 1971, *Astron. Astrophys.* **12**, 165.
[26] Dachs, J.: 1971, *Astron. Astrophys.* **12**, 286.
[27] Kuiper, G. F. G.: 1971, *Astron. Astrophys.* **14**, 70.
[28] Lippincott, S. L.: 1972, *Astron. J.* **11**, 679.

or

$$\theta_{\text{eff}} = 0.030\,n + 0.015 \quad \text{respectively}, \tag{30b}$$

where the spectral-type indicator n is equal to 5 for B0 V and increases to $n = 15$ for A0 V.

Formula (30a) gives the temperatures according to Schild *et al.* (1971) and formula (30b) according to formula (29b) in which Auer en Mihalas' (1972) results are included. For the A0 V and later type stars mean effective temperatures were determined from the data published by Johnson (1962a), Keenan (1963), Morton and Adams (1968), and Schmidt (1972).

With these temperatures M_{bol} is calculated according to formula (2) for those stars of which the radii are known except for V 444 Cyg B, UW CMa A and B, A0 Cas A and B. For the latter stars no reliable temperatures are thought to be available. The calculated M_{bol} values are given in the 10th column of Table V.

For the 70 components of eclipsing binaries the mass-luminosity relation could be represented as follows if Equation (30a) is used:

$$M_{bol} = 4.54 - 11.54 \log \mathcal{M}/\mathcal{M}_\odot + 2.41 \log^2 \mathcal{M}/\mathcal{M}_\odot\,, \tag{31a}$$

if Equation (30b) is used:

$$M_{bol} = 4.54 - 11.45 \log \mathcal{M}/\mathcal{M}_\odot + 2.05 \log^2 \mathcal{M}/\mathcal{M}_\odot\,. \tag{31b}$$

With these relations absolute bolometric magnitudes were calculated for the 48 components of astrometric binaries and for the first five stars given in column 11 of Table V. At present no detailed conclusions can be drawn from the differences between the published and calculated M_{bol} values. Much more reliable observations of M_v and $(U-B)_0$ values are necessary and at the same time the determination of such a mass-luminosity relation has to be done in a much more refined way. The uncertainties in the hot part of this empirical mass-luminosity relation cause rather large differences in the very cool part of this relation. However in the cool part of the relation up to star No. 112 of Table V this empirical mass-luminosity relation gives quite reasonable results.

From the extrapolated M_{bol} the effective temperatures of V 444 Cyg B (O6) and A0 Cas B (O9 III) are 34000 K and 31000 K respectively according to equation (31b) and 30000 K and 28000 K respectively according to Equation (31a). For comparison: Auer and Mihalas find for HD 54662 (06.5): 41000 K, for S Mon (O7 Vf): 39000 K and for λ Ori (O8 IIIf): 37500 K.

Acknowledgements

I wish to thank Dr E. P. J. van den Heuvel for a critical reading of the manuscript.

References

Auer, L. H. and Mihalas, D.: 1972, *Astrophys. J. Suppl.* **24**, 193.
Allen, C. W.: 1963, *Astrophysical Quantities*, 2nd ed. The Athlone Press, London.
Aller, L. H.: 1963, *The Atmospheres of the Sun and the Stars*, 2nd ed., The Ronaical Press Company, New York.
Blanco, V. M., Demers, S., Douglas, G. G., and FitzGerald, M. P.: 1968, *Publ. U. S. Naval Obs.* **21**, 2nd series.
Clariá, J. J.: 1972, *Astron. Astrophys.* **19**. 303.
Collins, G. W.: 1970, in A. Slettebak (ed.), *Stellar Rotation*, Reidel Publishing Co., Dordrecht, p. 85.
Collins, G. W. and Harrington, J. P.: 1966, *Astrophys. J.* **146**, 152.
Crawford, D. L.: 1963, *Astrophys. J.* **137**, 530.
Edmonds, F. N., Schlüter, H., and Wells, D. C.: 1967, *Mem. Roy. Astron. Soc.* **71**, 271.
Eggen, O. J.: 1962, *Quart. J. Roy Astron. Soc.* **3**, 259.
Eggen, O. J.: 1969, *Astrophys. J.* **158**, 1109.
Fernie, J. D., Hagen Jr., J. P., Hagen, G. L., and McClure, L.: 1971, *Publ. Astron. Soc. Pacific* **83**, 79.
FitzGerald, M. P.: 1970, *Astron. Astrophys.* **4**, 234.
Fricke, K., Stobie, R. S., and Strittmatter, P. A.: 1971, *Astrophys. J.* **171**, 593.
Gallouet, L.: 1964, *Ann. Astrophys.* **27**, 423.
Gingerich, O.: 1969, *Theory and Observation of Normal Stellar Atmospheres*, M.I.T. Press, Cambridge.

