THE ABSOLUTE CALIBRATION OF THE HR DIAGRAM: FUNDAMENTAL EFFECTIVE TEMPERATURES AND BOLOMETRIC CORRECTIONS

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1. INTRODUCTION

Scales of fundamental bolometric connections (B.C.) and effective temperatures (T_{eff}) as a function of spectral type or color are necessary for the comparison of observations and theory in the HR **diagram**. The basic equation defining T_{eff} may be written

$$f = (\theta^2/4)\sigma T^4_{eff} \tag{1}$$

where f is the total apparent flux, and θ is the angular diameter ($\theta = 2R/d$). The **apparent bolometric** magnitude is

$$m_{bol} = -2.5 \log_{10} f + C = V + B.C. \tag{2}$$

The zero point constant, C, may be determined by reference to the Sun:

$$m_{bol,*} - m_{bol,\odot} = -2.5 \log_{10}(f_*/f_\odot) \tag{3}$$

We see from Eqns. (2) and (3) that the zero-point of the B.C. scale is arbitrary and that a B.C. scale may be measured by measuring f and V for a suitable sample of stars. The Earth's atmosphere blocks off a significant part of f, and interstellar hydrogen blocks the Lyman continuum, which is significant in the O-stars. The measurement of θ requires the knowledge of limb darkening, which is extremely difficult to measure, at present. Traditionally, unmeasurable portions of f have been estimated by model atmosphere calculations, as has been the limb darkening. This resort to models is "non-fundamental".

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Can we make truly fundamental measurements of T_{eff} and B.C.? In the strict sense, the answer is no. But the limb darkening connections to θ have a very small effect upon T_{eff}. Similarly, we have not measured θ of an O-star hot enough for the Lyman continuum flux to be a large fraction of the total flux. For cooler stars, we are now able to make measurements covering nearly all of the significant parts of the spectrum. So we can, indeed, make adequately fundamental measurements of T_{eff} and B.C.

Previous summaries of the determination of T_{eff} and B.C. are those by Kuiper (1938), Popper (1958), Harris (1963), Johnson (1966; hereafter simply "Johnson") and Code, et al. (1976; hereafter CDBB). The increase in the degree to which scales of T_{eff} and B.C. have become fundamental is clearly marked in these papers, particularly in Johnson's paper, in which extensive IR photometry is introduced, and in CDBB in which they introduce not only extensive UV photometry, but also the catalogue of θ's for hot stars measured by Hanbury Brown and his colleagues. The θ's available to Kuiper, Popper and Harris were mainly from the measurements by Michelson and Pease; there were not many of these, they were limited to K and M giants and supergiants, and some of them were of doubtful quality. In recent years, there has been a revolution in the measurement of θ's of cool stars, resulting from the introduction of speckle interferometry, the revival of amplitude interferometry, and particularly from the photometry of lunar occultations. The primary limitation still remaining relates to spectral types and luminosity classes. There is a serious lack of measurements of all cool dwarfs and of giants of middle spectral types. In this paper I use θ's of 18 K and M giants for the determination of the T_{eff}-scale for cool stars. These are only those which are most useful in the present context; it is by no means an exhaustive list of what is available.

I use Johnson's and CDBB's work wherever possible. Since Johnson's paper, much IR photometry has been published, but his mean colors and B.C.'s for cool stars have a sufficiently large data base that it does not appear profitable to revise them for this project. I regard the T_{eff} and B.C. scales for B-stars reported by CDBB to be essentially definitive. Additional UV spectrophotometry from the TD 1 satellite is available but a revision of the work by CDBB does not appear to be indicated.

2. ANGULAR DIAMETERS

I list θ's for 24 stars in Table I. Included in this list are Regulus, Vega, γ Gem, Altair and Procyon, all of which are treated by CDBB. The total fluxes for these stars, given in Table I, are not fundamental, in that they result from the fitting of model atmospheres to the visual energy distributions. The motive for this procedure is discussed in § III. The θ's are those given by CDBB. YY Gem is included in Table I, and it is the only eclipsing system represented. A number of eclipsing systems have been analyzed for radii, but for T_{eff} we need an accurate parallax as well as photometry which would give f. Only YY Gem seemed to add useful information to this study, but it is particularly important since it is the only dwarf among the cool stars included.

