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Celestial Background Radiation

1. A Revised Scale of Bolometric Corrections

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Abstract

A short review is given of the literature pertinent to the bolometric correction. A recommended scale of bolometric corrections is presented based upon recent model atmospheres for stars of early spectral type, and upon stellar energy distributions synthesized from photoelectric observations of stars later than F0 V. The reduction of various photoelectrically determined magnitude and color systems to a common system and the further reduction of these measurements to absolute energy units is discussed in some detail.

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1. INTRODUCTION

It is the purpose of this paper to rediscuss the scale of bolometric corrections from the point of view of our present understanding of the observed distribution of energy in stellar spectra.

The classical discussion of the bolometric correction is that of Kuiper (1938) in which he made extensive use of the model atmospheres of Pannekoek (1936) and Hertzsprung (1906) to derive bolometric corrections for stars earlier than F0, and the radiometric data of Pettit and Nicholson (1928) for stars later than F0. The scale derived is defined by the equation

$$B.C. = m_{bol} - IP_v - 0.07 \qquad (1)$$

where B.C. is the bolometric correction, IP_v is the international photovisual magnitude on the system of the North Polar Sequence of 1922, and $m_{bol} - 0.07$ is the apparent bolometric magnitude with the zero point of the system of bolometric magnitudes chosen so that a star of solar type has a B.C. equal to -0.07. This selection of the zero point requires that B.C. = 0.0 at an effective temperature (T_e) of 6600°K and B.C. < 0.0 for all other values of T_e. In terms of the radiometric

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magnitudes m_r of Pettit and Nicholson, Eq 1 becomes

$$B.C. = (m_r - \Delta m_r) - 1P_v + 0.62 \qquad (2)$$

where Δm_r is a correction term for instrumental losses and atmospheric extinction. Kuiper's adopted values are shown in Table 1.

TABLE 1. Bolometric corrections derived by Kuiper (1938)

Sp.	Dwarfs	Giants	Super-giants	Sp.	Dwarfs	Giants	Super-giants
F2	-.04	-.04	- .04	K4	- .55	-1.11	-1.56
F5	.04	.08	.12	K5	.85	1.35	1.86
F8	.05	.17	.28	K6	1.14		
G0	.06	.25	.42	M0	1.43	1.55	2.2
G2	.07	.31	.52	M1	1.70	1.72	2.6
G5	.10	.39	.65	M2	2.03	1.95	3.0
G8	.10	.47	.80	M3	(2.35)	2.26	-3.6
K0	.11	.54	.93	M4	(2.7)	2.72	
K2	.15	.72	1.20	M5	-(3.1)	-3.4	
K3	-.31	-.89	-1.35				

T_e	B.C.	T_e	B.C.	T_e	B.C.
6500	0.00	13000	-1.18	22000	-2.40
7000	-.01	14000	1.35	25000	2.69
7500	.12	15000	1.51	30000	3.12
8000	.22	16000	1.66	35000	3.5
9000	.40	17000	1.80	40000	3.8
10000	.57	18000	1.94	45000	4.1
11000	.78	19000	2.06	50000	-4.3
12000	-.98	20000	-2.18		

Among the more recent discussions of B.C. are those of Stromberg (1946), Lohmann (1948), Eggen (1956), Limber (1958), Arp (1958), Schwarzschild (1958), Popper (1959), and Johnson (1962).

Stromberg's values, presented in Table 2, are based entirely on the data of Pettit and Nicholson. They were derived in the same manner as that employed by Kuiper, with the substitution of m_v from the Henry Draper Catalogue in place of IP_v used by Kuiper. The chosen zero point of the scale is not the same as Kuiper's, thus, to compare the two sets of data, one must add a zero point correction of -0.1 magnitude to the values of Stromberg.

TABLE 2. Bolometric corrections derived by Stromberg (1946)

Sp.	B.C.	Sp.	B.C.	Sp.	B.C.	Sp.	B.C.
A0	-.3	dG5-dG9	0.0	dM0	-1.3	gG3	-0.1
A2	- 1	dK0	-.1	dM3	-1.9	gK1	-0.4
A3-A4	0.0	dK3	-.4	dM5	-2.5	gK5	-1.1
A5-dG4	+.1	dK6	-.7	dM6	-2.8	gM2	-1.8

Lohmann (1948) reduced the radiometric magnitudes obtained by Emberson (1941) to the system of Pettit and Nicholson and derived the bolometric corrections shown in Table 3. He noted that the magnitudes measured by Emberson were systematically less in absolute value than those of Pettit and Nicholson, the difference increasing with stars of later spectral type and approaching a maximum of 0.23 magnitude near K0. This discrepancy is attributed to the difference in atmospheric extinction at the two observatories.

TABLE 3. Bolometric corrections derived by Lohmann (1948)

Sp.	B.C.	Sp.	B.C.	Sp.	B.C.
B0	-3.06	F0	-.04	K0	- .28
B5	-2.00	F5	-.00	K5	- .78
A0	- .98	G0	-.00	M0	-1.25
A5	- .37	G5	-.10	M5	-1.90

Eggen (1956) derived a scale of bolometric corrections from the data of Pettit and Nicholson according to the relation

$$B.C. = (m_r - \Delta m_r) - V_E + 0.62 \qquad (3)$$

where the zero point is coincident with that of Kuiper's and V_E is the V magnitude determined photoelectrically by Eggen (1955). These data are given in Table 4 where the color index $(P-V)_E$ and the absolute visual magnitude M_V determined from trigonometric parallaxes are the running parameters.

TABLE 4. Bolometric correction according to Eggen (1956)

$(P-V)_E$	B.C.	$(P-V)_E$	B.C.	$(P-V)_E$	B.C.
+0.2	-0.05	+0.8	-0.15	+1.2	-0.80
+0.4	-0.05	+0.9	-0.22	+1.3	-1.00
+0.6	-0.07	+1.0	-0.41	+1.4	-1.19
+0.7	-0.10	+1.1	-0.61		
M_V	B.C.	M_V	B.C.	M_V	B.C.
+1.0	-0.44	+5.0	-0.06	+9.0	-1.31
+1.5	-0.28	+5.5	-0.08	+9.5	-1.52
+2.0	-0.10	+6.0	-0.12	+10.0	-1.72
+2.5	-0.06	+6.5	-0.30	+10.5	-1.93
+3.0	-0.05	+7.0	-0.48	+11.0	(-2.14)
+3.5	-0.05	+7.5	-0.70	+11.5	(-2.35)
+4.0	-0.05	+8.0	-0.90	+12.0	(-2.55)
+4.5	-0.06	+8.5	-1.11		

A discussion of the bolometric correction for K and M dwarfs has been given by Limber (1958). Here the data of Kuiper were corrected to the U, B, V system of Johnson and Morgan (1953) and the zero point of the resulting scale made coincident with that of Kuiper's. A comparison of the two scales shows the values of Limber to be systematically smaller than Kuiper's by about 10 percent. Limber also finds that there is a strong tendency for the radiometric magnitudes for the faintest stars measured by Pettit and Nicholson to be too bright by as much as 0.4 to 0.5 magnitude.

Arp's (1958) tabulation of bolometric corrections is essentially the same as Kuiper's, but with the values for stars earlier than B5 determined from the model atmospheres of Underhill and McDonald (1952). The compilation of bolometric corrections and effective temperatures presented by Schwarzschild (1958) with B-V as the argument, is the same as that presented by Kuiper, using the temperature scale of Keenan and Morgan (1951).

The most recent extensive discussion of the scales of effective temperature and bolometric correction was given by Popper (1959). The V magnitude on the U, B, V system was used to obtain bolometric corrections from the original data of Pettit and Nicholson. Also included were Emberson's radiometric measures of highest weight after a reduction of +0.23 magnitude to lower them to a common zero point. The bolometric correction was derived from

$$B.C. = (m_r - \Delta m_r) - V + 0.58 \qquad (4)$$

the constant being chosen to reproduce Kuiper's values for main sequence stars of type G0-G8. The resulting values were plotted versus the B-V color of the star, and a mean curve was drawn through the points. His adopted values read from the mean line are shown in Table 5. Popper notes that there are no systematic differences in B.C. depending upon luminosity class except perhaps for the reddest stars.

TABLE 5. Bolometric corrections from Popper (1959)

B-V	B.C.
+0.4	0.00
+0.5	-0.02
+0.6	-0.07
+0.7	-0.11
+0.8	-0.17
+0.9	-0.28
+1.0	-0.40
+1.1	-0.53
+1.2	-0.72

For stars earlier than F0, Popper calculated bolometric corrections from the model atmospheres of Hunger (1954), Osawa (1956) and Saito (1956). His values, which are included in Table 7, depart from Kuiper's by 0.2 magnitude at T_e = 10,000°K.

Recently Johnson (1962) has obtained photoelectric measurements in the atmospheric windows at 2.2 and 3.6 microns (K and L magnitudes) which he has combined with data from U, B, V photometry six color photometry of Stebbins and Kron (1956), and R, I photometry of Kron, White, and Gascoigne (1953), Kron and Gascoigne (1953) and Kron and Mayall (1960) to obtain stellar energy distributions over a wide spectral range. From an integration of these curves on an intensity basis relative to that of the Sun, he derived the values reproduced in Table 6. The zero point of the scale is B.C. = 0.0 for a star of solar type, and thus differs from Kuiper's by -0.07 magnitude.

TABLE 6. Bolometric correction of Johnson (1962)

Sp.	B.C.	Sp.	B.C.	Sp.	B.C.
F5V	+.05	M0V	-1.0	K5III	-0.9
G0V	0.0	M2V	-1.4	M0III	-1.1
G2V	0.0	M4V	-1.8	M2III	-1.4
G8V	0.0	M5V	-2.0	M4III	(-2.0)
K0V	-0.1	G8III	-0.1	M6III	(-2.7)
K2V	-0.2	K0III	-0.2	F5I	+0.1
K5V	-0.6	K2III	-0.4	M0-2I	-1.8

It is interesting to note that all determinations of the bolometric correction subsequent to that of Kuiper's have resulted in an appreciable decrease in absolute value for the stars of late spectral type.

2. THE BOLOMETRIC CORRECTION FOR STARS OF EARLY SPECTRAL TYPE

For stars earlier than F0 V an appreciable portion of the total radiant energy lies in the ultraviolet at wavelengths shorter than the atmospheric cutoff and is not observable with Earth-fixed instrumentation. For this reason, our knowledge of the energy distribution in the spectrum of the hotter stars relies upon the predictions of model atmospheres.

Table 7 is a compilation of a number of recent atmospheric models for stars of early spectral type. The spectra listed in column 1 and the atmospheric parameters (logarithm of the surface gravity, the boundary temperature T_0, and the effective temperature T_e) listed in columns 2, 3, and 4 are as given by the referenced authors. Bolometric corrections given by Underhill (1952, 1956), McDonald (1952), and Pecker (1950) have been corrected to the zero point of Kuiper's (1938) scale. Bolometric corrections for the models of Saito (1956), Osawa (1956), and Hunger (1955) have been taken from Popper (1959), while those for the models of DeJager and Neven (1957) and Melborne (1960) have been obtained by the author from integration of the published flux distributions in the manner of Underhill (1956), that is,

$$B.C. = 2.5 \log \frac{\int_0^\infty V_\nu F_\nu \, d\nu}{\int_0^\infty V_\nu F_\nu (\odot) \, d\nu} - 10 \log \frac{T_e}{T_e (\odot)} - 0.07 \qquad (5)$$

where V_ν is the spectral response curve of the V magnitude given by Johnson (1955), $T_e (\odot)$ = 5778°K is the effective temperature of the sun (Blanco and McCuskey, 1961), and the monochromatic solar flux $F_\nu (\odot)$ is taken from Goldberg and Pierce (1959). Column 6 contains the values of $(B-V)_C$ calculated by the referenced authors, and column 7 the $(B-V)_J$ color determined from the spectral type, according to the list of Johnson and Morgan (1953).

The values of B.C. plotted in Figure 1 as a function of effective temperature lie along a reasonably well defined curve. This curve falls 0.33 mag. below Kuiper's relationship (also shown in Figure 1) near T_e = 14,000°, is nearly coincident with his values in the region 24,000° $< T_e <$ 36,000°, and predicts values larger than Kuiper's at higher temperatures. The values of Table 8 were read from the mean line of Figure 1. Due to the significant advancements made in the theoretical treatment of stellar atmospheres during the past two decades, they are considered preferable to those given by Kuiper.

TABLE 7. Bolometric corrections derived from model atmospheres

Spect.	log g	T_o	T_e	B.C.	$(B-V)_C$	$(B-V)_J$	Author
05	4.20	35000	44600	-4.27			Underhill (1952)
09	4.20	25200	36800	-3.75			Underhill (1952)
	4.00	25000	29700	-3.03			DeJager and Neven (1957)
B1.5V	4.20	18800	29500	-3.00	-.31	-.26	Underhill (1956)
B1.5V	3.80	18800	28470	-2.87	-.31	-.26	Underhill (1956)
B2.5V	4.20	16800	27870	-2.90	-.31	-.22	Underhill (1956)
B1V	4.48	17700	27300	-3.00		-.28	Pecker (1950)
B2.5V	3.80	16800	27000	-2.81	-.30	-.22	Underhill (1956)
B1.5V	4.48	17300	26360	-2.83		-.26	Pecker (1950)
B2V	3.80	16800	22700	-2.59		-.24	McDonald (1952)
	4.00	18000	21400	-2.22			DeJager and Neven (1957)
B2V	3.80	16550	20500	-2.00		-.24	Saito (1956)
	4.00	14000	16620	-1.52			DeJager and Neven (1957)
B5V	3.80	12750	15400	-1.22		-.16	Saito (1956)
	4.00	10000	11850	-.64			DeJager and Neven (1957)
A0V	4.20	8680	10600	-.39		0.0	Saito (1956)
	4.30	7810	9500	-.24			Hunger (1955)
	4.30	7481	9000	-.18			Hunger (1955)
A3V	4.00	6760	8900	-.24	+.09	+.09	Osawa (1950)
	4.30	7140	8660	-.14			Hunger (1955)
	4.30	6730	8160	-.11			Hunger (1955)
A9V	4.00	6000	7560	-.15	+.27		Osawa (1956)
	4.39	5680	7000	-.02	+.35		Melborne (1960)
	4.42	5190	6400	-.03	+.45		Melborne (1960)
	4.43	4940	6100	-.06	+.50		Melborne (1960)
	4.44	4700	5800	-.07	+.55		Melborne (1960)
	4.44	4460	5500	-.11	+.63		Melborne (1960)

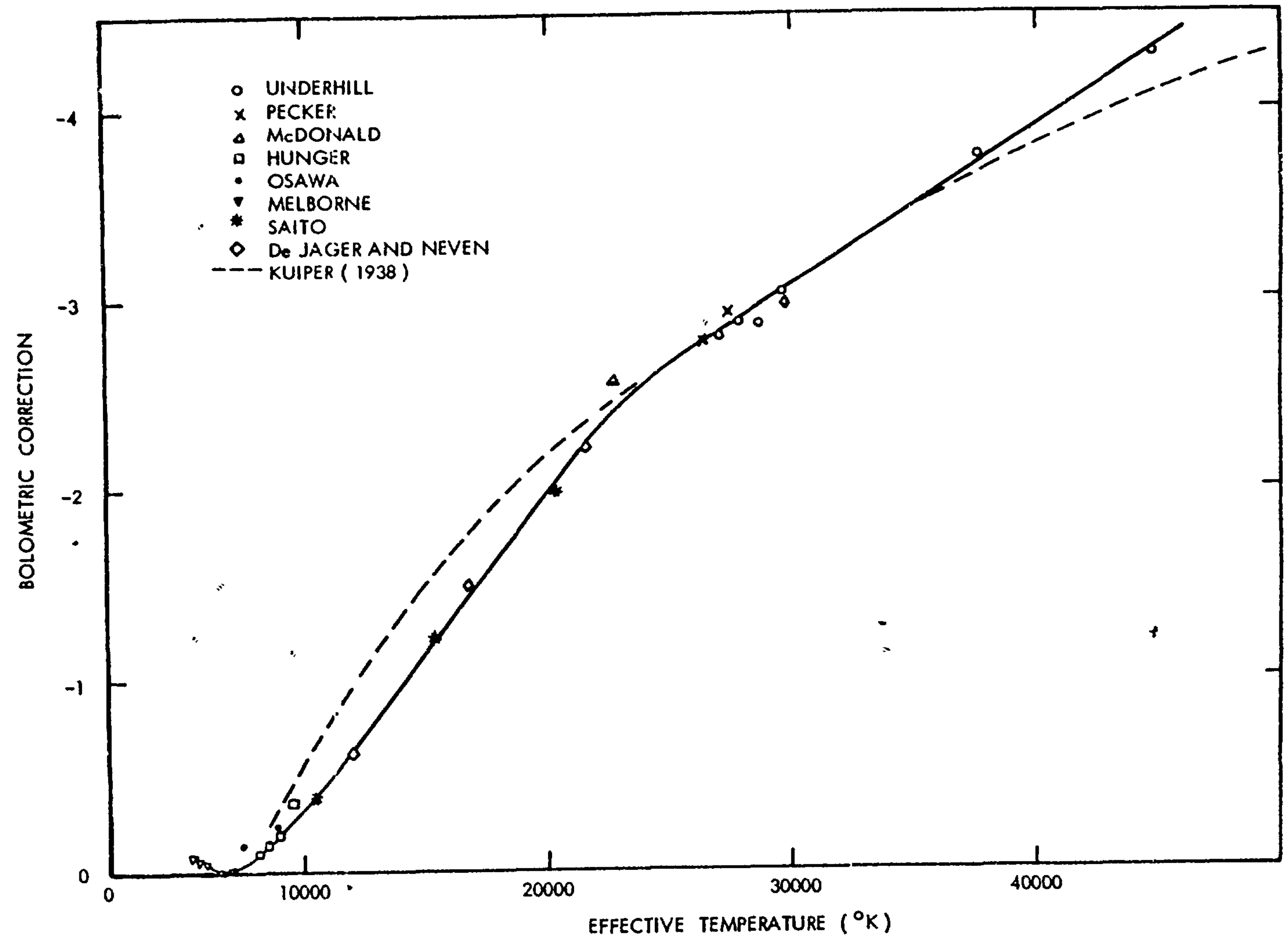

Figure 1. Bolometric Correction from Model Atmospheres.