Gliese, W.: 1957, *Mitt. Astr. Rechen-Inst. Heidelberg Ser. A.*, No.8.
Gray, D. F.: 1967, *Astrophys. J.* **149**, 317.
Greenstein, J. L.: 1969, *Stellar Astronomy*, Vol. 1, Gordon Breach New York, pp. 89, 90.
Griem, H. R.: 1967, *Astrophys. J.* **147**, 1092.
Hanbury Brown, R., Davis, J., Allen, L. R., and Rome, J.: 1967, *Monthly Notices Roy. Astron. Soc.* **137**, 393.
Hayes, D.: 1967, Thesis UCLA; see also 1970, *Astrophys. J.* **159**, 165.
Heintze, J. R. W.: 1968, *Bull. Astron. Inst. Neth.* **20**, 1.
Heintze, J. R. W.: 1969, *Bull. Astron. Inst. Neth.* **20**, 154.
Hiltner, W. A. and Morgan, W. W.: 1969, *Astron. J.* **74**, 1152.
Hobbs, L. M.: 1972, *Astrophys. J. Letters*, **175**, 145.
Hodge, P. W. and Wallerstein, G.: 1966, *Publ. Astron. Soc. Pacific* **78**, 411.
Hyland, A. R.: 1969, in O. Gingerich (ed.), *Theory and Observation of Normal Stellar Atmospheres*, M.I.T. Press, Cambridge, p. 271.
Jaschek, M. and Jaschek, C.: 1963, *Publ. Astron. Soc. Pacific* **75**, 365.
Johnson, H. L. and Morgan, W. W.: 1953, *Astrophys. J.* **117**, 313.
Johnson, H. L.: 1958, *Lowell Observ. Bull.* **4**, 37.
Johnson, H. L.: 1962, *Astrophys. J.* **135**, 69.
Johnson, H. L.: 1962, *Astrophys. J.* **136**, 1135.
Johnson, H. L.: 1966, *Ann. Rev. Astron. Astrophys.* **4**, 193.
Jones, B. F.: 1972, *Astrophys. J. Letters* **171**, 57.
Keenan, P. C.: 1963, *Stars and Stellar Systems* **3**, 91.
Klinglesmith, D. A.: 1971, *Hydrogen Line Blanketed Model Stellar Atmospheres*, NASA SP-3065.
Klinglesmith, D. A.: 1972, *Astrophys. J*, **171**, 79.
Kuiper, G. P.: 1938, *Astrophys. J.* **88**, 429.
Maeder, A. and Peytremann, E.: 1970, *Astron. Astrophys.* **17**, 120.
Maran, S. P., Kurucz, R. L., Strom, K. M., and Strom, S. E.: 1968, *Astrophys. J.* **153**, 147.
Matthews, T. A. and Sandage, A. R.: 1963, *Astrophys. J.* **138**, 30.
Mihalas, D.: 1965, *Astrophys. J. Suppl.* **9**, 321.