The remaining 18 stars are K and M giants. I have excluded supergiants, Mira variables and carbon stars. I have not used stars whose only measurement of θ is an older one. I have used θ's corrected for darkening, and, in cases where the original source lists only an undarkened diameter, I have adopted a darkened diameter from a secondary source, most commonly Barnes and Evans (1976). My sources of θ are given in the Table.

3. INFRARED PHOTOMETRY AND THE PHOTOMETRY OF THE SUN

For the 18 giants listed in Table I, BVRIJK photometry is available, as is (V-L) for most of them, and (V-M) for a few. For YY Gem, UBVRIKL photometry is available. I have not attempted direct numerical integration of these data, preferring, instead, to interpolate B.C.'s in Johnson's tables. Each B.C. was corrected for a change in absolute calibration (see below) and for a change in zero point (see § IV). Then, using new values of V and f for the Sun (see below), f was calculated. Finally, each θ and f was used to calculate T_{eff}. The final values of these quantities are listed in Table I.

Infrared photometry in the 1-5 μ region has never been properly calibrated, although an attempt was made by Walker (1969). Johnson's (1965) calibration of UBVRIJKL is mainly based upon the solar energy distribution and assumed values for the solar IR colors. I have constructed a new absolute calibration based upon model atmospheres fitted to the visual photometry of Regulus, Vega, γ Gem, Altair and Procyon. The visual photometry is on the absolute system of Hayes and Latham (1975) with a new value for the flux at 5556Å. This latter flux is based upon the mean of the Palomar Mtn. (Oke and Schild 1970, see rediscussion by Hayes and Latham 1975), Mt. Hopkins (Hayes and Latham 1975) and Lowell Observatory (Tüg, *et al*. 1977) calibrations of Vega; for Vega at 5556Å I use $F_\nu = 3.52 \times 10^{-20}$ ergs/cm^2/sec/Hz. The details of the calibration will be published elsewhere. The calibration requires corrections in the 10% range at some wavelengths, but the correction at K is opposite in sign to the others. Since K is located near the wavelength of maximum energy of K- and M-stars, the net effect of the change in

TABLE I

THE FUNDAMENTAL STARS

HD	Name	Type	θ_{LD}(Milliarcsec)	Source	f(ergs/cm^2/sec)	T_{eff}	B.C.
18191	RZ Ari	M6III	10.18	(7)	3.440-6	3160	-3.81
29139	α Tau	K5III	24.6	(10)	3.340-6	3590	1.21
44478	μ Gem	M3III	13.65	(7)	1.107-5	3650	2.02
47105	γ Gem	A0IV	1.39	(3)	4.569-6	9180	0.10
60179C	YY Gem	M0.5V	0.458	(1)	1.076-8	3520	1.45
61421	α CMi	F5IV-V	5.50	(3)	1.797-5	6500	0.04
86663	π Leo	M2III	5.9	(8)	1.380-6	3300	1.59
87837	31 Leo	K4III	3.55	(7)	1.076-6	4000	0.99
87901	α Leo	B7V	1.37	(3)	1.312-5	12040	0.68
91232	46 Leo	gM2	5.6	(1)	6.792-7	2950	1.74
99998	87 Leo	K4III	3.7	(1)	8.472-7	3690	1.13
112142	ψ Vir	M3III	5.86	(7)	1.770-6	3530	1.96
124897	α Boo	K2IIIp	23.1	(11)	4.875-5	4070	0.71
139663	42 Lib	K4III	2.5	(1)	4.920-7	3920	0.74
168574	HR6861	gM5	3.6	(1)	1.028-6	4150	2.82
169916	λ Sgr	K2III	4.4	(1)	2.729-6	4540	0.44
172167	α Lyr	A0V	3.24	(3)	2.836-5	9490	0.19
175775	ϵ^2Sgr	K1III	3.8	(7)	1.514-6	4210	0.50
187642	α Agl	A7IV-V	2.98	(3)	1.224-5	8020	0.01
196777	υ Cap	M2III	4.72	(7)	1.038-6	3440	1.68
207005	47 Cap	gM3	3.2	(1)	6.855-7	3760	2.23
216386	λ Aqr	M2III	8.2	(1)	3.733-6	3590	1.76
217906	β Peg	M2II-III	18	(1)	1.528-5	3450	1.96
219215	φ Aqr	M2III	4.9	(1)	1.923-6	3940	-1.47