TABLE 8. Bolometric correction for stars of early spectral type

T_e	B.C.	T_e	B.C.	T_e	B.C.
6500	0.00	12000	-.63	19000	-1.82
7000	-.02	13000	-.80	20000	-1.99
7500	-.04	14000	-.97	22000	-2.32
8000	-.08	15000	-1.14	25000	-2.67
9000	-.18	16000	-1.31	30000	-3.08
10000	-.24	17000	-1.48	35000	-3.50
11000	-.47	18000	-1.65	40000	-3.93

Although T_e is a fundamental parameter characteristic of a stellar atmosphere, it cannot be directly observed. Correlation of T_e with readily observable parameters such as spectral type and color is difficult. Spectral types quoted for model atmospheres are often derived from spectral characteristics which are more sensitive to the temperature gradient in the atmosphere than to the value of T_e. Limb temperatures, T_o. obtained by Cayrel de Strobel (1960) from the central intensities of the Balmer lines show dispersions of more than 3000°K for stars of the same spectral type near B1V, while correlation of his T_o with B-V breaks down for B-V less than about -0.07 mag. Association of observed B-V colors with those calculated from model atmospheres can lead to appreciable errors due to the effects of line blanketing, (Melborne, 1960, Rozes-Saulgeot, 1960). At the present time blanketing coefficients are not available for stars earlier than A0 V.

The relationship of the B-V color to effective temperature has been recently discussed by Popper (1959). Based upon the determination of the angular diameter of Sirius (Brown and Twiss, 1956) and Hunger's (1954) model atmosphere for Vega. Popper derived a scale of effective temperatures which departs markedly from Kuiper's scale (1938) at B-V = 0.0, and gradually approaches it at B-V = +.50. Popper's scale is adopted here. Table 9 lists the T_e, B-V relationship determined by Popper with the associated values of B.C. read from the curve of Figure 1. For stars hotter than A0 V one might adopt the temperature scale of Keenan and Morgan (1951); however, Popper's discussion implies that major revisions are in order, and data from rockets and/or satellites will be necessary to resolve the question.

TABLE 9. The bolometric correction as related to Popper's (1959) scale of effective temperatures

B-V	T_e	B.C.
0.00	9400	-.23
+.10	8800	-.16
+.20	8100	-.09
+.30	7350	-.02
+.40	6700	0.00
+.50	6300	-.03

Recently, data obtained by Stecher and Milligan (1962) from a high altitude rocket have provided our first glimpse of the continuous spectrum of hot stars in the region below the atmospheric cutoff. The most striking feature of this data is the large deficiency of energy in the 2000 Å region when compared to that predicted by model atmospheres. Various mechanisms have been discussed by Stecher and Milligan to account for the observed discrepancy. These include absorption by the interstellar medium, absorption by a circumstellar cloud, and the sudden increase in opacity of the stellar atmosphere due to molecular absorption, line blanketing, and absorption by quasi-molecules. Meinel (1963) has recently proposed a model for B stars which attributes the high observed flux in the 2500 Å region to the emission continuum resulting from the dissociation of the H_2 molecule which has been observed in the laboratory by Coolidge (1944).

It was felt that possibly some additional information might be gained if Stecher and Milligan's data were compared with other data available for these stars. Auxiliary data were first reduced to Code's (1960) system of monochromatic magnitudes by the methods described in Appendix I. The resulting monochromatic magnitudes were then converted to absolute flux units using the calibration of the V magnitude given by Code. For comparison with model atmospheres, the normalization was made at λ 5560 Å through the relation

$$H_\lambda = \left(\frac{5560}{\lambda}\right)^2 \cdot \frac{F_\nu}{F_\nu\,(5560)}\; H_\lambda\,(5560) \qquad (6)$$

where H_λ is the monochromatic irradiance at wavelength λ, F_ν is the flux from the model atmosphere, and $\left(\frac{5560}{\lambda}\right)^2$ converts from frequency units to wavelength units.

Figure 2 shows a comparison of the data for ε Canis Majoris over a wider spectral range than considered by Stecher and Milligan. Six Color data were not available for this star, the values shown having been computed from means measured for this spectral type. The overlap of the two sets of data in the 3500 to 4000 Å region is encouraging and attests to the high quality of the rocket data on both a relative and absolute basis. Saito's (1956) Model III is also shown in Figure 2. It is obvious from this figure that the slope of the rocket data is considerably greater than that predicted by the model atmosphere in the region from 2500 to 3500 Å. Also, if allowance is made for the finite resolving power of the spectrometer, the observed Balmer discontinuity will greatly exceed that predicted by the model. These data are in direct conflict. To reproduce the Balmer discontinuity, a model of lower effective temperature is indicated, while to reproduce the observed intensity gradient, a higher temperature is indicated. Changes in the adopted value of surface gravity in the model will not rectify the situation.

Much the same may be said for the data of Figure 3 for β Canis Majoris. Here the Six Color data are those measured for the star by Stebbins and Kron (1956). Although the Balmer discontinuity is poorly defined by the rocket data, the steep slope near λ 3000 is still evident.

The data for α Leonis are plotted in Figure 4, where the solid dots are the photoelectric measures of Johnson (1962, 1953), U, V, B, K, and L, Six Color photometry of Stebbins and Kron (1956), and the scanner data of Oke (1960), Bonsack and Stock (1957), and Hall (1941). The curve is reasonably well defined, although there appears to be some systematic difference between the scans of Oke and Bonsack and Stock. Saito's model for T_e = 15,500°K, as adopted by Stecher and Milligan, clearly does not represent the data. The model of DeJager and Neven (1957) for T_o = 10,000°K provides a fairly good fit in the region of the Balmer discontinuity. The bolometric correction derived for α Leonis by the methods described in the following section and on the assumption that $F_\nu/F_\nu(1.80)$ = 0.0 for $1/\lambda$ greater than 6.0 is B.C. = -0.28 mag. For comparison, that given by DeJager and Neven s model is B.C. = -0.64 magnitude.

For α Carinae F0 Ia the spectrum is in much better agreement with that obtained from model atmospheres in the λ 2000 region, however, comparison with a model atmosphere at a slightly higher temperature than the one shown in Figure 5 would lead to better agreement in the visual.

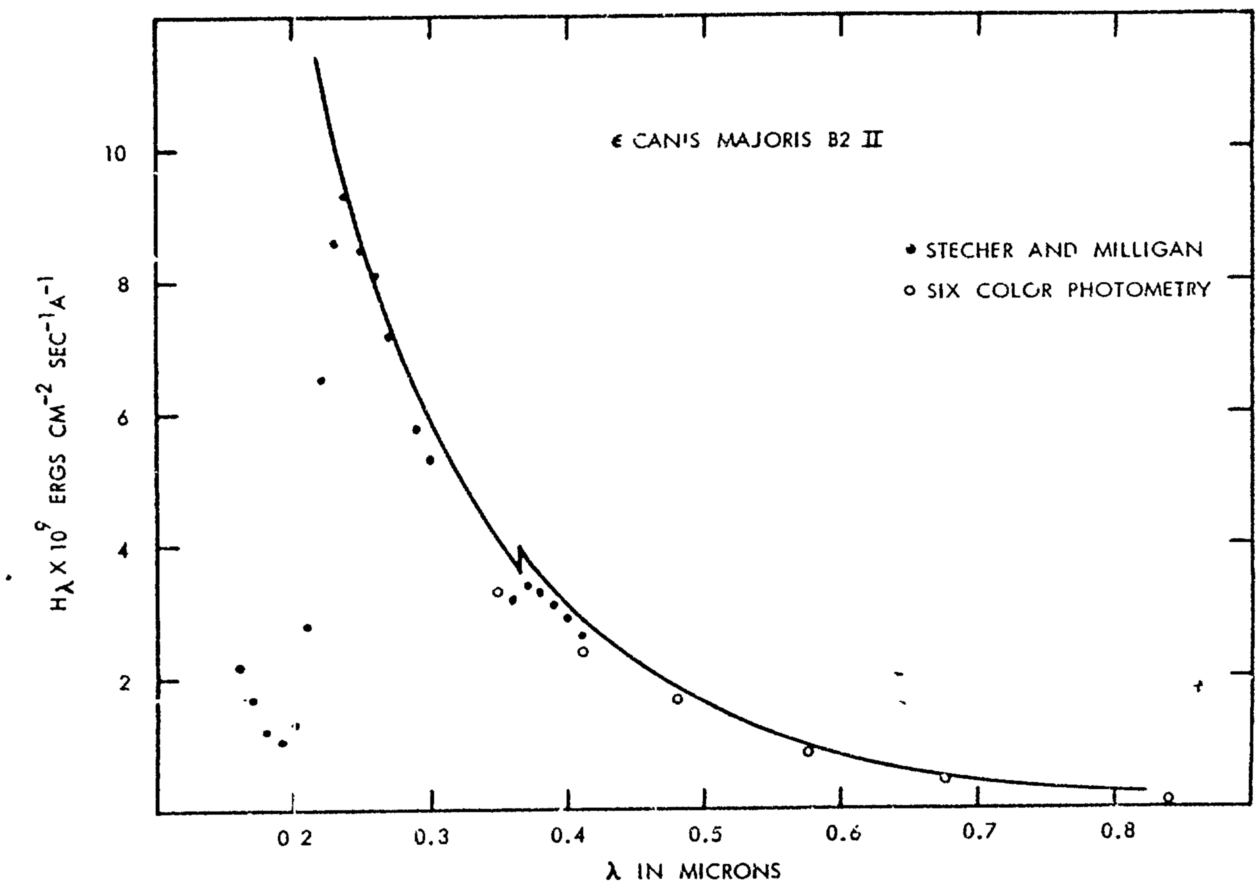

Figure 2. Spectrum of ε Canis Majoris. The solid curve is the model atmosphere of Saito (1956) T_e = 20,400, log g = 3.80.

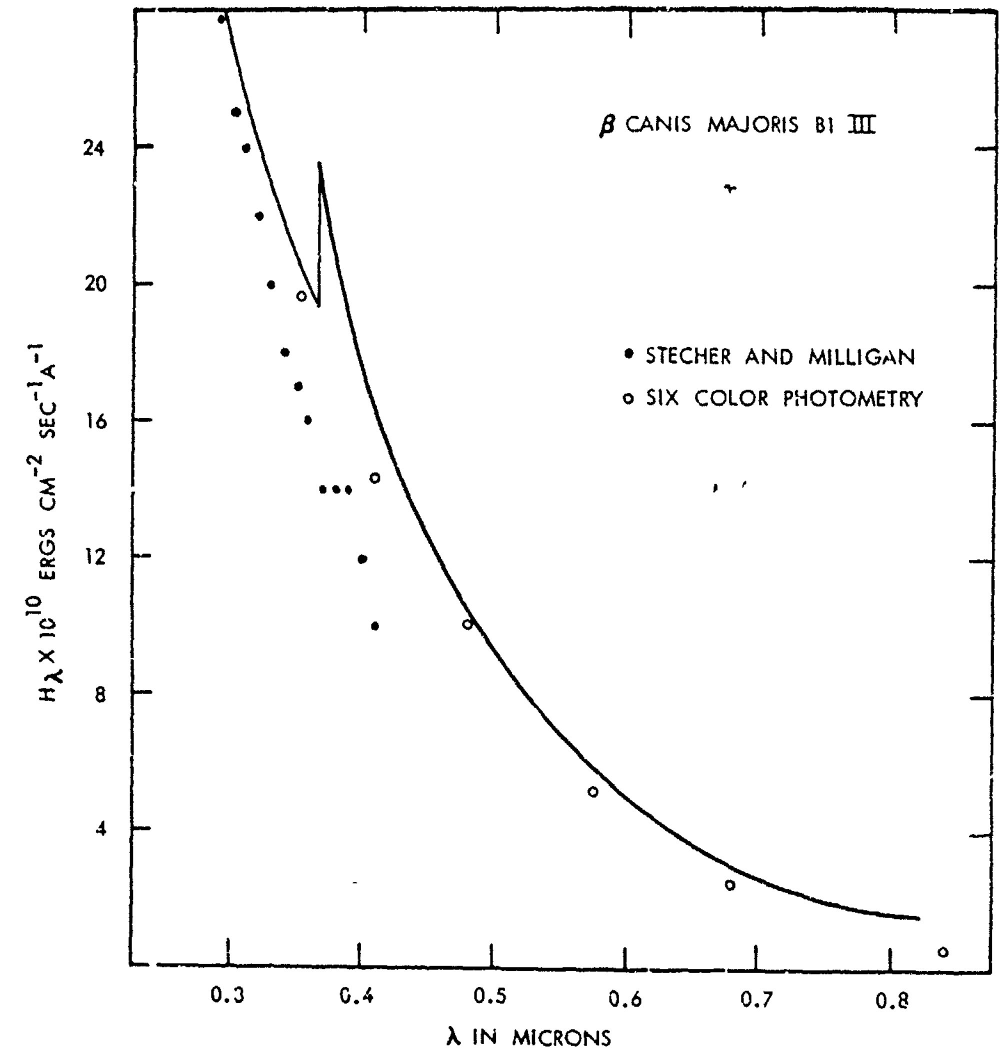

Figure 3. Spectrum of β Canis Majoris. The solid curve is the model atmosphere of Saito (1956) T_e = 20400, log g - 3.8.

No problems have been resolved from the consideration of this limited amount of data, however, apparent contradictions in the spectra of ε Canis Majoris, β Canis Majoris, and α Leonis near the Balmer limit lend some support to the mechanism proposed by Meinel (1963). Calculation of a bolometric correction for α Leonis gives an indication of the large errors which may be present in bolometric corrections based upon currently accepted atmospheric models.