Mihalas, D.: 1966, *Astrophys. J. Suppl.* **13**, 1.
Morgan, W. W., Harris, D. L., and Johnson, H. L.: 1953, *Astrophys. J.* **118**, 92.
Morton, D. C. and Adams, T. F.: 1968, *Astrophys. J.* **151**, 611.
Oke, J. B.: 1961, *Astrophys. J.* **133**, 90; **134**, 214.
Oke, J. B.: 1965, *Ann. Rev. Astron. Astrophys.* **3**, 23.
Oke, J. B. and Schild, R.: 1970, *Astrophys. J.* **161**, 1015.
Ostriker, J. P. and Hesser, J. E.: 1968, *Astrophys. J. Letters*, **153**, 151.
Parker, R., Greenstein, J. L., Helfer, H. L. and Wallerstein, G.: 1961, *Astrophys. J.* **133**, 101.
Pettit, E. and Nicholson, S. B.: 1928, *Astrophys. J.* **68**, 279.
Popper, D. M.: 1959, *Astrophys. J.* **129**, 647.
Roxburgh, I. W. and Strittmatter, P. A.: 1966, *Monthly Notices Roy. Astron. Soc.* **133**, 345.
Sandage, A. R. and Eggen, O. J.: 1959, *Monthly Notices Roy. Astron. Soc.* **119**, 278.
Sandage, A. R. and Tamman, G. A.: 1969, *Astrophys. J.* **157**, 683.
Sargent, W. L. W.: 1968, *Astrophys. J.* **152**, 885.
Schild, R., Peterson, D. M., and Oke, J. B.: 1971, *Astrophys. J.* **166**, 95.
Schmidt, E. G.: 1972, *Astrophys. J.* **174**, 605.
Serkowski, K.: 1963, *Astrophys. J.* **138**, 1035.
Strittmatter, P. A.: 1966, *Astrophys. J.* **144**, 430.
Strom, S. E.: 1968, unpublished.
Underhill, A. B.: 1966, *Vistas Astron.* **8**, 41.
Underhill, A. B.: 1972, NASA GSFC Preprint X-670-72-102.
Wallerstein, G., Herbig, G. H., and Conti, P. S.: 1965, *Astrophys. J.* **141**, 610.
Wallerstein, G. and Hodge, P. W.: 1967, *Astrophys. J.* **150**, 951.
Wayman, P. A., Symms, L. S. T., and Blackwell, K. C.: 1965, *Roy. Observ. Bull.* No. 98.
Weidemann, V. and Bues. I.: 1967, *Z. Astrophys.* **67**, 416.
Westerlund, B. E.: 1963, *Monhtly Notices Roy. Astron. Soc.* **127**, 83.
Wildey, R. L., Burbidge, E. M., Sandage, A. R., and Burbidge, G. R.: 1962, *Astrophys. J.* **135**, 94.
Young, A., Nelson, B., and Mielbrecht, R.: 1972, *Astrophys. J.* **174**, 27.