Sources of θ: (1) Barnes and Evans (1976), (2) Blazit, et al. (1977), (3) Code, et al. (1976), (4) Currie, et al. (1974), (5) Gezari, et al. (1972), (6) Hanbury Brown (1968), (7) Ridgway, et al. (1977) (8) Vilas and Lasker (1977), (9) Worden (1976), (10) Ref's 4, 5, (11) Ref's 2, 4, 5, 6, 9.

absolute calibration upon the B.C. is only $0^m.01$ maximum, relative to the Sun.

I have made corrections to the visual and infrared fluxes of seven A- and late-B-stars listed by CDBB in order to correct them from the visual absolute calibration of Oke and Schild (1970) to that described above. CDBB tied their IR fluxes to the visual absolute calibration, so the correction has been applied to all $\lambda > 3400$Å. The corrections to f are small, ranging from 0.4% (α Eri, B3Vp) to 1.5% (αPsA, A3V). They have a negligible effect upon T_{eff}, but a noticeable effect upon the B.C. scale.

It is necessary to have V and (B-V) for the Sun in order to determine its B.C. and to place it into the stellar sequence of colors. Direct UBV photometry of the Sun is very difficult, and has only been tried once (Gallouët 1964). Stebbins and Kron (1957) made measurements on the six-color system, which can be transformed into V and (B-V). Otherwise, we must rely upon indirect measurements. I have re-examined all of the available evidence, and will summarize it elsewhere. For this project, I have adopted $V_{\odot} = -26^m.74$, $(B-V)_{\odot} = +0^m.65$ and $(V-R)_{\odot} = +0^m.54$. Measurements of the solar constant have been reviewed by Forgan (1977), whose recommended value is equivalent to f = 1.375 x 10^6 ergs/cm^2/sec which results in T_{eff} = 5786K.

4. EMPIRICAL BOLOMETRIC CORRECTIONS AND EFFECTIVE TEMPERATURES

I have summarized the final scales of B.C. and T_{eff} in Tables II and III. The B.C. scale for B-stars is that of CDBB with a shift in zero point, whereas that for stars later than the Sun is Johnson's, again with a shift in zero point. For O-stars, I have taken B.C.'s from Panagia (1973). For the A- and F-stars I have determined a new scale of B.C.'s based upon stars from CDBB corrected as described above. I have taken the zero of B.C. to be at its minimum absolute value, with the result that $B.C._{\odot} = -0^m.14$. For the O-stars, one must rely upon non-fundamental data, since we have θ only for ζ Oph, O9.5V. (CDBB). Furthermore, an increasing fraction of f is in the Lyman continuum, which must be calculated. I have used T_{eff}'s by Conti (1973), based upon the line spectrum interpreted by model atmospheres, with some guidance from a scale of T_{eff} published by me (Hayes 1970) which was based upon the Balmer jump. The intrinsic colors of the O-stars are not well known, and I have used my own (Hayes 1970). In Fig. 1 I show these scales of T_{eff} along with CDBB's. I also show CDBB's fundamental stars in this range, excluding supergiants. In the case of ζ Oph and δ Sco (open circles) I have used my own intrinsic colors (both stars are reddened). The dashed line with long dashes shows the line I