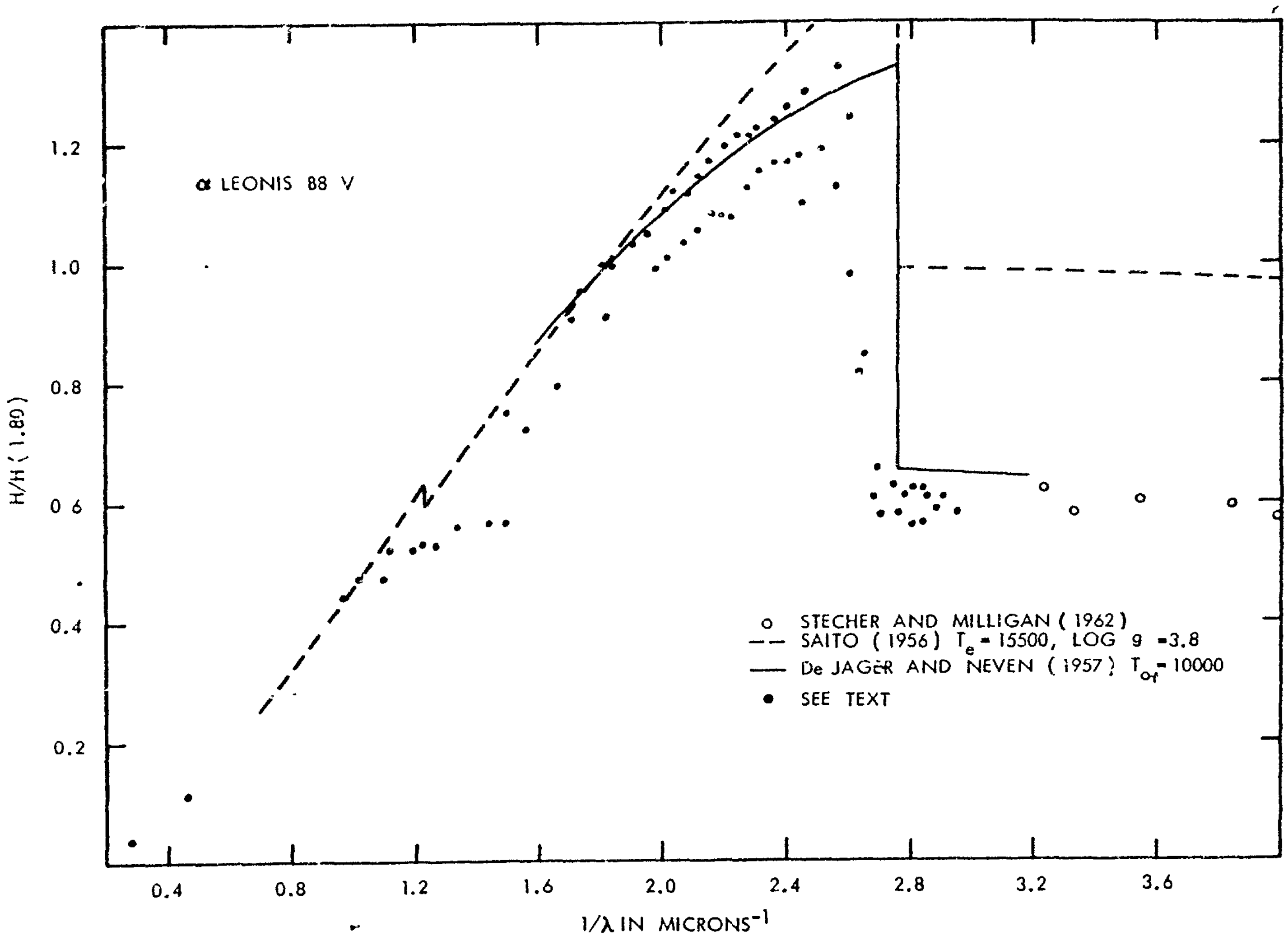

Figure 4. Spectral Energy Distribution of α Leonis.

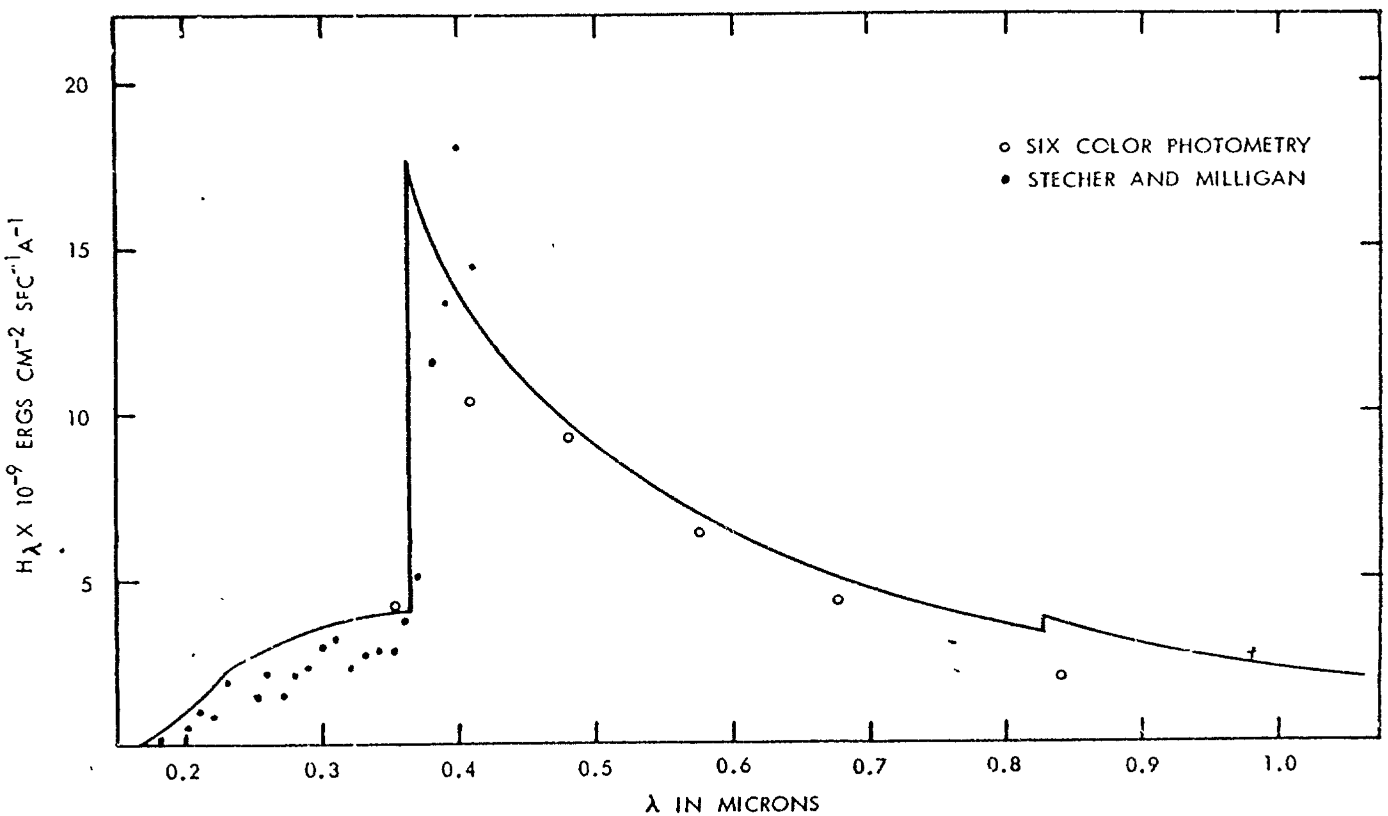

Figure 5 Spectrum of Alpha Carinae. The solid curve is the atmospheric model of Canavaggia and Pecker (1953) $T_e = 6700$, log g = 1.80.

3. THE BOLOMETRIC CORRECTION FOR STARS OF LATE SPECTRAL TYPE

The discussion given here is in the nature of an extension of the recent work of Johnson (1962), (see Introduction). Johnson's bolometric corrections are based upon the derived spectral energy distributions for 24 stars of which only 18 are later than F0. His original observations contain 37 stars later than F0 for which a similar analysis can be made. Search of the recent literature reveals that Lunel (1960) has obtained the infrared magnitudes of 20 stars with narrow band filters centered at 1.1 and 2.2 microns, and that Mitchell and Hayme (1961a,b) have measured 42 stars with instrument responses similar to that of the K and L magnitudes of Johnson (1962). Consequently, if additional data for other wavelength regions could be found, it would be possible to synthesize spectral energy distributions and derive bolometric corrections for a relatively large number of stars.

It was decided that as much additional data as possible would be used, thus, data obtained from photoelectric spectrum scanners were included along with data of the type used by Johnson. Magnitudes and colors were obtained from the following data sources and reduced to the system of monochromatic magnitudes of Code (1960) by the methods described in Appendix I: U,B,V - Johnson and Morgan (1953), Johnson and Hiltner (1956), Johnson (1955), Johnson and Harris (1954), P,V - Eggen (1955, 195[illegible]), R,I - Kron and White (1953), Kron and Gascoigne (1953), Kron, Gascoigne, and White (1957), Six Color photometry - Stebbins and Whitford (1945), Stebbins and Kron (1956), Kron (1958), Scanner data - Bonsack and Stock (1957), Code (1960), Oke (1960), Hall (1941). The decision to use only photoelectric observations precluded the use of the relative energy distributions which were determined photographically (Hoff, 1939 and Kienle, Strassl, and Wempe, 1941).

Lack of sufficient auxiliary data for 18 stars reduced the original list to 71, of which 53 are later than F0 V. Of the 53 stars used for determination of bolometric corrections, 6 stars have only 5 data points per star distributed across the spectrum, 67 percent have more than 10 points per star, and 46 percent have in excess of 20 points per star. The maximum number of data points available on any one star is 92.

Since the total number of magnitudes and colors to be reduced to Code's (1960) system exceeded 1500, a computer program was written and the reductions carried out on the Philco 2000 computer located at the Air Force Cambridge Research Laboratories in Bedford, Massachusetts.

The monochromatic magnitudes m(n) obtained were reduced to monochromatic irradiances H_ν (n) relative to the irradiance at λ 5560 Å through Code's definition

$$m(n) = -2.5 \log \frac{H_\nu\ (n)}{H_\nu\ (1.80)} \tag{7}$$

where n = 1/λ in microns^{-1} and H_ν (n) is the monochromatic irradiance at the top of the earth's atmosphere in units of ergs cm^{-2}sec^{-1}cps^{-1} evaluated at the wavenumber n.

The resulting values of relative irradiance were plotted versus the wavenumber and the curves integrated by means of a polar planimeter. Typical examples of the spectral distributions obtained are shown in Figures 6 through 10. Few spectra exhibited greater dispersion than those shown. Integration of the spectra yields the quantity

$$I\ (*) = \frac{1}{H_\nu\ (1.80)} \int_0^\infty H_\nu\ d\nu. \tag{8}$$

Calibration of the V magnitude of Johnson and Morgan by Code (1960) and Willstrop (1958) implies the following relation

$$V = -2.5 \log H\ (1.80) + \text{Const.} \tag{9}$$

and thus one may write from Eqs. 8 and 9

$$-2.5 \log I(*) = m_{bol}(*) - V + \text{Const.} \tag{10}$$

or

$$-2.5 \log I(*) = B.C.(*) + \text{Const.} \tag{11}$$

The constant in Eq. 11 may be evaluated for the sun by setting B.C.(*) = B.C. (⊙), and the resulting expression for the bolometric correction is

$$B.C.(*) = -2.5 \log I(*) + 2.5 \log I(\odot) + B.C.\ (\odot). \tag{12}$$

Adoption of Eq. 9 for the V magnitude implies that there is no dependence of V on the color of the star. This appears to be justified from the work of Willstrop (1958). His correlation of the V magnitude with magnitudes obtained through a narrow band-pass interference filter at λ 5400 showed no dependence on B-V and only a residual scatter of about 0.02 magnitude. His data covered the range B-V = -.24 to B-V = +1.4 magnitudes.

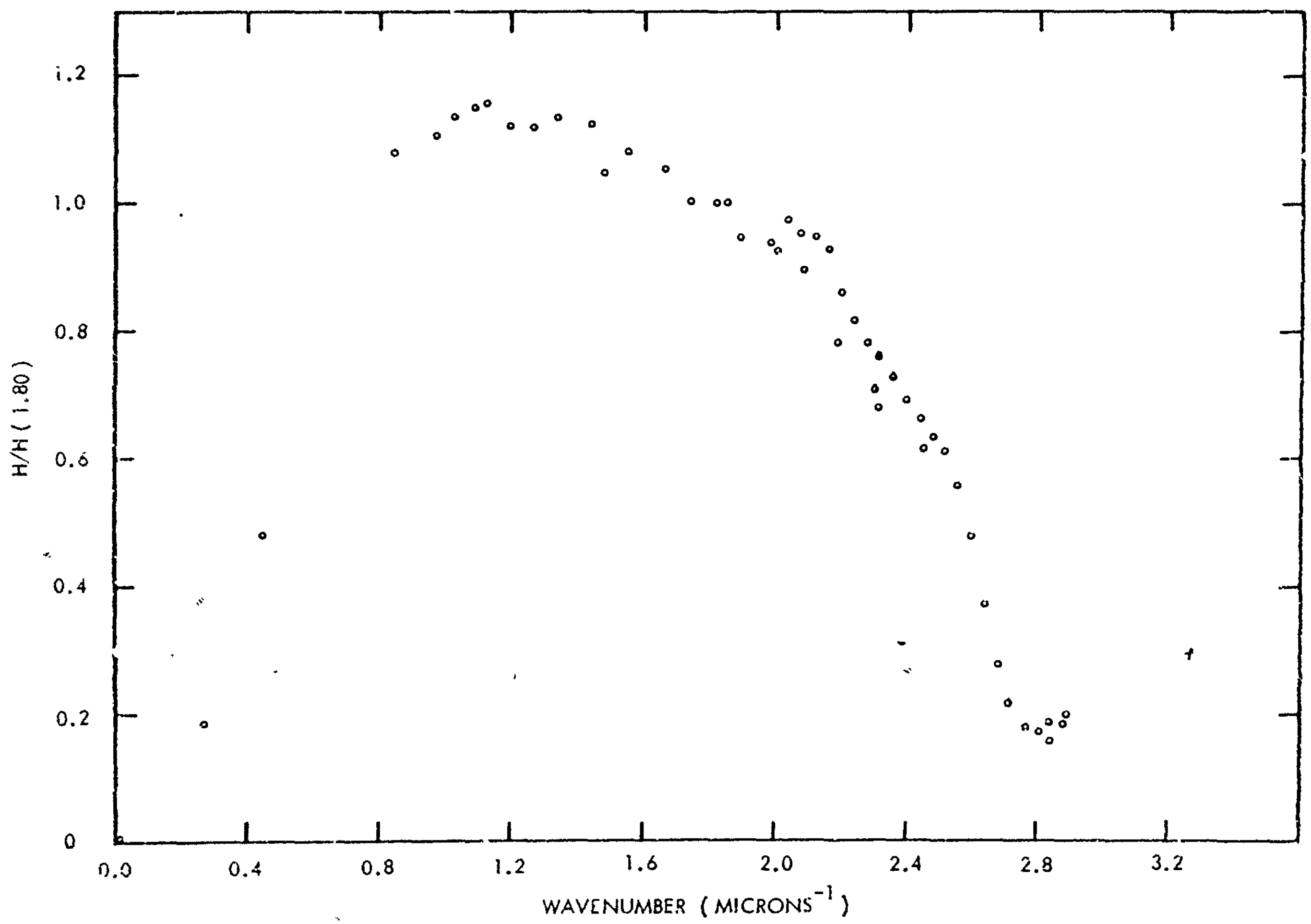

Figure 6. Spectral Distribution for Alpha Persei F5 I_b.