DISCUSSION

Schild: The $Q-\theta_{\text{eff}}$ relation published in the contribution by Drs Peterson and Oke and myself shows a linear relation reminiscent of your linear $(U-B)_0-\theta_{\text{eff}}$ relation.

Our $Q-\theta_{\text{eff}}$ relation makes use of the most reliable available data for these stars rather than an average based upon all published values. Most of the stars for which we measured energy distributions are in the list of secondary standards of the *UBV* system, as published by Harris and Johnson (1961 or 1962). I therefore believe that our *UBV* photometry is free of systematic effects and should have negligible random errors.

I should like to make a final comment with which I expect concurrence from both Dr Heintze and Prof. Pecker. In my experience of deriving an effective temperature scale based upon detailed energy distribution compared to blanketed stellar models, and in my comparison of the effective temperature scale with the works of others based upon different data and models, I find that the difference between effective temperature scales appear to be less than the probable systematic errors of these scales. As we have seen best from the results presented by Prof. Code, large discrepancies still exist between observed and model-predicted far UV fluxes, and these differences will cause errors in our bolometric corrections far larger than our effective temperature scales would lead us to expect.

I propose that we concentrate our efforts upon deriving bolometric corrections and then effective temperatures, from direct measurements of far UV fluxes such as those presented by Prof. Code. The spacecraft in orbit, and others being prepared as well as an already large amount of available UV data, make it possible for most astronomers to use far UV data without becoming specialists in spacecraft instrumentation. Furthermore, as noted by Prof. Code, use of UV data is the *only* way to determine temperatures of the hottest stars, for which the concept of effective temperature breaks down.

Divan: **Remarques sur la définition des discontinuités de Balmer de la spectrophotométrie BCD.** Théoriquement, si λ_0 est la longueur d'onde à laquelle se produit la discontinuité de Balmer, $D = \log (I_{\lambda_0+}/I_{\lambda_0-}$, I_{λ_0+} et I_{λ_0-} étant les intensités du rayonnement continu à la longueur d'onde λ_0 du côté rouge et du côté bleu de la discontinuité. Dans la pratique, pour les rayonnements stellaires, la discontinuité de Balmer ne se produit pas à une longueur d'onde bien définie λ_0; elle apparaît progressivement sur un intervalle de longueurs d'onde plus ou moins large et se termine du côté ultraviolet à une longueur d'onde λ'_0, variable d'une étoile à l'autre, mais toujours plus grande que la limite théorique $\lambda_0 = 3647$ Å. On est donc conduit à donner de D une définition arbitraire:

$$D = \log(I_{3700^+}/I_{3700^-}).$$

La valeur $\lambda = 3700$ Å a été choisie car à cette longueur d'onde la discontinuité de Balmer de la plupart des étoiles est déjà terminée; le continu ultraviolet est alors observable et l'on peut mesurer sans difficulté I_{3700^-}, à condition que le pouvoir de résolution du détecteur utilisé ne soit pas trop faible.

La difficulté réside dans la détermination de I_{3700^+}, car le continu visible cesse généralement d'être observable entre les raies spectrales dès $\lambda = 4000$ Å même pour les étoiles B et A, et il faut l'extrapoler de 4000 à 3700 Å. La valeur précise trouvée pour D dépend de la manière dont cette extrapolation est faite, et si l'on veut comparer les valeurs de D données par une grille de modèles aux valeurs observées on doit dans les deux cas faire l'extrapolation de la même manière; c'est pourquoi nous donnons ici quelques précisions sur la procédure utilisée dans la spectrophotométrie BCD.

Les opérations se passent en deux temps:

(a) pour chaque étoile on détermine la *différence Δ D* entre sa discontinuité de Balmer et celle d'une étoile étalon;

(b) le *zéro de l'échelle* ainsi obtenue est déterminé à l'aide d'une seule étoile, bien choisie, dont on mesure directement la discontinuité de Balmer sur l'enregistrement microphotométrique d'un spectre à grande dispersion, calibré en intensité.