TABLE II

MAIN SEQUENCE STARS

TYPE	(U-V)	(B-V)	T_{eff}	B.C.
O5	$-1^{m}.48$	$-0^{m}.319$	47000K	$-4^{m}.3$
O6	1.46	.315	42000	3.9
O7	1.44	.311	38500	3.6
O8	1.41	.305	35600	3.4
O9	1.38	.298	33200	3.2
O9.5	1.35	.294	31900	3.1
B0	1.32	.286	30300	2.96
B0.5	1.28	.277	28600	2.83
B1	1.19	.26	25700	2.59
B2	1.10	.24	23100	2.36
B3	0.91	.20	18900	1.94
B5	0.72	.16	15300	1.44
B6	0.63	.14	14000	1.17
B7	0.54	.12	13000	0.94
B8	0.39	.09	11500	0.61
B9	-0.25	-0.06	10180	0.31
A0	0.00	0.00	9410	-0.15
	(B-V)	(V-R)		
B9	-0.06	0.00	10180	-0.31
A0	0.00	+0.02	9410	.15
A2	+0.06	.08	8900	.08
A5	.14	.16	8210	.02
A7	.19	.19	7920	.01
F0	.31	.30	7160	.01
F2	.36	.35	6880	.02
F5	.43	.40	6560	.03
F8	.54	.47	6190	.08
G0	.59	.50	6010	.10
G2	.63	.53	5860	.13
G5	.66	.54	5780	.14
G8	.74	.58	5580	.18
K0	.82	.64	5260	.24
K2	.92	.74	4850	.35
K5	1.15	.99	4270	.66
K7	1.30	1.15	4030	.93
M0	1.41	1.28	3880	1.21
M1	1.48	1.40	3720	1.49
M2	1.52	1.50	3600	1.75
M3	1.55	1.60	3480	1.96
M4	1.56	1.70	3370	2.28
M5	1.61	1.80	(3260)	2.59
M6	1.72	1.93	(3140)	2.93
M7	1.84	2.20	(2880)	3.46
M8	(+2.00)	(+2.50)	(2620)	-4.0

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TABLE III

K AND M GIANTS

Type	(V-R)	T_{eff}	B.C.	Type	(V-R)	T_{eff}	B.C.
K0	$+0^{m}.77$	4600K	$-0^{m}.42$	M0	+1.23	3750K	$-1^{m}.28$
K1	.81	4460	.48	M1	1.28	3700	1.36
K2	.84	4370	.53	M2	1.34	3640	1.52
K3	.96	4100	.60	M3	1.48	3510	1.91
K4	1.06	3950	.90	M4	+1.74	3290	-2.55
K5	+1.20	3790	-1.19				

have adopted for the transition from CDBB's scale to Conti's. **For the K- and M- giants, there are plentiful fundamental data, but I found that they do not define the shape of the T_{eff}-scale well.** As a result, I resorted to an interplay with the scale of T_{eff} for dwarfs. I have assumed that Johnson's scales of T_{eff} for dwarfs and giants correctly give the difference in T_{eff} for the two classes, at a given color. Thus, in Fig. 2 I show the fundamental giants translated to look like dwarfs. The Sun and YY Gem are also shown, and the adopted mean relation was based upon these data. An extension of the mean relation beyond the fundamental data is also shown as a lighter dashed line; it is based upon the T_{eff}'s by Greenstein, et al. (1970), Frogel, et al. (1972) and Veeder (1974). In all three cases, blackbody curves were fitted to IR photometry, with some allowance for line blocking. Also shown are the scales of T_{eff} by Johnson and by Mould and Hyland (1976) whose scale is based upon fitting model atmospheres to IR photometry.

The mean relation for dwarfs has been translated back to T_{eff}'s for giants, using Johnson's differences, and this scale is shown with the fundamental stars in Fig. 3. The mean relation defined in this way appears to be quite satisfactory, and has been adopted. Also shown in Fig. 3 is Johnson's scale for giants.