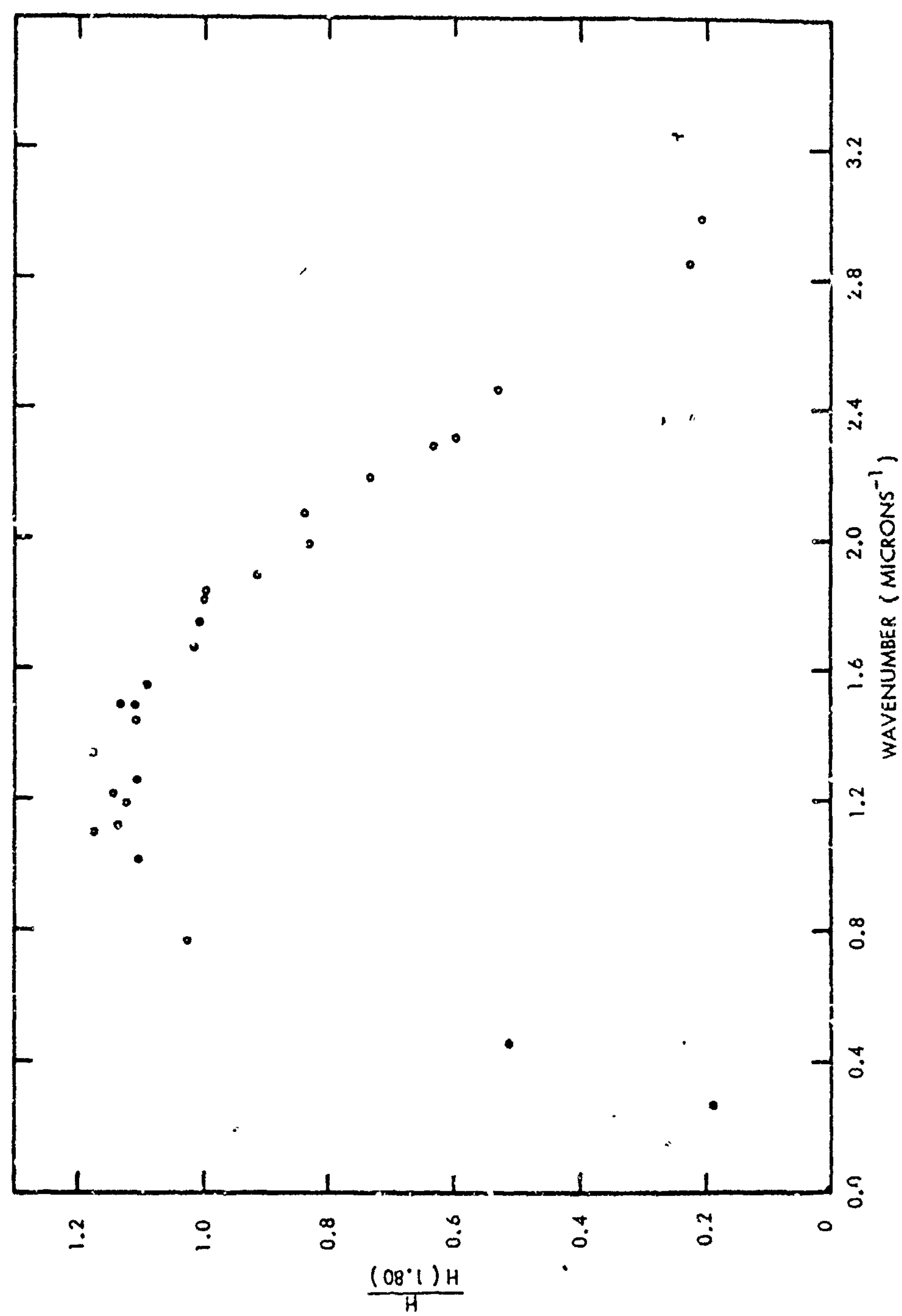

Figure 7. Spectral Distribution for Eta Bootis G0 IV.

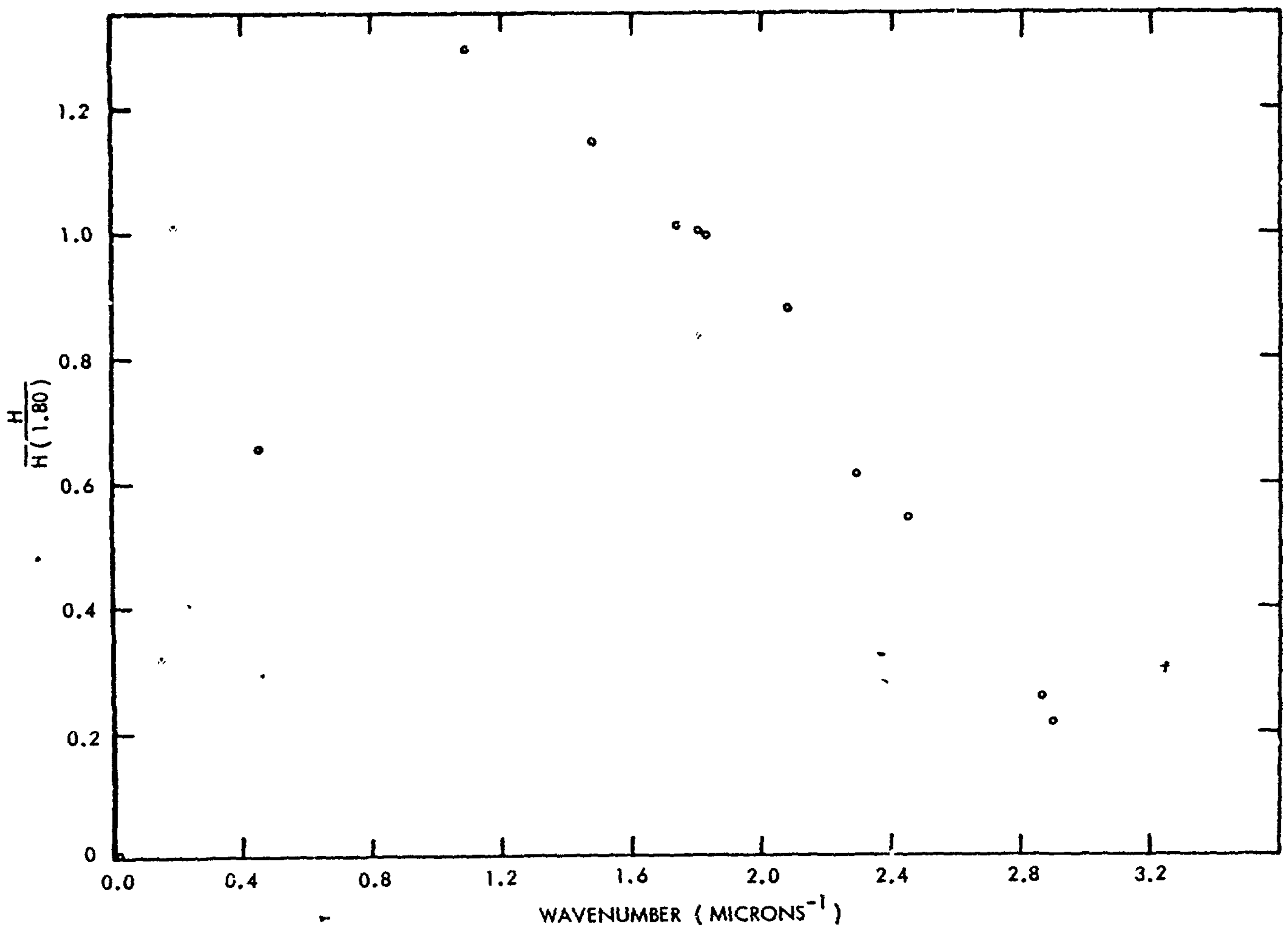

Figure 8. Spectral Distribution for HR 483 G2 V.

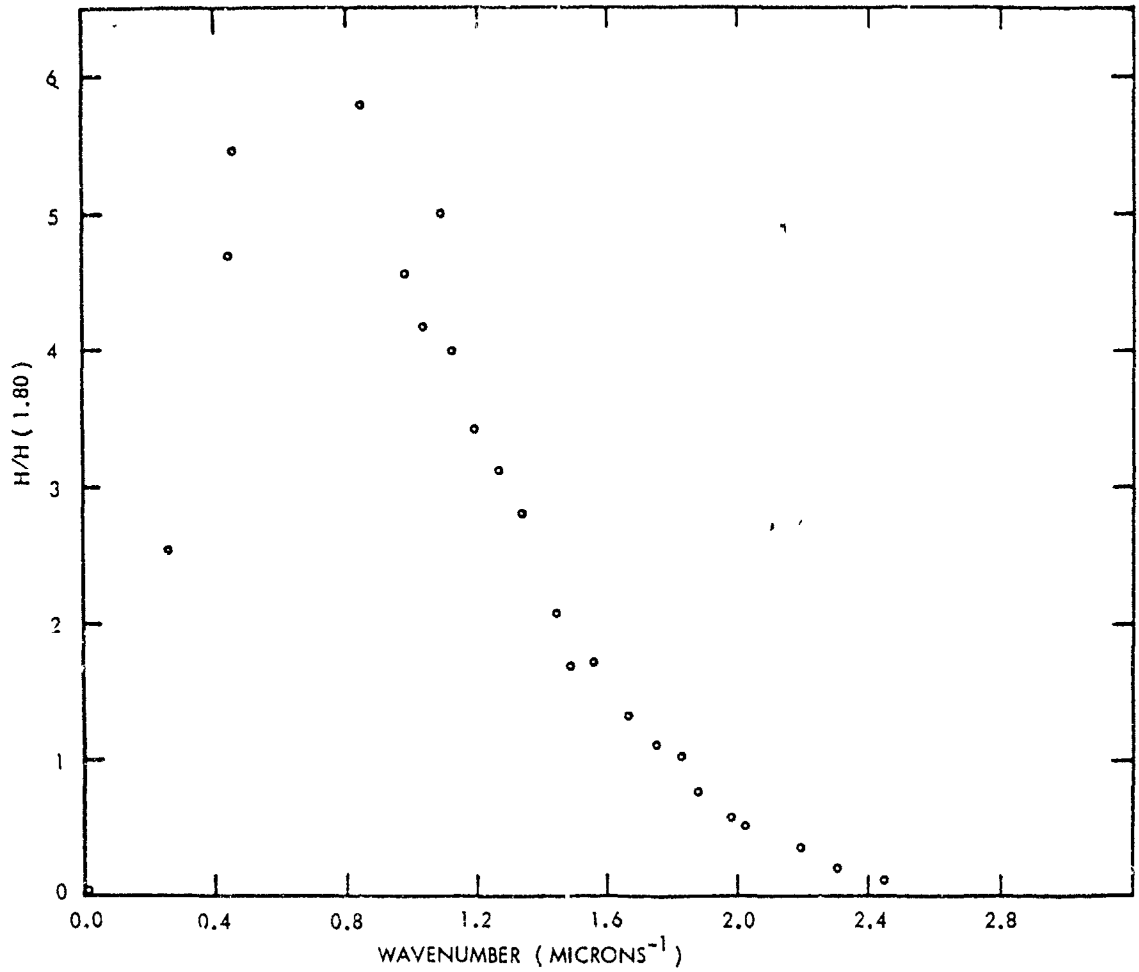

Figure 9. Spectral Distribution for Beta Andromeda M0 III.

In order to perform the integrations required by Eqs. 8 and 12, it is necessary to select a curve which best represents the spectral distribution defined by the plotted data points. In an attempt to reduce to a minimum the amount of subjectivity which might enter into the selection of such a curve and to provide some estimate as to the effects of data scatter on the derived bolometric corrections, three curves were drawn for each star. The first curve was drawn by eye estimate as a "best fit" to the data points. The second was drawn to include all the data points below it, that is, it represents the maximum envelope defined by the data points. The third curve was drawn to exclude all the data points above it, it represents the minimum envelope consistent with the data. The area under each

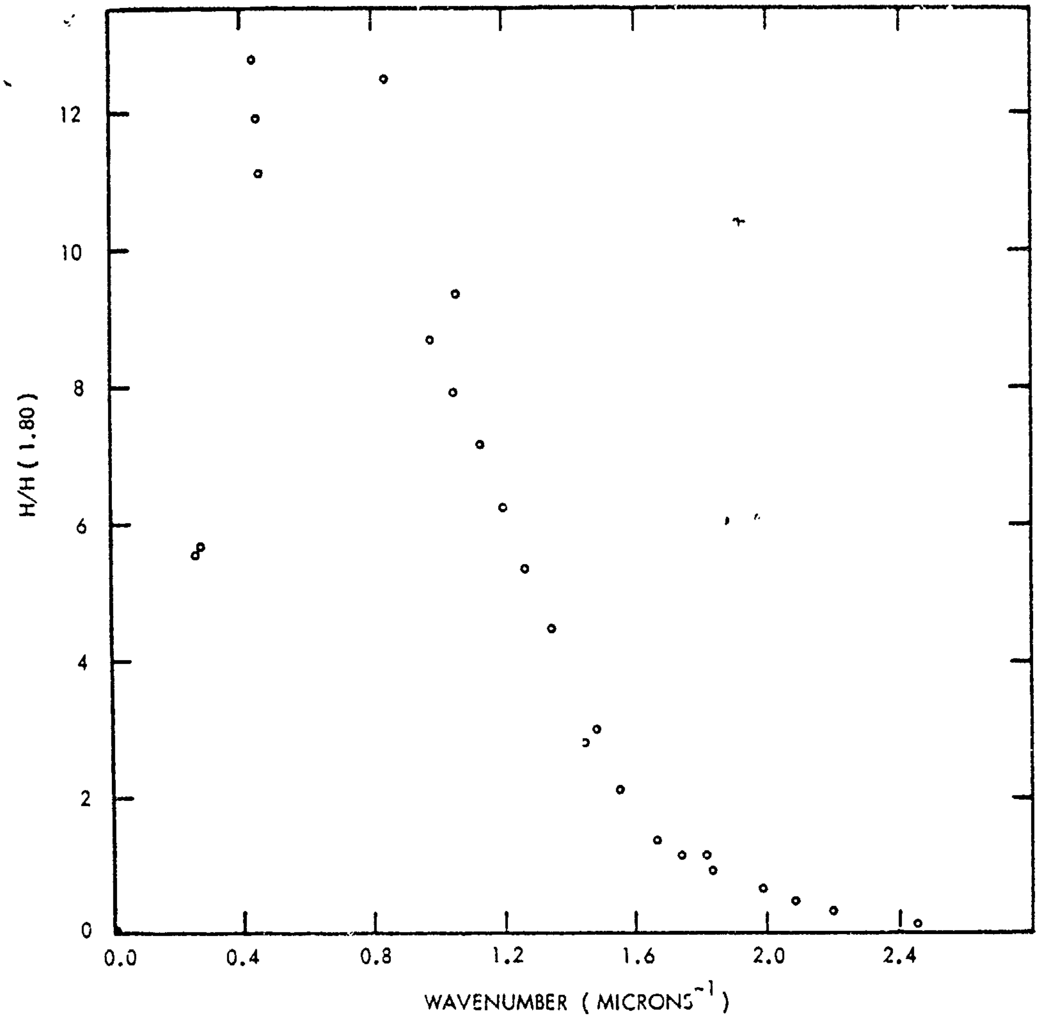

Figure 10. Spectral Distribution for Beta Pegasi M2 II.

curve was planimetered and a corresponding bolometric correction was derived from Eq. 12. The mean value of these three values of B.C. was adopted as the bolometric correction for the star, and the standard deviation of the three from the mean was adopted as a measure of the error.

Values of B.C. and the standard deviation derived in the above manner are listed in columns 5 and 6 of Table 10 for all the stars considered. Those values enclosed in parentheses are for stars for which only 6 data points were available and are thus of low weight. Stars for which no standard deviations are given have well-defined spectra, but either an insufficient number of data points or insufficient scatter in the data to give a meaningful estimate of the error.