L'opération (a) telle que nous la décrivons ci-dessous, est justifiée par le fait d'observation suivant: si l'on porte $\log(I_2/I_1)$ en fonction de $1/\lambda$ pour deux étoiles O ou B de températures différentes mais non rougies, dans le domaine 6200–4000 Å où le continu est observable on obtient des points alignés sur une droite. L'extrapolation de cette droite de 4000 à 3700 Å donne la différence ΔD entre les discontinuités de Balmer des deux étoiles. Pour les étoiles A et F on opère de la même façon mais le domaine spectral doit être réduit à l'intervalle 4600–4000 Å (au détriment de la précision sur ΔD) car les points situés au-delà de 4600 Å ne se placent plus sur la droite. Nous insistons sur le fait que l'extrapolation ne se fait pas sur la fonction $\log I = f(1/\lambda)$ qui est très loin d'être une droite et ne pourrait donner qu'une définition complètement arbitraire des discontinuités, ni même sur la fonction log $[I/B\lambda(T)]$ que l'on ne peut déterminer que par des comparaisons d'une étoile à un corps noir terrestre, comparaisons si difficiles à réaliser que les discontinuités ainsi obtenues ont encore une marge d'incertitude relativement grande. Tout ce qui précède ne concerne que les étoiles sans rougissement interstellaire. Dans le cas général (étoiles rougies) la relation $\log(I_2/I_1) = f(1/\lambda)$ n'est pas linéaire et la simple extrapolation précédente ne peut plus être faite; on peut cependant encore calculer le ΔD que l'on observerait en l'absence de matière interstellaire si l'on connaît la forme de la loi d'absorption pour les deux étoiles et une valeur au moins approximative de leur rougissement. Pour les discontinuités de la classification BCD, ce calcul est toujours fait car c'est à cette condition seulement que le paramètre D est réellement indépendant du rougissement interstellaire; il est conduit de manière à utiliser l'ensemble de tous les points du domaine 6200–4000 Å pour éviter la perte de précision sur ΔD qu'entraînerait la réduction du domaine spectral au petit intervalle dans lequel la loi d'absorption interstellaire est sensiblement linéaire en $1/\lambda$.

L'opération (b) a été réalisée sur des spectres (dispersion 40 Å mm^{-1}; domaine spectral 6200–3000 Å) de ε Ori. Cette supergéante B0 a été choisie à la fois pour la finesse de ses raies (sur les spectres utilisés le continu visible est observable jusque vers 3850 Å) et pour la faible valeur de sa discontinuité de Balmer. Cette faible valeur de D réduit la marge d'erreur possible en facilitant l'extrapolation sur les enregistrements microphotométriques du continu visible: celui-ci doit en effet présenter à 3700 Å une température de couleur (donc, sur les enregistrements, une pente) très voisine de celle du continu ultraviolet, ce qui ne serait pas du tout le cas pour une étoile à grande discontinuité. L'incertitude sur la valeur de D pour ε Ori semble ainsi être seulement environ ± 0.005.

Une incertitude supplémentaire de ± 0.015 sur le zéro de l'échelle des discontinuités BCD publiées jusqu'ici vient d'un rattachement insuffisant de ε Ori à l'ensemble des étalons habituels; ce zéro n'est donc défini qu'à ± 0.02 près alors que les ΔD sont connus en général à ± 0.01 près. Un meilleur rattachement de ε Ori permettra de faire disparaître en grande partie cette incertitude supplémentaire; le travail est en cours.

Il résulte de tout ceci que si l'on veut comparer les discontinuités de la classification BCD à une grille de modèles il y a intérêt, à déterminer une échelle relative des discontinuités de la grille par la même méthode que dans les observations, c'est-à-dire en comparant chaque modèle de la grille à l'un d'entre eux et en extrapolant les $\log(I_2/I_1)$ obtenus de 4000 à 3700 Å. On peut ensuite comparer les discontinuités individuelles des modèles aux discontinuités observées, mais en se rappelant les incertitudes inhérentes à la définition du zéro des échelles de discontinuités.

Remarque. Les méthodes décrites pour l'extrapolation du continu sous les dernières raies de la série de Balmer peuvent servir également à déterminer le continu sous une raie ou une bande large; par exemple, on peut déterminer le continu d'une étoile rougie sous la bande 4430 en prenant sur la même plaque le spectre d'une étoile non rougie de type voisin; à partir des valeurs de $\log(I_2/I_1)$ en dehors de la bande et du continu de la deuxième étoile on peut reconstituer celui de la première.