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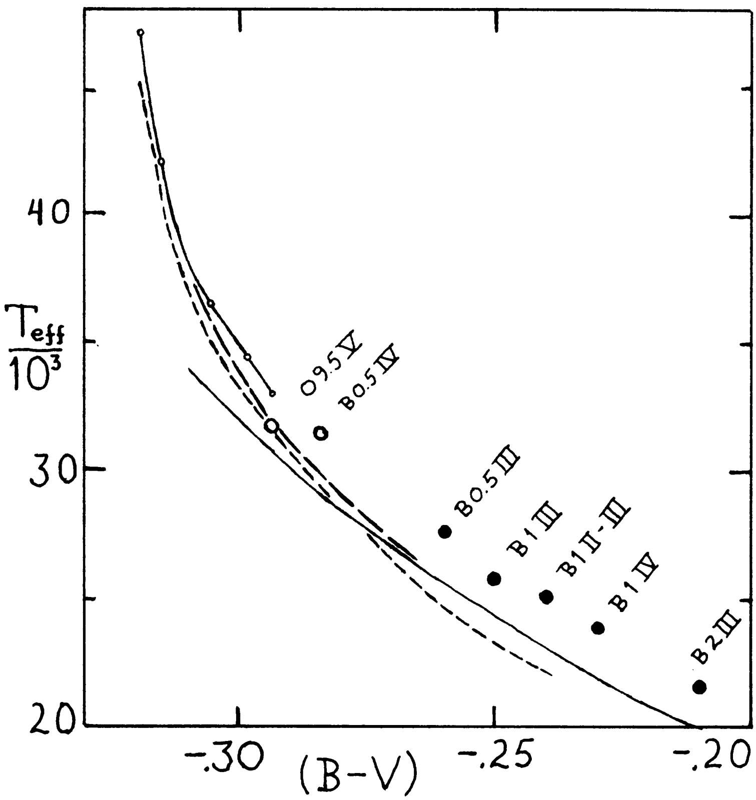

Fig. 1. The effective temperatures of hot main sequence stars. The open and closed circles are fundamental stars from Code, *et al*. 1976; the open circles denote stars plotted according to the mean colors by Hayes (1970). The full line is the mean relation from Code *et al*. (1976). The full line with small circles shows temperatures by Conti (1973) plotted with the mean colors by Hayes (1970). The line with short dashes is the mean relation by Hayes (1970); the line with long dashes is the transition line adopted for this paper.

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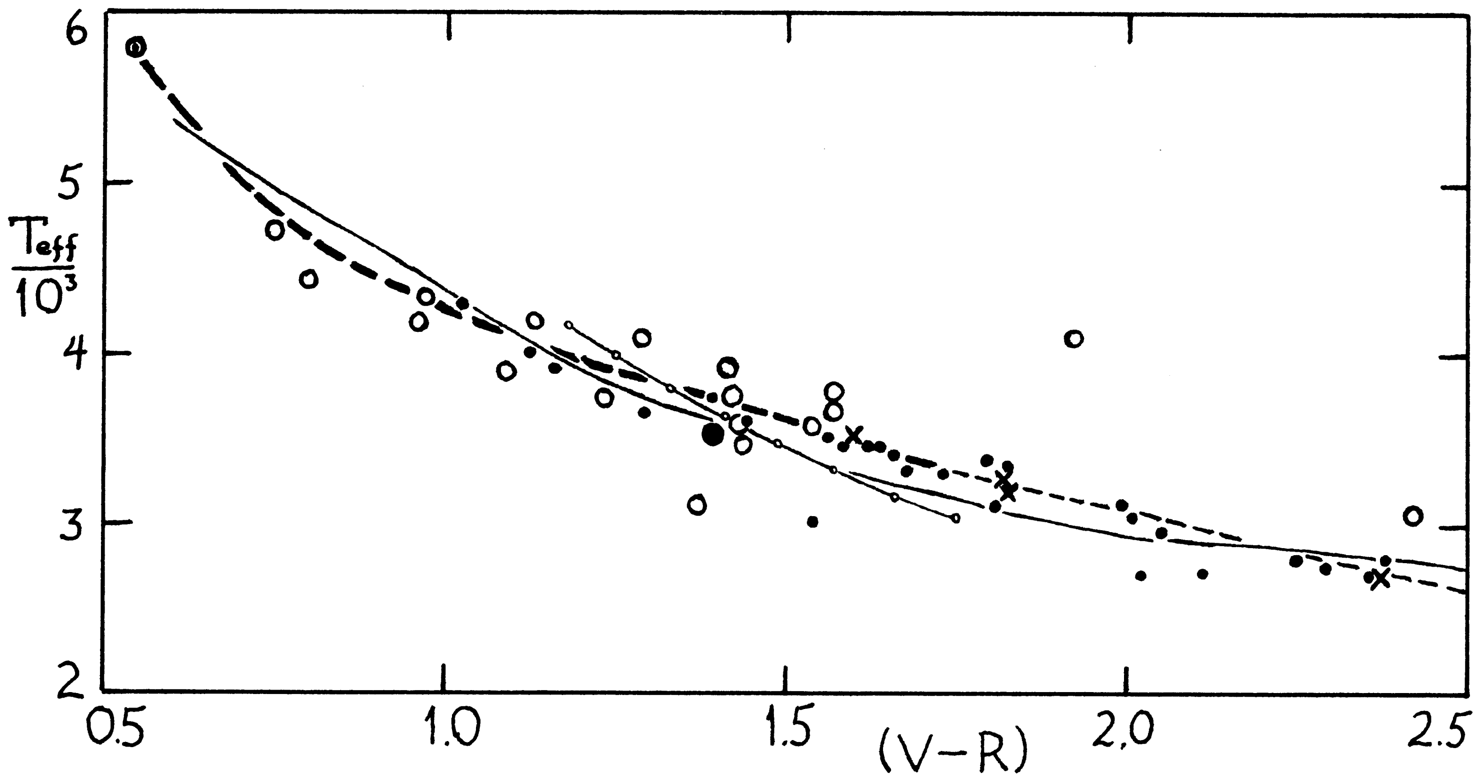