TABLE 10. Derived bolometric corrections for individual stars

Star	Sp.	B-V	V-I	B.C.	Std. Dev.	Star	Sp.	B-V	V-I	B.C.	Std. Dev.
γ Vir	F0 V	+.36		+.10	±.040	α Tau	K5 III	+1.51	+2.38	-1.03	.130
ρ Cas	F2 IV	+.35	-.93	+.09	.028	α Hya	K4 III	+1.44	+1.91	-.79	.015
α C Mi	F5 IV	+.40	-.77	+.06	.045	γ Dra	K5 III	+1.52	+2.30	-.93	.063
α Lep	F0 I_b	+.21	-1.06	+.17	.037	ζ Cep	K1 I_b	+1.58	+2.08	-.82	.011
α Per	F5 I_b	+.48	-.50	-.01	.030	ε Peg	K2 I_b	+1.56	+2.05	-.72	.043
β Com	G0 V	+.56	(-.06)	-.08	.041	μ U Ma	M0 III	+1.54		-1.11	
η Boo	G0 IV	+.59	-.32	-.03	.022	β And	M0 III	+1.57	+2.56	-1.17	.037
ζ Her	G0 IV	+.64	.00	-.06	.007	Lal 21185	M2 V	+1.51		-1.20	
HR 483	G2 V	+.63	.25	-.10	.019	χ Peg	M2 III	+1.58		(-1.41)	
α Aur	G8 III	+.80	-.22	-.12	.041	μ Cep	M2	+2.41		-2.48	
σ Dra	K0 V	+.79		-.08	.009	α Ori	M2 II-III		+3.38	-1 60	.110
ε Eri	K2 V	+.89		-.11	.009	β Peg	M2 II-III		+3.26	-1.88	.057
61 Cyg B	K7 V	+1.38	+2.01	-.88	.017	α Cet	M2 III	+1.64	+2.96	-1.38	.033
α U Ma	K0 IV	+1.06	+.89	-.40	.044	μ Gem	M3 III	+1.64	+3.32	-1.74	
α Cass	K0 II		+1.11	-.43	.045	η Gem	M3 III		+3.10	-1.69	
γ Agl	K3 II	+1.49	+2.08	-.76	.038	δ Sge	M2		+2.80	-1.70	
ι Aur	K3 II	+1.52	+2.13	-.94	.020	ψ Peg	gM3			-1.54	
θ Cen	K0 III	+1.06		(-.27)		δ Lyr	M4		+3.76	-2.77	
δ Tau	K0 III	+.98	+.65	-.31	.012	Barnard's	M5 V	+1.74		-2.35	
γ Leo	K0 III			(-.37)		HR 5299	gM4			-2.18	
β Gem	K0 III	+1.00	+.72	-.23	.032	2 Cen	sgM6			(-2.68)	
ε Cyg	K0 III	+1.12	+.86	-.28	.036	30g Her	gM6			(-3.87)	

TABLE 10. Continued

Star	Sp.	B-V	V-I	B.C.	Std. Dev.	Star	Sp.	B-V	V-I	B.C.	Std.Dev.
α Boo	K2 IIIp	+1.23	+1.32	-.56	.035	α Her	M5 II			(-3.37)	
β Oph	K2 III	+1.16	+1.12	-.34	.032						
α Ari	K2 III	+1.15	+1.16	-.40	.040						
γ And	K2 III		+1.30	-.65							
α Ser	K3 III	+1.17	+1.17	-.36	.046						
ε Cr B	K3 III	+1.23		-.52							
δ And	K3 III	+1.27	+1.51	-.56							
β Cnc	K4 III	+1.48		-.76							

The value of I (☉) required in Eq. 12 was obtained by integration of the monochromatic solar irradiance relative to n = 1.80, which was calculated from the solar energy curve of Goldberg and Pierce (1959) (see Appendix I). The value -0.07 mag. was adopted as the bolometric correction for the Sun in agreement with the zero point of Kuiper's (1938) scale.

Mean values of B.C. as functions of spectral type derived from Table 10 are given in Table 11. Aside from the zero point correction of -0.07 mag. the values are in close agreement with those obtained by Johnson (1962) for luminosity class III, but tend to be generally smaller for main sequence stars. For the purpose of computing means it has been assumed that gM3, gM4, and sgM6 can be equated to M3 III, M4 III, and M6 III (Eggen, 1955).

TABLE 11. The bolometric correction as a function of spectral type

Sp.	B.C.	Sp.	B.C.	Sp.	B.C.
G8III	(-.12)	M0III	-1.14	G0V	-.06
K0III	-.28	M2III	-1.52	G2V	-.07
K2III	-.47	M3III	-1.68	K0V	-.08
K3III	-.50	M4III	(-2.18)	K2V	-.11
K4III	-.77	M6III	(-2.68)	K7V	-.87
K5III	-.98			M2V	-1.20
K0II	-.43			M5V	-2.35
K3II	-.85				

Figure 11 shows the relationship of B.C. to the B-V color of Johnson and Morgan (1953) as determined by 40 stars of the list for which B-V colors are available (Table 10, column 3). The plotted points show considerable scatter as well as a tendency for main sequence objects to lie above the mean curve. The three stars of luminosity class I_b all lie below the mean curve. It should be noted from examination of Table 10 that the majority of stars considered are of luminosity class III, and thus relationships between the bolometric correction and color indices are biased in this sense. Values read from the curve of Figure 11 are listed in Table 12.

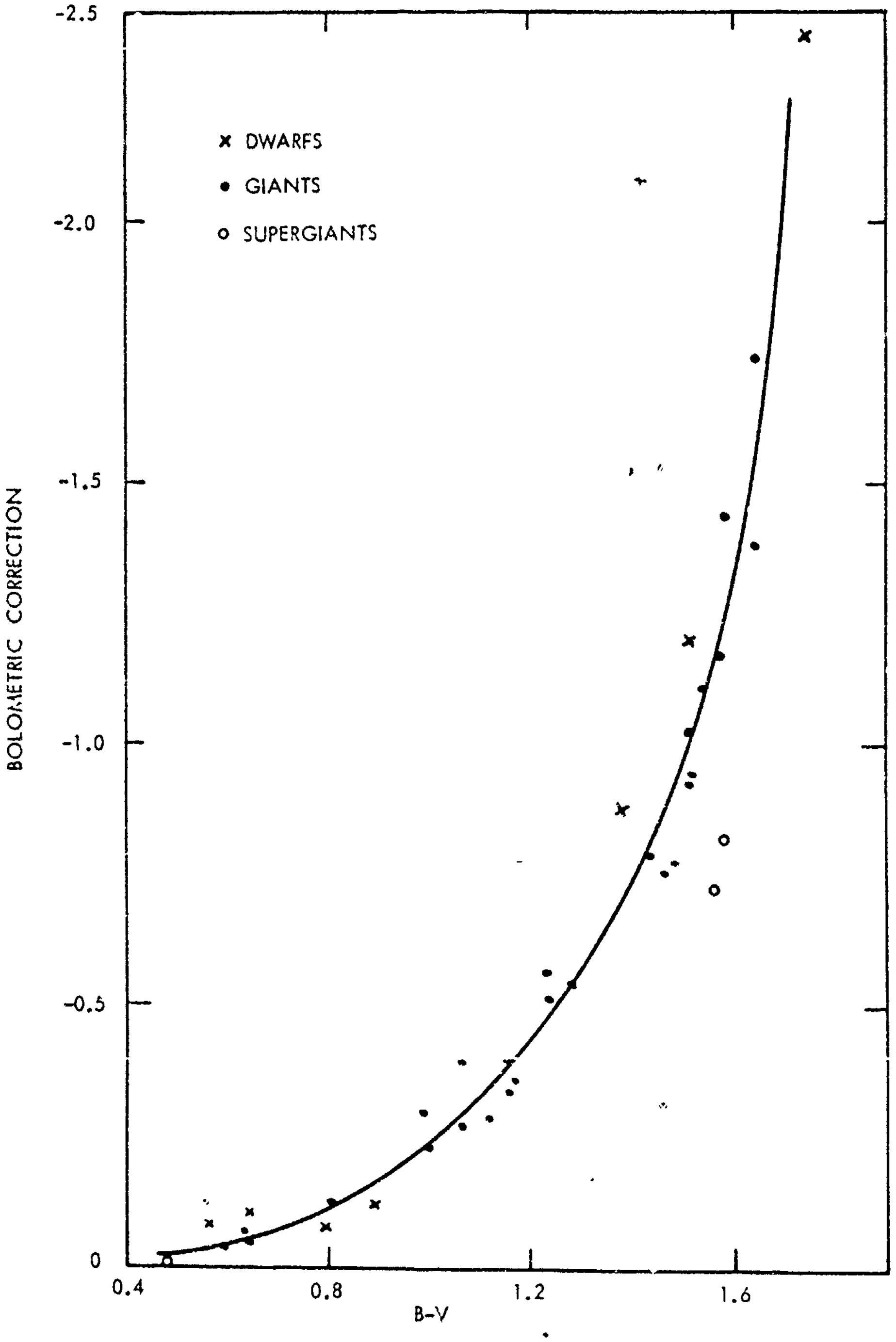

Figure 11. Bolometric Correction vs. B-V of Johnson and Morgan.

TABLE 12. The bolometric correction as a function of the B-V color of Johnson and Morgan (1953)

B-V	B.C.	B-V	B.C.
+.5	-.03	+1.1	-.34
+.6	-.06	+1.2	-.45
+.7	-.09	+1.3	-.59
+.8	-.12	+1.4	-.75
+.9	-.17	+1.5	-.95
+1.0	-.24	+1.6	-1.31

The relationship of B.C. to the V-I index of Six Color photometry is plotted in Figure 12 for 31 stars in the list for which V-I data are available (Table 10, column 4). A mean curve seems fairly well defined and the scatter of points are random with the exception of γ And (V-I = +1.30) which appears to have a much too large B.C. for its color index. This star is known to be a member of a binary system (spectral type of companion is A0), however, the separation is fairly large, being about 12 seconds of arc.

From the limited data available there is no evidence of separation of the stars according to luminosity class. Values read from the curve of Figure 12 are listed in Table 13.

TABLE 13. The bolometric correction as a function of the V-I index of Stebbins and Whitford (1945)

V-I	B.C.	V-I	B.C.	V-I	B.C.
0.00	-.07	+1.50	-.54	+2.75	-1.29
+.25	-.13	+1.75	-.66	+3.00	-1.50
+.50	-.18	+2.00	-.78	+3.25	-1.74
+.75	-.26	+2.25	-.93	+3.50	-2.04
+1.00	-.34	+2.50	-1.09	+3.75	(-2.38)
+1.25	-.43				

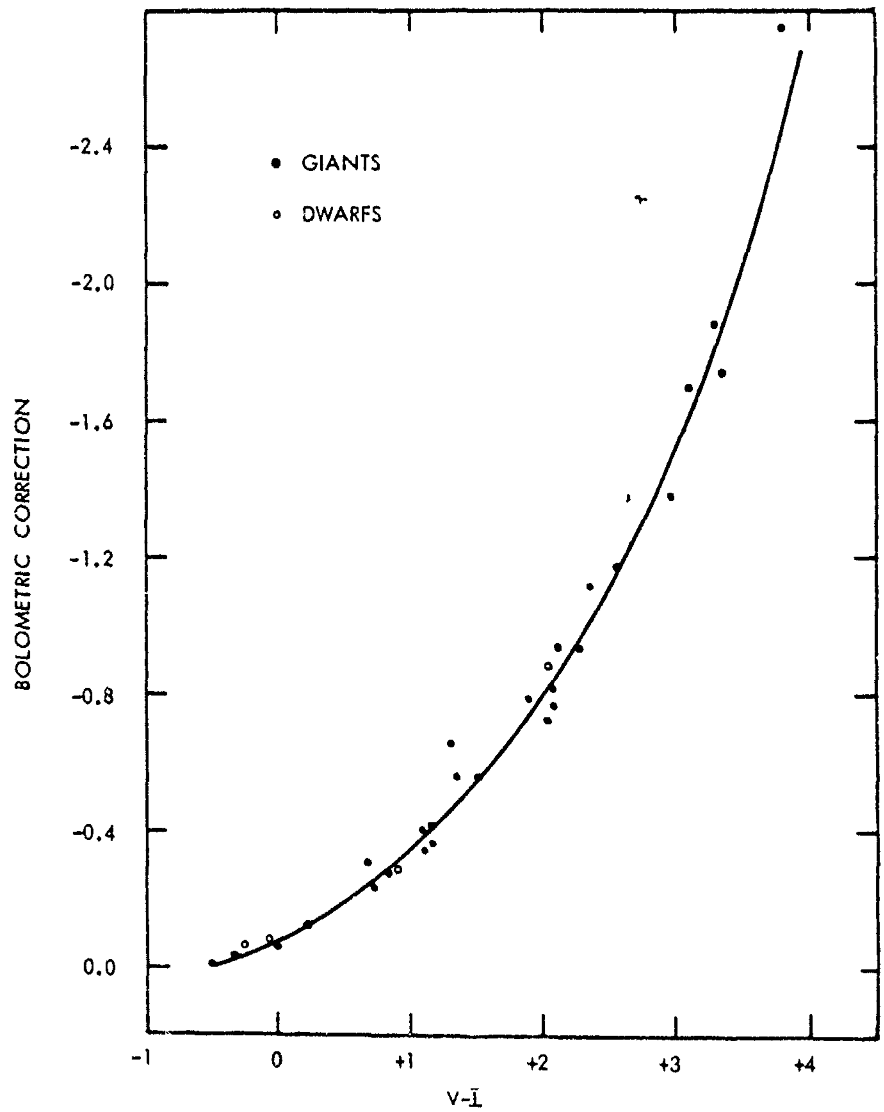

Figure 12. Bolometric Correction as a Function of the V-I Index of Six Color Photometry.

With the exception of Johnson (1962) the bolometric corrections obtained here are systematically smaller in absolute value than those derived in previous discussions. Comparison of B.C. for 27 stars in common with Kuiper's list shows the derived values to be 24 percent smaller than those obtained by Kuiper. A similar comparison between Eggen (1956) and Kuiper (1938) shows Eggen's values to be 16 percent smaller than Kuiper's. Since the same data were used by both authors and treated in the same manner, one must attribute the 16 percent reduction to a systematic difference between the photoelectrically measured V_E magnitudes and the photographically determined IP_v used by Kuiper. Thus, the definition of a scale of bolometric corrections in terms of only photoelectrically observed quantities implies a new scale which will differ systematically from that adopted in 1938 and in the direction indicated by Eggen.

All determinations of bolometric corrections previous to Johnson (1962) have relied upon measures of radiometric magnitudes. Corrections for atmospheric extinction in the zenith amount to about 0.4 or 0.5 mag. Furthermore, reduction of the observed magnitudes to the zenith have assumed the following dependence on zenith angle z

$$m = k(\sec z - 1) \tag{13}$$

while the recent paper of Gates (1960) implies that air mass corrections for radiometric quantities would more nearly follow a relation of the form

$$m = k_1(\sec z - 1) + k_2(\sec z - 1)^{1/2} \tag{14}$$

where the relative values of the coefficients k_1 and k_2 would be dependent on the temperature of the star. The linear term accounts for scattering processes and weak molecular absorption such as occur in the far wings of the atmospheric absorption bands of H_2O, and the term in the square root accounts for extinction within the molecular absorption bands.

Values for the zenith extinction used at Mount Wilson were obtained from measures of the extinction of the solar spectrum. It is well-known that for the cooler stars, depression of the stellar continuum by contribution of molecular absorption bands to the opacity can become large. In particular, the great abundance of the H_2O molecule predicted for late type stars might well be expected to depress the continuum in the same spectral regions as are obscured by water vapor in the earth's atmosphere. Corrections for zenith extinction based upon the solar spectrum would then be overestimated and lead to an overestimate of the bolometric correction.

Magnitudes measured in the infrared through narrow band filters which peak the photometer response in the atmospheric "windows" require only small corrections for extinction as compared to the broad band radiometric measurement. In addition, the use of a narrow band of wavelengths greatly reduces the effects of color on the extinction.

Advances made in the last few years in infrared detectors and technology together with the selection of narrow spectral regions not subject to large fluctuations in water vapor transparency, allow one to obtain measurements of faint stars at signal-to-noise ratios far greater than those attainable by Pettit and Nicholson.