Van den Bergh: Could Dr Fitzgerald perhaps comment on the proposed revisions of the intrinisic $U-B$ vs $B-V$ relation for main sequence stars. This point is important because the proposed revisions are particularly large in the region $-0.5 < U-B < 0.0$ which is used to obtain the reddening of globular clusters via observations of cluster horizontal branch stars. With the proposed new intrinsic colour-colour relation halo clusters that are now regarded as unreddened would have $E_{B-V} \approx 0.03$.

Fitzgerald: The colours presented by Heintze for $(U-B)_0 < 0.00$ are consistent with my colours. At most they differ systematically by 0.02 to the ultraviolet in $(B-V)_0$. This amount is within as yet undetermined intrinsic scatter of the two-colour relation for class V stars. This scatter and the real values of $(B-V)_0$ should be determined from cluster studies. For the colours $(U-B)_0 > 0$ Heintze's sequence is from Westerlund's 1963 list of 'bluest' stars. Again because of intrinsic scatter, 'bluest' stars should *not* be used. Plots of $(B-V)$ vs m_v are able to give good $(B-V)_0$ if a few stars of given spectral class are unreddened. This was the procedure I used for A0 V stars and later for stars later than A0 V and I see no reason to change my colours, (given in *Astron. Astrophys.* **4**).

The $(U-B)_0$ colours of O-stars show an apparent turn toward smaller negative values. This turn appears to rely perhaps too much on the very young clusters. If the $(B-V)_0$ colours based on 7 visual binaries are correct, then the turn off referred to above is in approximate agreement with the two-colour reddening lines.

Note added after meeting. For the intrinsic colours of stars later than about B8 the colours indicated by Heintze represent an envelope around the observed colours. The intrinsic colours as a function of spectral type have a cosmic scatter in them as demonstrated in an earlier paper (FitzGerald, 1970, *Astron Astrophys*. **4**, 234,), so envelopes around the observed colours should not be used for mean intrinsic colours of class V stars. At present I see no reason to change the colours for stars later than B8 from those given in the paper cited above.

Hauck: I agree with your comment concerning the inhomogeneity of the photometric data; it is not only the case for the UBV system! It would be urgent to ask observers for more homogeneous data. Perhaps a by-product of the Blanco *et al.* catalogue is the astronomer's variability more than star's variability.

Garrison: I would like to make two general comments concerning the use of observational data for transformation to theoretical parameters. First, we assume that by taking means of many observers, we improve the accuracy. I would like to suggest that by submitting to this 'tyranny of the mean' we usually decrease the accuracy. This is because of difficulties of transformation to a common system, as well as to observational errors. If I were interested in such a calibration, I would choose one careful observer who has observed a large sample and calibrate *his* system and filters, because the internal accuracy would be higher.

The second comment is that, too often, it is assumed that there is a unique relation between spectral type and colour and that one or the other is 'wrong' if they don't agree. In such a relation, the spread is greater than the acceptable errors in either. An extreme example is the Bp class of stars. The spectra are slightly peculiar and the difference between the spectrum and the colour gives an additional piece of information. But, there are other examples in which the spectra are normal, but significantly different from the colours. When colours and spectra are different, most spectroscopists know better than to say that the colours are wrong, and some photometrists have learned not to conclude that the classification is wrong. They are just different.

Jaschek: I would like to write down a few figures to pin down what Garrison said before. There does not exist such a thing as *the* intrinsic colour of a given spectral type. In early *B*-type stars, classified by a single astronomer, usually the dispersion is of the order of $0\overset{m}{.}07$ in $(U-B)_0$. This is not simply a question coming in because of the use of spectral type; if we analyse only the colours, we find that for a given $(B-V)$ colour we get (for A type dwarfs) a dispersion of about $0\overset{m}{.}04$. Therefore one should not think of the main sequence as being a curve, but rather a band. The Q method which is often used, assumes implicitly, that there exists such a curve and should therefore be used very cautiously. (The results quoted here are from a paper by the Jaschek's in *IAU Symp*. **50**.)