Fig. 2. The temperatures of cool dwarfs. The large open circles are fundamental giants, translated by Johnson's (1966) difference in temperatures of giants and dwarfs. The large filled circle is YY Gem, ⊙ denotes the Sun, and the dots are from Veeder (1974). Three x's are groups from Greenstein, et al. (1970); the fourth (coolest) x is Proxima Cen from Frogel, et al. (1972). The full line is from Johnson; the line with small circles is from Mould and Hyland (1976). We adopt the dashed line.

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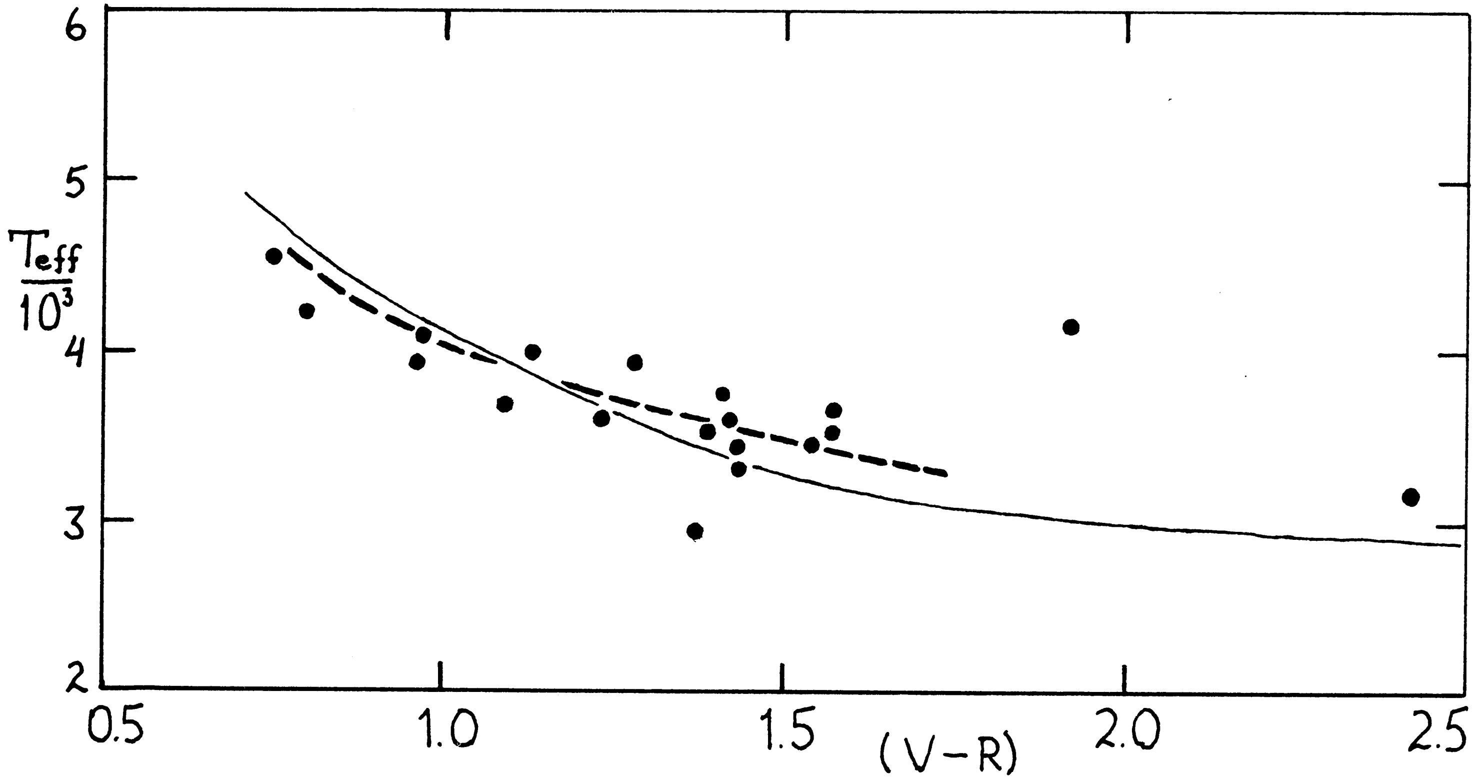

Fig. 3. The effective temperatures of K and M giants. The filled circles are fundamental stars. The full line is the mean relation for giants by Johnson (1966). The dashed line is the relation adopted for this paper.

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DISCUSSION

GARRISON: Would you be willing to give a value for the uncertainty in (B-V) for the Sun, from your work and/or that of others?

HAYES: I estimate the uncertainty in my value to be $\pm 0\overset{m}{.}02$. Note that two other papers in this Symposium discuss this point, and they should be more definitive.

D. EVANS: I much appreciate your favorable remarks about occultation determinations of angular diameters. Things have changed since the criticism in the early days. In addition to YY Gem I would like to mention CM Dra investigated in what will become a classical study by Claud Lacy. He has also added data from a number of other eclipsing binaries.