The above considerations require one to conclude that the bolometric corrections derived from stellar spectral distributions are inherently better determined than those derived from radiometric magnitudes. One may argue that the spectral distribution method suffers from the necessity to interpolate the energy curve over wide regions in the infrared for which ground based measurements are not possible. However, in the process of reducing radiometric magnitudes, the required interpolations are implicit.

The average value of the standard deviations listed in column 6 of Table 10 is 0.04 mag., and for the most part reflects the errors incurred in transformation of the various magnitude systems.

4. CONCLUSION

The bolometric corrections in Table 9 are recommended for the range B-V = 0.0 to B-V = +0.50. Their accuracy relies upon the carefully revised temperature scale of Popper (1959) and fairly detailed model atmospheres.

For stars hotter than A0 the situation is not as favorable. Current model atmospheres predict a fairly well defined scale of bolometric corrections; however, the data of Stecher and Milligan (1962) suggest that our current concepts of the atmospheres of early stars may be incorrect. If stellar models such as those proposed by Meinel (1963) are indeed representative of hot stars, the scale of bolometric corrections will require a drastic revision, as well as present theories of stellar evolution. Until additional data are available from rocket or satellite observations of the spectrum down to the Lyman limit, it is recommended that the bolometric corrections of Table 8 be used with caution.

For stars with B-V greater than +0.50 the values listed in Tables 11, 12, and 13 are recommended. The precision of these values relies on photoelectric measurements and the accuracy of the transformation of magnitude and color systems. The infrared magnitudes were measured in spectral regions of high atmospheric transparency, thus minimizing the errors inherent in the correction for extinction. It is noted again that the stars considered here are largely of luminosity class III. Infrared observations of main sequence objects for which auxiliary data are already available would put this scale on a more firm basis.

Measurements of radiometric magnitudes from a high altitude balloon platform would provide conclusive data on the bolometric correction for the stars of late spectral type. Observations from rocket and satellite altitudes will be necessary for the hotter stars.

The scale of bolometric corrections presented here embodies revisions of sufficient magnitude to warrant a rediscussion of the empirical mass-luminosity law.

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Appendix I: Conversion of Magnitudes and Colors to Monochromatic Fluxes

1. GENERAL CONSIDERATIONS

The definition of an apparent stellar magnitude m is given by

$$m = -2.5 \log \int_0^\infty S_\nu H_\nu \, d\nu + C_m \qquad \text{(I-1)}$$

where m is the apparent magnitude outside the earth's atmosphere, S_ν is the normalized receiver sensitivity function and includes the transmission of filters and optics as well as the spectral response of the detector, H_ν is the monochromatic stellar irradiance at the top of the atmosphere (ergs cm^{-2} sec^{-1} cps^{-1}), and C_m is a constant which determines the zero point of the magnitude system.

In multicolored photometry it is convenient to relate magnitudes measured with different receiver sensitivity functions to each other through a color index which is reduced to a common zero point for stars of selected spectral type. Consider, for example, a two-color system, m, k, then

$$m = -2.5 \log \int_0^\infty S_\nu H_\nu \, d\nu + C_m \qquad \text{(I-2)}$$

$$k = -2.5 \log \int_0^\infty T_\nu H_\nu \, d\nu + C_k \qquad \text{(I-3)}$$

where T_ν is the receiver sensitivity function corresponding to the magnitude, k. The zero point for the system is arbitrarily defined such that the color index (m-k) = 0.0 for a star of spectral type and luminosity class X, that is, m = k for a star of spectrum X. Thus one may write:

$$C_m = k\,(X) + 2.5 \log \int_0^\infty S_\nu H_\nu (X)\, d\nu \qquad \text{(I-4)}$$

$$C_k = m\,(X) + 2.5 \log \int_0^\infty T_\nu H_\nu (X)\, d\nu \qquad \text{(I-5)}$$

or

$$(m-k) = -2.5 \log \frac{\int_0^\infty S_\nu H_\nu\, d\nu}{\int_0^\infty S_\nu H_\nu (X)\, d\nu} + 2.5 \log \frac{\int_0^\infty T_\nu H_\nu\, d\nu}{\int_0^\infty T_\nu H_\nu (X)\, d\nu} \qquad \text{(I-6)}$$

where $H_\nu(X)$ is the monochromatic irradiance from a star of spectrum X.

Since it is desired to derive H_ν from the measured magnitudes and color indices one must consider the integral

$$\bar{I} \equiv \int_0^\infty S_\nu H_\nu\, d\nu \qquad \text{(I-7)}$$

It has been shown by Stromgren (1937) that H_ν may be expanded about $H_{\nu_\circ}$ to give the following form

$$\bar{I} = \left\{ H_{\nu_0} + (1/2) \frac{d^2H}{d\nu^2}\bigg|_{\nu_0} \mu_2\,(\nu_0) + \cdots \right\} \int_0^\infty S_\nu\, d\nu \qquad \text{(I-8)}$$

where

$$\nu_0 = \frac{\int_0^\infty \nu S_\nu\, d\nu}{\int_0^\infty S_\nu\, d\nu} \qquad \text{(I-9)}$$

and

$$\mu_2(\nu) = \int_0^\infty (\nu-\nu_0)^2\, S_\nu\, d\nu \Big/ \int_0^\infty S_\nu\, d\nu \qquad \text{(I-10)}$$

Thus Eq. I-1 may be rewritten as

$$m = -2.5 \log (H_{\nu_0} + \Delta H) - 2.5 \log \int_0^\infty S_\nu \, d\nu + C_m \tag{I-11}$$

where ΔH is considered a correction term given by the second and possibly succeeding terms of the expansion in Eq. I-8. Expanding the logarithm one obtains

$$\log (H_{\nu_0} + \Delta H) = \log H_{\nu_0} + 2 \left[\frac{\Delta H}{2H + \Delta H} + \frac{\Delta H^3}{3(2H + \Delta H)} + \cdots \right], \tag{I-12}$$

which for $\Delta H << H_{\nu_0}$ reduces to

$$\log (H_{\nu_0} + \Delta H) = \log H_{\nu_0} + \frac{\Delta H}{H} \tag{I-13}$$

and Eq. I-11 becomes

$$m = -2.5 \log H_{\nu_0} - 2.5 \left(\frac{\Delta H}{H}\right) - 2.5 \log \int_0^\infty S_\nu \, d\nu + C_m \tag{I-14}$$

Consider now the term in ΔH. Dropping terms higher than the second in the expansion of Eq. I-8 we derive,

$$-2.5 \left(\frac{\Delta H}{H}\right) = \left(\frac{-2.5}{H}\right) \frac{\mu_2}{2} \left. \frac{d^2 H}{d\nu^2} \right|_{\nu_0} = -2.5 \left(\frac{\mu_2}{2}\right) \frac{d}{d\nu} \left(\frac{dH}{H d\nu}\right)_{\nu_0} \tag{I-15}$$

or

$$-2.5 \left(\frac{\Delta H}{H}\right) = -2.5\, b \frac{d}{d\nu} \left(\frac{d \log H}{d\nu}\right)_{\nu_0} = b \frac{d}{d\nu} \left(\frac{dm}{d\nu}\right)_{\nu_0} \tag{I-16}$$

where b is a constant. From Eq. I-16 it is seen that $\frac{\Delta H}{H}$ is a "color term", that is, it represents a change in color index with frequency.

Extending the above to the previous two-color example, Eq. I-6 becomes

$$(m-k) = -2.5 \log \frac{H_{\nu_m}}{H_{\nu_k}} + 2.5 \log \frac{H_{\nu_m}(X)}{H_{\nu_k}(X)} - \left\{ \left[\frac{\Delta H_{\nu_m}}{H_{\nu_m}} - \frac{\Delta H_{\nu_k}}{H_{\nu_k}} \right] - \left[\frac{\Delta H_{\nu_m}(X)}{H_{\nu_m}(X)} - \frac{\Delta H_{\nu_k}(X)}{H_{\nu_k}(X)} \right] \right\} \times 2.5 \tag{I-17}$$

and since the last term in Eq I-17 vanishes for (m-k) = 0, it must be a function of (m-k), that is

$$\frac{\Delta H_{\nu_m}}{H_{\nu_m}} - \frac{\Delta H_{\nu_k}}{H_{\nu_k}} = \phi\ (m-k) \qquad \text{(I-18)}$$

2. MONOCHROMATIC MAGNITUDES

In order to synthesize the absolute energy distribution in a stellar spectrum, it is necessary to reduce the measurements of magnitude and color on various systems to monochromatic fluxes. However, for the purpose of deriving bolometric corrections, it is only necessary to obtain the monochromatic fluxes relative to the flux at a common frequency. The monochromatic magnitudes of Code (1.80) provide an accurate and convenient system to which the magnitudes and colors of other systems may be reduced.

The monochromatic magnitude is defined by

$$m\ (n) = -\ 2.5 \log \frac{H\ (n)}{H\ (1.80)} \qquad \text{(I-19)}$$

where m (n) is the magnitude per unit frequency interval relative to n = 1.80 microns^{-1}, H (n) is the monochromatic irradiance at the top of the atmosphere, and n is the wavenumber in reciprocal microns, that is

$$n = \frac{1}{\lambda}\ \text{microns}^{-1} = \frac{10^4 \nu}{c} \qquad \text{(I-20)}$$

where c is the velocity of light. Consider now the magnitude X where

$$X = -\ 2.5 \log H\ (\nu_{0X}) - 2.5 \left(\frac{\Delta H_{\nu_{0X}}}{H_{\nu_{0X}}}\right) - 2.5 \log \int_0^{\infty} S_\nu(X)\, d\nu + C_X \qquad \text{(I-21)}$$

and substituting Eq. I-19 gives

$$X = m\ (n_{oX}) - 2.5 \log H\ (1.80) - 2.5 \left(\frac{\Delta H_{\nu_{0X}}}{H_{\nu_{0X}}}\right) + \text{constant} \qquad \text{(I-22)}$$

Now let $\phi\ (\Delta n) = -\ 2.5 \left(\frac{\Delta H_{\nu_{0X}}}{H_{\nu_{0X}}}\right)$. Defining a magnitude V such that n (V) = 1.80 microns^{-1} one may write

$$V = -\ 2.5 \log H\ (1.80) - \phi'\ (\Delta n') + \text{constant} \qquad \text{(I-23)}$$

which, after substitution and rearrangement yields the result

$$m\,(n_{0X}) = (X-V) + [\phi\,(\Delta n) - \phi'\,(\Delta n')] + \text{constant} \tag{I-24}$$

where the term $\phi\,(\Delta n)$ is proportional to the rate of change of the color curve evaluated at the constant energy wavenumber n of the X magnitude, and $\phi'\,(\Delta n')$ is proportional to the rate of change of the color curve evaluated at n = 1.80. Thus, the transformation from a color system containing V to a monochromatic magnitude will be a function of color only.

3. REDUCTION OF U, B, V DATA TO THE SYSTEM OF CODE (1960)

Constant energy wavenumbers for the U, B, V magnitudes of Johnson and Morgan (1953) computed from Eq. I-9, (Code 1960), are shown in Table I-1.

TABLE I-1. Wavenumbers for U, B, V system

	U	B	V
n	2.89	2.29	1.83

Writing Eq. I-17 in terms of the B and V magnitudes one obtains

$$(B-V) = 2.5 \log \frac{H\,(1.83)}{H\,(2.29)} + 2.5 \log \frac{H\,(2.29)\,(A0V)}{H\,(1.83)\,(A0V)} - 2.5 \left[\frac{\Delta H\,(2.29)}{H\,(2.29)} - \frac{\Delta H\,(1.83)}{H\,(1.83)}\right] + \text{constant} \tag{I-25}$$

Eq. I-19 in terms of the B and V magnitudes becomes

$$m\,(2.29) - m\,(1.83) = 2.5 \log \frac{H\,(1.83)}{H\,(2.29)} \tag{I-26}$$

and combining with Eq. I-16 and I-25

$$(B-V) = m\,(2.29) - m\,(1.83) + 2.5 \log \frac{H\,(2.29)\,(A0V)}{H\,(1.83)\,(A0V)} - \phi\,(B-V) + \text{constant} \tag{I-27}$$

Noting that the third term on the right side of Eq. I-27 is a constant and m (1.83) ≈ m (1.80) = 0, Eq. I-27 may be written

$$m\ (2.29) = (B-V) + \phi\ (B-V) + C \tag{I-28}$$

or representing Φ by a polynomial expansion we have

$$m\ (2.29) = a_0 + a_1\ (B-V) + a_2\ (B-V)^2 + - - - , \tag{I-29}$$

and in a similar manner

$$m\ (2.89) = b_0 + b_1\ (U-V) + b_2\ (U-V)^2 + - - - . \tag{I-30}$$

The coefficients, a_0, a_1, - - - - b_0, b_1, - - - -, may be evaluated from the monochromatic magnitudes of the stars in Code's (1960) list, and their U, B, V magnitudes as measured by Johnson and Morgan (1953), Johnson and Hiltner (1956), Johnson (1955), and Johnson and Harris (1954). Table I-2 presents the stars from Code's list for which U, B, V data are available together with the interpolated values of m(2.29) and m(2.89). Figure I-1 is a plot of m(2.29) against B-V, and Figure I-2, a plot of m(2.89) versus U-V. It is evident from these figures that if a nonlinear term is present in these relations, then there is insufficient data to evaluate the magnitude of that term.

On the basis of these plots the data were fit by the method of least squares to

$$m\ (2.29) = a_0 + a_1\ (B-V) \tag{I-31}$$

and

$$m\ (2.89) = b_0 + b_1\ (U-V), \tag{I-32}$$

and the following transformation equations derived:

$$m\ (1.83) = 0.0$$
$$m\ (2.29) = 1.000\ (B-V) - 0.102$$
$$m\ (2.89) = 1.049\ (U-V) + 0.881$$

TABLE I-2. U,B,V data and associated monochromatic magnitudes for the stars of Code (1960)

Star	Spect.	B-V	U-B	U-V	m(2.29)	m(2.89)
10 Lac	09 V	-.20	-1.04	-1.24	-.30	-.46
ϵ Ori	B0 I_a	-.20	-1.06	-1.26	-.24	-.43
ν Ori	B0 V	-.27	-1.11	-1.38	-.36	-.53
η U Ma	B3 V	-.20	-.68	-.88	-.31	+.03
β Ori	B8 I_a	-.03	-.69	-.72	-.13	+.04
α Lyr	A0 V	0.00	-.01	-.01	-.16	+1.09
α Cyg	A2 I_a	+.09	-.25	-.16	+.07	+1.03
β Tri	A5 III	+.13	+.08	+.21	0.00	+1.48
β Ari	A5 V	+.14	+.10	+.34	-.04	+1.30
ρ Gem	F0 V	+.31	-.04	+.27	+.21	+1.37
π^3 Ori	F6 V	+.46	0.00	+.46	+.32	+1.34
λ Ser	G0 V	+.60	+.11	+.71	+.54	+1.56
16 Cyg A	G2.5 V	+.64	+.19	+.83	+.58	+1.66
51 Peg	G4 V	+.68	+.20	+.88	+.54	+1.59
16 Cyg B	G4 V	+.66	+.20	+.86	+.57	+1.73
α Tau	K5 III	+1.51	+1.81	+3.32	+1.76	+4.36
61 Cyg A	K5 V	+1.19	+1.10	+2.29	+1.26	+3.38
α Ori	M2 I_a	+1.68	+2.47	+4.15	+2.15	+4.96