Schild: Your estimated intrinsic plus observational scatter in $(U-B)_0$ for early type stars is really an upper limit to the true value, since your derivation assumes all stars of given spectral type to have the same $(B-V)_0$; the well known scatter of several hundredths in intrinsic $(B-V)$ at given spectral types immediately implies an even greater scatter in intrinsic $U-B$. The procedure of de-reddening all stars of given spectral type to a single value of $(B-V)_0$ guarantees an intrinsic scatter of several hundredths in $(U-B)_0$ even if there are no errors in photometry or spectral classification.

Schmidt-Kaler: I have a remark and two questions. First the remark: I did almost exactly the same 11 yr ago (cf. *Astron. Nachr*. **286**, 113 and Landolt Börnstein, 1965). The resulting intrinsic colours have been given in the Landolt-Börnstein tables. The difference in procedure may have been, e.g. to retain the quadratic term, to use only reliable series of *UBV* measurements like, of course, Hiltner's, to check on residual reddening of apparently blue unreddened stars by means of measurements of interstellar polarization etc. I have just made a quick check of the $(U-B)_0$ vs $(B-V)_0$ relation and I find full agreement with your results within at most $\pm 0\overset{.}{.}01$ for the B5–A0 stars; for the earlier types my $(U-B)_0$'s are ca. $0\overset{m}{.}06$ redder than yours for a given $(B-V)_0$ but still bluer than Johnson's for a given spectral type. This difference is probably due to the different treatment of the interstellar reddening quadratic term. Regarding the scatter of the $U-B$'s I might say that we observe $U-B$ to, say, $\pm 0\overset{m}{.}005$, but we do not know whether we are exactly on Johnson's system. This is due to the fact that Johnson had the ultraviolet cut-off by the atmosphere, and since the height of the observatories above sea level is different, in general, there remains some basic ambiguity in the $U-B$ definition.

I have now two questions to you as a theoretician: Firstly – since I have dealt with quite a few spectra: Do you have a receipe to draw the continuum?

Secondly: The temperatures of B-stars you gave are 'cooling off', so does also the total energy output? This would be very important for stellar evolutionary considerations.

Heintze: Not feeling like a theoretician I should say in general no. For the hot B type stars a very good first approximation is to draw by eye or by computer a mean lines through the graininess of the microphotometer trace. Only the very weak lines will be missed in this way.

These weak lines could be found by superposing several spectra of the same star on each other by computer. The traces have to be made with a microphotometer-comparator with high positional accuracy which gives the intensity of the spectrum (in a relative scale) as a function of plate position. Such a machine, built by Faul-Coradi, Scotland, is just installed at the Utrecht Observatory; (the minimum step size is one micron). I think each spectrum has to be splitted up in parts with at any case at both ends a spectral line of which the centre can be determined rather accurately from the profile. The spectrum intensities of the different spectra at the positions where the intensities will be added have in general to be found by interpolation between two successive measured points laying at both sides of the 'adding'-position. A linear interpolation is possible if the distance between two successive measurements is small enough (on low dispersion spectra with high resolution a few micron, on high dispersion spectra 10–50 μ).

It seems to me that this procedure can be used also for spectra of later type stars. It is quite well possible that windows (parts in the spectrum without lines) will show up much more clearly in this way.

I do not know how many spectra will be necessary; perhaps 5–10. Whenever long exposure times are possible much can already be done by widening the spectra to 0.5 or even 1 mm.

A check whether the continuum above symmetric lines with extended wings is drawn correctly is possible by superposing on each other the long- and short wavelength part of the line (plotted on transparant semi-logarithmic paper, one part being mirrored against wavelength). The red and violet relative intensities at each distance $\Delta\lambda$ from the centre have to be the same. If not a correction can easily be found now.

In this way also the point where the H-lines start to confluence can be found. Going one by one to higher members of the Balmer series by example it is possible in this way to find the continuum above the confluencing Balmer lines. The point $1/\lambda = 2.4\ \mu^{-1}$ ($\lambda = 4167$ Å; see Section 1.6.2 of my paper) is chosen such that no difficulties caused by the blending of the Balmer lines arise.