WESSELIUS: I have compared the absolute calibrations of the ultraviolet experiments in OAO-2(WEP), TD1A(S2/68) and ANS. I find that TD1 and ANS agree quite well (within 5 to 10%) while the OAO-2(WEP) scanner data are brighter by 40% at 1550 Å and 20% at 1800 Å.

HAYES: This agrees with what I remember from the recent paper by Beeckmans in Astronomy and Astrophysics. So, it may be that the TD-1 absolute calibration is to be preferred over the OAO-2 absolute calibration. However, for the T_{eff} and B.C.- scale, Beeckmans shows that the differences which result are smaller than the uncertainties in the T_{eff} and B.C.- scale, evaluated either way.

KODAIRA: So far as I know, there is substantial scatter among the angular diameter data of individual stars. Have you used a simple average of them in deriving your temperature scale for red giants, or have you preferred some particular ones to others?

HAYES: I have taken a simple average.

FLOWER: How do your effective temperatures differ from those of Johnson's?

HAYES: My effective temperatures differ from Johnson's by up to about 200 K, as shown in Figs. 2 and 3.

FLOWER: What is the temperature difference you find between the effective temperatures of giants and dwarfs?

HAYES: The temperature difference between giants and dwarfs is between zero and about 250 K; I don't have the numbers here, but they are the same as are given by Johnson's T_{eff} - scales.