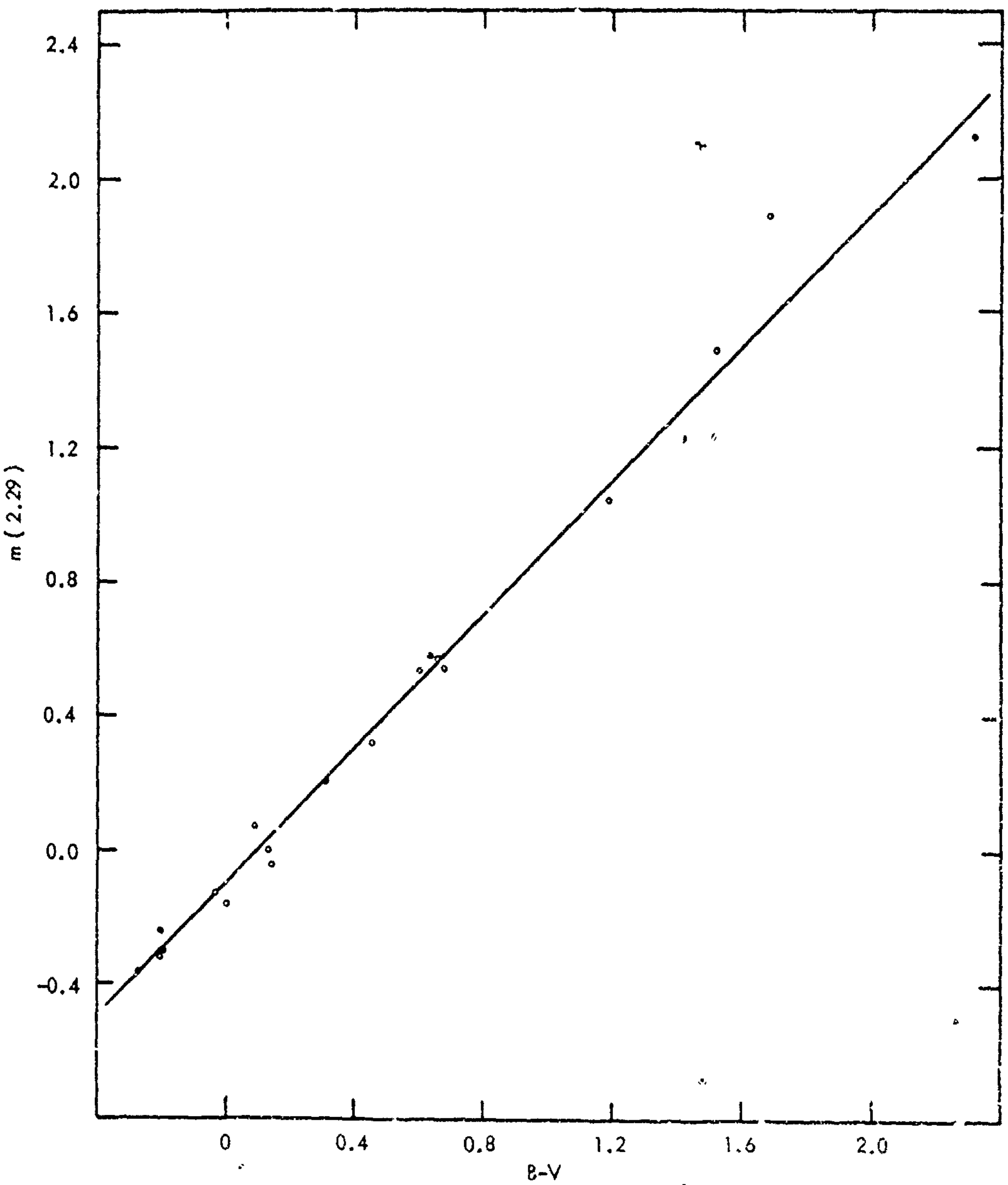

Figure I-1. Plot of m(2.29) from the Data of Code (1960) versus the B-V Index of Johnson and Morgan (1953).

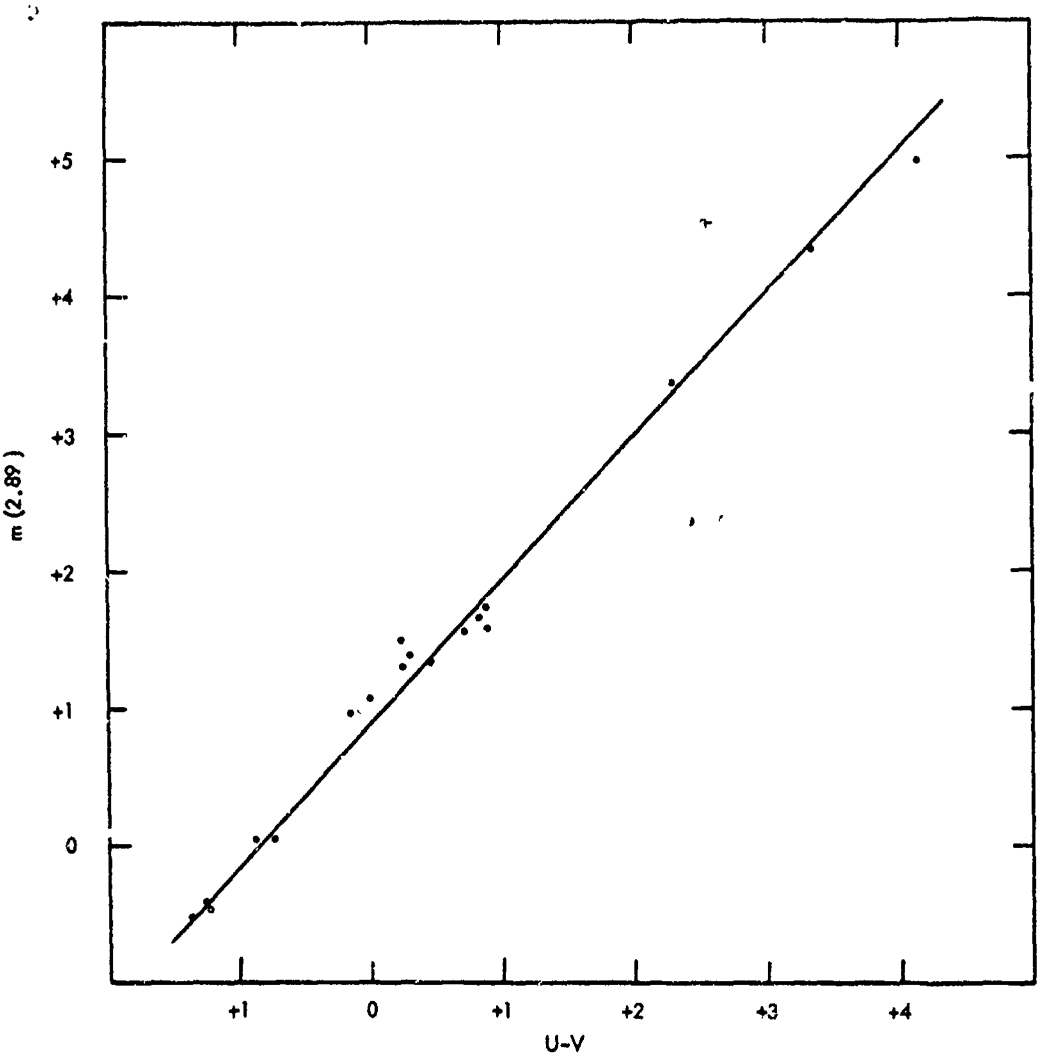

Figure I-2. Plot of m(2.89) from the Data of Code (1960) versus U-V of Johnson and Morgan (1953).

4. REDUCTION OF THE P, V DATA OF EGGEN (1955, 1957) TO THE SYSTEM OF CODE (1960)

The constant energy wavenumbers for the P and V magnitudes calculated from numerical integration of the published sensitivity curves of Eggen (1955) are

$$n\,(V) = 1.89 \text{ microns}^{-1}$$
$$n\,(P) = 2.31 \text{ microns}^{-1}.$$

In the same manner as Section 3, one may derive an equation analogous to Eq. I-27, that is

$$(P-V) = m\,(2.31) - m\,(1.89) + 2.5 \log \frac{H\,(2.31)\,(P-V = 0)}{H\,(1.89)\,(P-V = 0)} + \phi\,(P-V)$$

or

$$m\,(2.31) = (P-V) + m\,(1.89) - 2.5 \log \frac{H\,(2.31)\,(P-V = 0)}{H\,(1.89)\,(P-V = 0)} + \phi\,(P-V) \qquad \text{(I-33)}$$

However, m (1.89) may be considered a correction term due to the shift of zero point with wavenumber from Code's m (1.80) and thus m (1.89) will be a function of color, that is, m (1.80) = m (1.89) + Δm (P-V), and expanding in a series of polynomials,

$$m\,(1.89) = a_0 + a_1\,(P-V) + a_2\,(P-V)^2 + \cdots$$

and

$$m\,(2.31) = b_0 + b_1\,(P-V) + b_2\,(P-V)^2 + \cdots.$$

Table I-3 is a tabulation of the stars from Code's list for which P, V data are available. Although the number of stars is small, the relationships as shown in

TABLE I-3. P,V data and the associated monochromatic magnitudes for the stars of Code (1960)

Star	Spect.	V	P-V	m(1.89)	m(2.31)
η U Ma	B3 V	1.89	-.312	-.066	-.32
δ Cyg	B9.5 III	2.87	-.155	-.031	-.17
β Ari	A5 V	2.70	+.021	0.00	-.04
ρ Gem	F0 V	4.21	+.207	+.046	+.23
σ Boo	F2 V	4.48	+.236	+.052	+.31
π^3 Ori	F6 V	3.16	+.334	+.051	+.34
λ Ser	G0 V	4.39	+.504	+.087	+.54
51 Peg	G4 V	5.46	+.572	+.098	+.65
α Tau	K5 III	0.77	+1.454	+.291	+1.70

Figures I-3 and I-4 appear to be fairly well defined and a least squares solution yields the transformation equations

$$m\ (1.89) = 0.195\ (P-V) - 0.003$$

and

$$m\ (2.31) = 1.163\ (P-V) - 0.014.$$

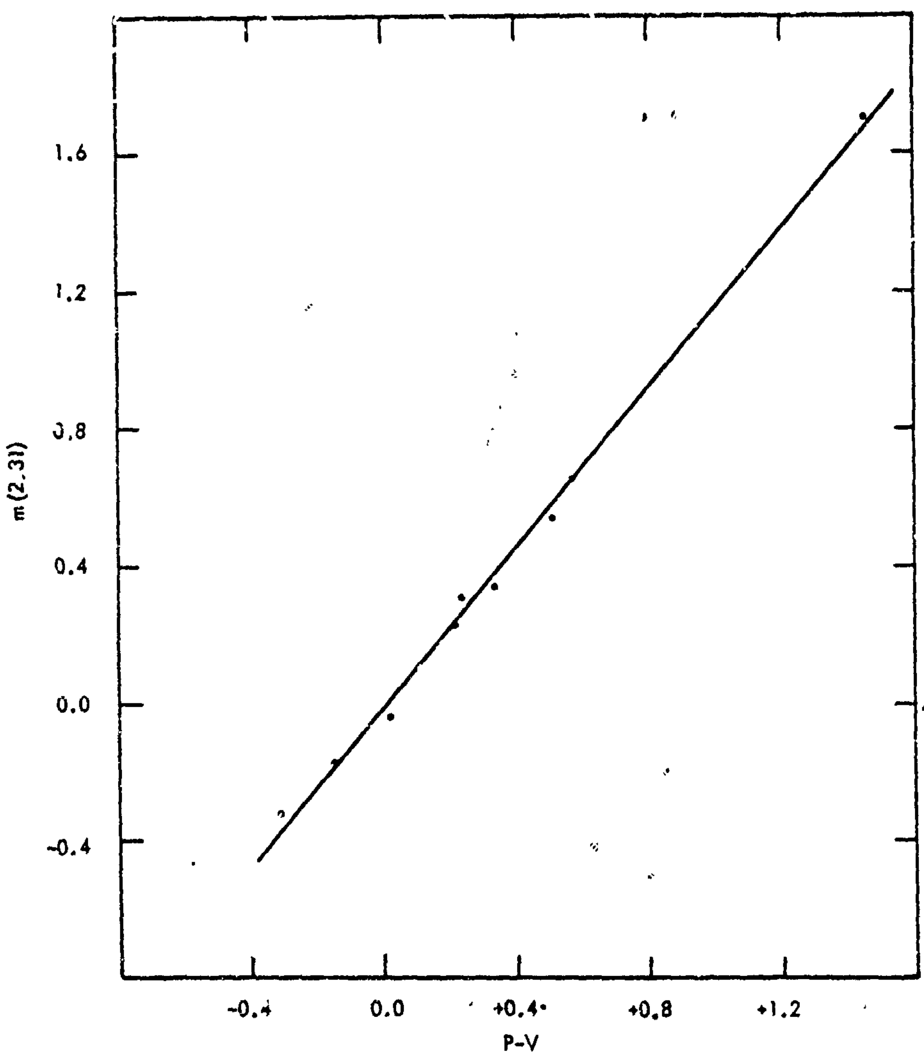

Figure I-3. Plot of m (2.31) from the Data of Code (1960) versus the P-V Index of Eggen (1955,1957).

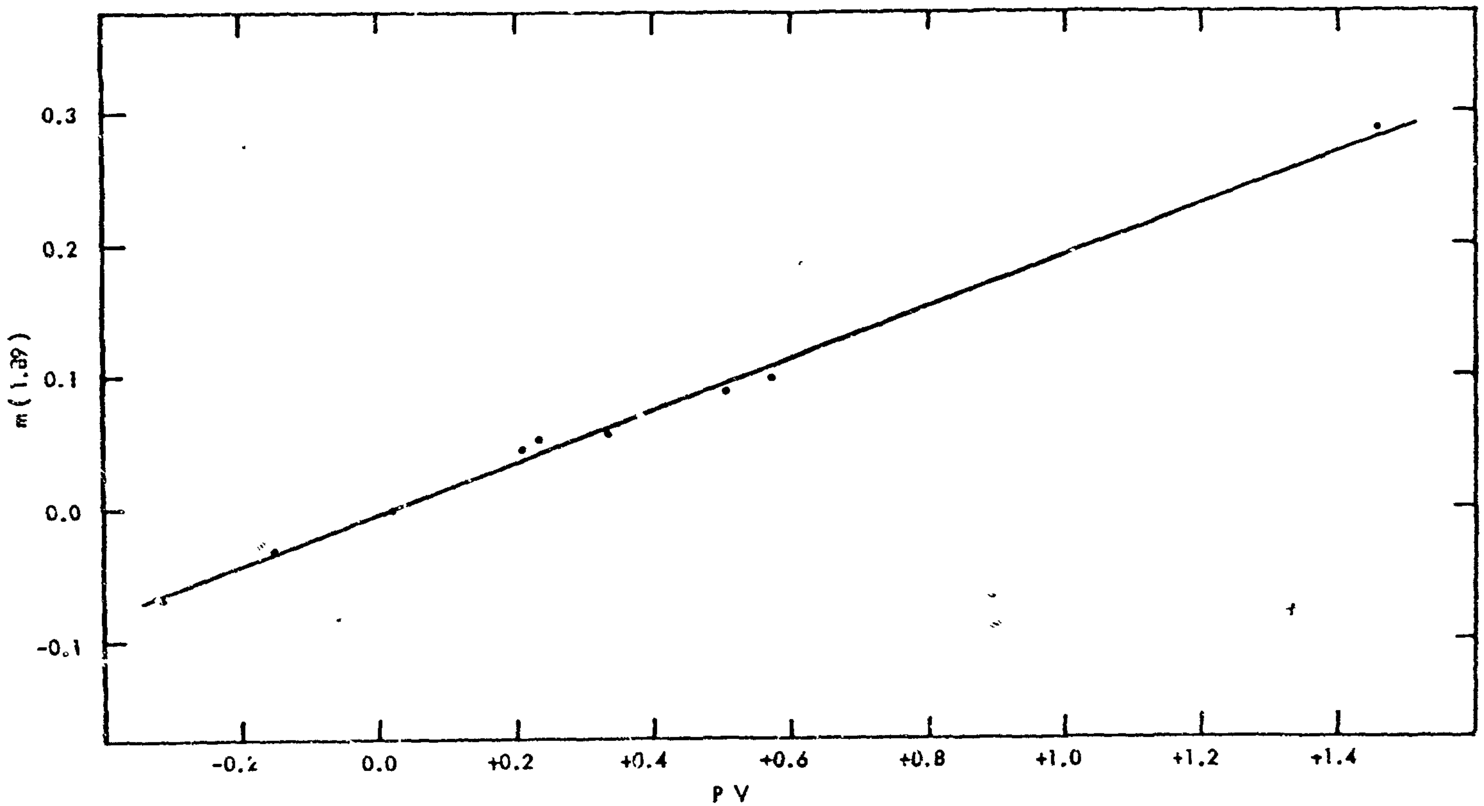

Figure I-4. Plot of m(1.89) from the Data of Code (1960) versus P-V of Eggen (1955,1957).