Only the effective temperatures of the O9 and the early B type stars are now generally believed to be less than according to the Morton and Adams' (1968) scale. If no other forms of energy transport than radiation are working then indeed the total energy output of these stars has diminished at the same time.

Around A0 V however the effective temperatures are now believed to be a little bit higher: ≈ 10000 K instead of 9500 K.

Keenan: So much has been said about the relevance of spectral types that it should be remembered that although the photometric indices often have much smaller errors, frequently they do not distinguish between the physical variables as well as spectral types can – provided that the spectroscopic observer is careful to point out all the peculiarities that he can see on the spectrograms.

Jaschek: I agree completely with Dr. Keenan and would only like to add that the values I gave refer to dwarfs, which are recognized as such by spectroscopy. Therefore we are not using all the spectroscopic information available. The advantage consists of course largely in the possibility of sorting out everything which is not what you want (i.e. main sequence stars).

Maeder: I have a comment about the scatter, about which you are quite right, i.e. the scatter between the different *UBV* measurements of the same star by different authors. At least a part of this scatter comes from neglecting the colour-terms in the reduction for atmospheric extinction, as has been described by Rufener (1964, *Publ. Obs. Genève* **66**).

Crawford: I feel the dispersion that Jaschek finds is small rather than large, in light of the difference in $(U-B)_0$ between spectral types. Remember that spectral type is a quantized parameter; $(U-B)_0$ is not. Therefore a unique $(U-B)_0$ does not exist for any given spectral type for that reason alone.

The luminosity effects on the Balmer jump (or on $(U-B)_0$) that Miss Divan mentioned earlier, and with which I agree, also fuzz up the relation, if the stars you are averaging or plotting, are not of the same age. In a cluster, this spread is small, and the $(U-B)/(B-V)$ relations (from homogeneous data, i.e. not averaged) have very little scatter.

Fitzgerald: I thought it might be relevant to discuss briefly the internal consistency of the 'polyglot' of the observations in the Blanco-Demers-Douglass-Fitzgerald Photoelectric Catalogue (BDDF). In a paper to be published in Astronomy and Astrophysics Supplement Series I have analysed the internal consistency of observations of stars observed two or more times. Of the 20705 stars in BDDF

https://doi.org/10.1017/S0074180900055297 Published online by Cambridge University Press

about 7000 have two or more observations. Of these 532 have discordant results in one or more of V, $B-V$, $U-B$, or between colour and spectral-luminosity class. These discrepancies have been excluded from the following analysis. (They are listed in the *Astronomy and Astrophysics Supplement Series* article). The discrepancies are attributable to transcription errors (10%), contamination in visual binary stars (16%), variables (22%), reported photometry (53%), and classification or photometry (15%)

The resulting standard deviations from the mean magnitudes and colours were formed as a function of reference number and spectral class. These are shown in Figures 1 and 2 respectively of the *Astronomy and Astrophysics Supplement Series* article. In figure one we plot the number of references having a certain standard deviation from the mean (σ) versus σ for references with 15 or more stars in common with other references.

Obviously some references give poor photometry. The standard deviations for each reference will be given in the *Astronomy and Astrophysics Supplement Series* article by reference number (in order to preserve anonymity). The standard deviations as a junction of spectral class clearly show the greater tendency of M and Carbon stars to be variable. Possibly O stars are also variable but here the number of O stars with observations in common is only 20. (Perhaps other observers should reobserve some of the O stars to improve these statistics).

On average the consistency between magnitudes and colours is considerably better than I expected, but more than might be desired. The average standard deviations from the mean parallax observatons (excluding the discrepancies) is ± 0.015 in V, ± 0.011 in $B-V$ and ± 0.016 in $U-B$.