5. CONVERSION OF THE R AND I MAGNITUDES OF KRON AND WHITE (1953), KRON AND GASCOIGNE (1953), AND KRON, GASCOIGNE, AND WHITE (1957) TO THE MONOCHROMATIC MAGNITUDES OF CODE (1960)

The constant energy wavenumbers for the R and I magnitudes obtained from Kron and Smith (1950) are

$$n\,(R) = 1.49 \text{ microns}^{-1}$$
$$n\,(I) = 1.21 \text{ microns}^{-1}$$

The R, I magnitudes taken with the P, V magnitudes of Eggen may be considered to form a four color system, since the zero point for R, I is defined as R = I = P for stars which P-V = 0. Thus, in the manner of Section 3 one may derive

$$(R-I) = m\,(1.49) - m\,(1.21) + 2.5 \log \frac{H\,(1.49)\ (P-V = 0)}{H\,(1.21)\ (P-V = 0)} - \phi\,(R-I) \qquad \text{(I-33)}$$

and following Section 4

$$m\,(1.49) = a_0 + a_1\,(R-I) + a_2\,(R-I)^2 + \cdots \qquad \text{(I-34)}$$

$$m\,(1.21) = b_0 + b_1\,(R-I) + b_2\,(R-I)^2 + \cdots. \qquad \text{(I-35)}$$

The corresponding data of Code and Kron, and others, are presented in Table I-4 and plots of m (1.49) and m (1.21) versus (R-I) are shown in Figures I-5 and I-6 Least squares solutions yield the following reduction equations:

$$m\,(1.21) = 0.308 - 2.23\,(R-I)$$
$$m\,(1.49) = 0.106 - 1.208\,(R-I).$$

TABLE I-4. R,I data and the associated monochromatic magnitudes for the stars of Code (1960)

Star	Spect.	R	R-I	m(1.48)	m(1.21)
ε Ori	B0 I_a	1.88	-0.20	+.28	+.64
ν Ori	B0 V	4.84	-0.25	+.46	+.90
β Ori	B8 I_a	0.30	-0.08	+.16	+.48
α Lyr	A0 V	0.15	-0.09	+.23	+.48
β Tri	A5 III	2.76	+0.07	+.16	+.33
β Ari	A5 V	2.75	-0.02	+.17	+.40
π^3 Ori	F6 V	3.05	+.16	-.09	-.03
λ Ser	G0 V	4.20	+.20	-.16	-.15
61 Cyg A	K5 V	4.60	+.47	-.47	-.76

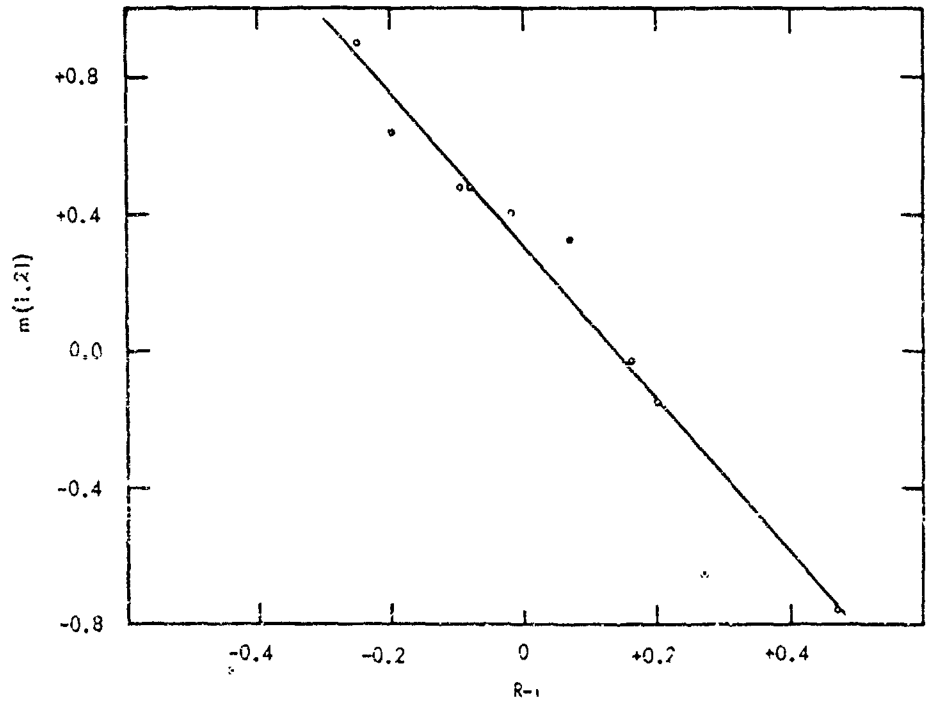

Figure I-5. Plot of m (1.21) of Code versus the R-I index of Kron.

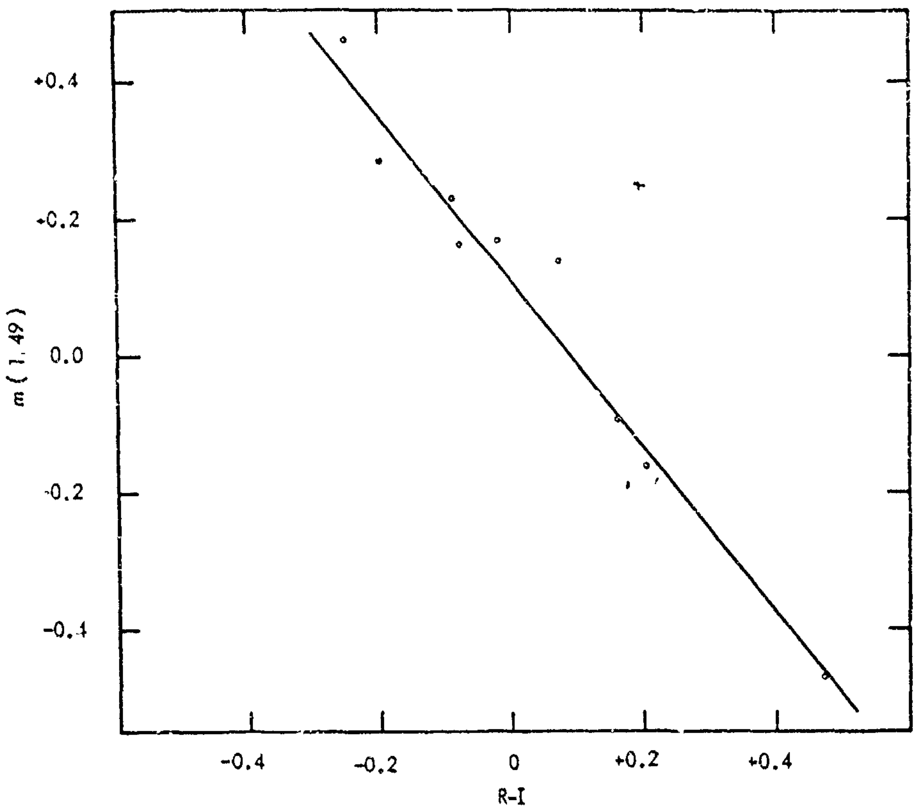

Figure I-6. Plot of m (1.49) of Code versus the R-I Index of Kron.

6. REDUCTION OF THE SIX COLOR PHOTOMETRY OF STEBBINS AND WHITFORD (1945), STEBBINS AND KRON (1956), AND KRON (1958)

Table I-5 gives the constant energy wavenumbers for the six color system as obtained by Stebbins and Kron (1957).

TABLE I-5. Wavenumbers of Six Color Photometry

	U	V	B	G	R	I
n	2.84	2.45	2.08	1.74	1.48	1.09

The six colors are color indices. They represent magnitude differences referred to the mean value of BGR for each star measured. The common zero point of the system is then set by reduction of the colors to the standard U = V = B = G = R = I = 0.0 for the mean value of the colors of ten stars of spectral type dG6.

Consider the magnitude Z_m where Z_m can be any one of the measured magnitudes for the above six colors, then in general

$$Z_m = -2.5 \log \int_0^\infty S_\nu (Z_m) H_\nu \, d\nu + \text{constant} \qquad \text{(I-36)}$$

and defining the mean of measured BGR magnitudes Z_B, Z_G, Z_R as $\bar{Z}$, then

$$\bar{Z} = \frac{Z_B + Z_G + Z_R}{3} = -\frac{2.5}{3} \Big[\log \int_0^\infty S_\nu (Z_B) H_\nu \, d\nu \qquad \text{(I-37)}$$

$$+ \log \int_0^\infty S_\nu (Z_G) H_\nu \, d\nu + \log \int_0^\infty S_\nu (Z_R) H_\nu \, d\nu \Big] + \text{constant.}$$

Defining Z' as the color of Z_m related to the mean of BGR and expanding in the form of Eq. I-14 one obtains

$$Z' = Z_m - \bar{Z} = \frac{2.5}{3} \log \left[\int_0^\infty S_\nu (Z_B) \, d\nu \cdot \int_0^\infty S_\nu (Z_G) \, d\nu \cdot \int_0^\infty S_\nu (Z_R) \, d\nu \right]$$

$$+ \frac{2.5}{3} \left\{ \log H_B + \log H_G + \log H_R + \frac{\Delta H_B}{H_B} + \frac{\Delta H_G}{H_G} + \frac{\Delta H_R}{H_R} \right\}$$

$$-2.5 \log H_{Z_m} - 2.5 \frac{\Delta H_{Z_m}}{H_{Z_m}} - 2.5 \log \int_0^\infty S_\nu (Z_m) \, d\nu$$

$$+ \text{constant} \qquad \text{(I-38)}$$

The reduction to the standard dG6 star then results in the color Z,

$$Z = Z' - Z'(dG6) = -2.5 \log \frac{H_{Z_m}}{H_{Z_m (dG6)}} - 2.5 \left[\frac{\Delta H_{Z_m}}{H_{Z_m}} - \frac{\Delta H_{Z_m (dG6)}}{H_{Z_m (dG6)}} \right]$$

$$+ 2.5 \left\{ \log \frac{H_B}{H_B (dG6)} + \log \frac{H_G}{H_G (dG6)} + \log \frac{H_R}{H_R (dG6)} \right.$$

$$+ \left[\frac{\Delta H_B}{H_B} - \frac{\Delta H_B (dG6)}{H_B (dG6)} \right] + \left[\frac{\Delta H_G}{H_G} - \frac{\Delta H_G (dG6)}{H_G (dG6)} \right]$$

$$\left. + \left[\frac{\Delta H_R}{H_R} - \frac{\Delta H_R (dG6)}{H_R (dG6)} \right] \right\} \qquad \text{(I-39)}$$

The term within the braces is a constant for any particular star and thus applies to all six colors. It provides normalization of the received flux to a constant energy wavenumber near that of the G magnitude. Thus, the color Z is a measure of the flux received at the n (Z) wavenumber relative to that received from a dG6 star of the same apparent magnitude.

The six colors may be reduced to a star of solar type (G2V) by comparison to stars common to the list of Stebbins and Kron (195⁻), for which the colors of the sun were taken to be zero, and the list of Stebbins and Kron (1956) referenced to dG5. Table I-6 presents these data and the derived correction term

$$\Delta m\ (n) = m(n)\ 1957\ - m(n)\ 1956.$$

TABLE I-6. Comparison of the data from Stebbins and Kron (1957) with Stebbins and Kron (1956) for reduction to the sun

Star	Spect.	U	V	B	C	R	I	
β Com	G0 V	-.08	-.07	-.05	+.03	+.02	-.01	m(n), 1957
		-.26	-.16	-.06	-.02	+.09	+.10	m(n), 1956
		+.14	+.09	+.01	+.05	-.07	-.11	Δm
λ Ser	G0.5 V	-.05	-.07	-.04	+.02	+.02	-.06	m(n), 1957
		-.13	-.10	-.03	+.01	-.03	+.17	m(n), 1956
		+.08	+.03	-.01	+.03	-.01	-.23	Δm
HR 483	G2 V	+.06	.00	.00	.00	.00	-.09	m(n), 1957
		-.21	-.14	-.03	-.02	+.05	+.11	m(n), 1956
		+.27	+.14	+.03	+.02	+.05	-.20	Δm
51 Peg	G4 V	+.15	+.05	.00	+.01	-.01	-.11	m(n), 1957
		+.02	-.03	-.01	-.01	-.02	+.10	m(n), 1956
		+.13	+.08	+.01	+.02	+.01	-.21	Δm
Mean Δm (n)		+.15	-.08	+.01	-.03	-.04	-.19	

The mean values of $\Delta m(n)$ from the Table I-6 have been chosen as the appropriate terms to be added algebraically to the six colors for reduction to G2V, and the monochromatic fluxes relative to n = 1.80 are calculated from

$$Z + \Delta m(n) - Z(1.80) = -2.5 \log \frac{H(n)}{H(1.80)} - 2.5 \log \frac{H(1.80)\ G2V}{H(n)\ G2V} \qquad \text{(I-40)}$$

or

$$m(n) = -2.5 \log \frac{H(n)}{H(1.80)} = Z + \Delta m(n) - Z(1.80) - 2.5 \log \frac{H(n)\ G2V}{H(1.80)\ G2V} \qquad \text{(I-41)}$$

where

$$Z(1.80) = -2.5 \log \frac{H(1.80)}{H(1.80)\ G2V}, \qquad \text{(I-42)}$$

and is determined from linear interpolation of the B and G colors,

$$Z(1.80) = B + \left(\frac{B-G}{.34}\right)(1.80-2.08)$$

$$Z(1.80) = 0.176B + 0.824G. \qquad \text{(I-43)}$$

The last term of Eq. I-41 is the monochromatic magnitude of the Sun at the wavenumber n. Values of the solar monochromatic irradiance H_ν (ergs cm^{-2} sec^{-1} cps^{-1}) are given in Table I-7 as calculated from the H_λ (watts/cm^2/micron) data of Goldberg and Pierce (1959). Also tabulated are monochromatic magnitudes calculated by Eq. I-19.

It should be noted that in Eq. I-41 terms of the form $\frac{\Delta H}{H}$ have been dropped. This could lead to a systematic error in the derived monochromatic fluxes; however, these terms will approach zero for stars of solar type, and Whitford's (1958) evaluation finds a maximum of $\frac{\Delta H}{H}$ = 0.03 magnitudes for stars of spectral type B. Thus, it is assumed that any systematic error introduced will be small.

The final reduction equations are as follows:

$$m(2.84) = U - Z(1.80) + 1.673$$
$$m(2.45) = V - Z(1.80) + 0.778$$
$$m(2.08) = B - Z(1.80) + 0.197$$
$$m(1.74) = G - Z(1.80) - 0.018$$
$$m(1.48) = R - Z(1.80) - 0.218$$
$$m(1.09) = I - Z(1.80) - 0.411.$$

TABLE I-7. Solar data derived from the solar energy distribution of Goldberg and Pierce (1959)

Wavenumber (microns^{-1})	Irradiance*	Monochromatic Magnitude	Wavenumber (microns^{-1})	Irradiance*	Monochromatic Magnitude
4.545	.0048	6.525	3.030	.4177	1.685
4.444	.0071	6.111	2.985	.4155	1.691
4.348	.0092	5.831	2.941	.4280	1.659
4.255	.0099	5.743	2.899	.4645	1.570
4.167	.0111	5.620	2.857	.4822	1.530
4.082	.0128	5.468	2.817	.4876	1.517
4.000	.0133	5.425	2.778	.5015	1.487
3.922	.0217	4.897	2.740	.5733	1.342
3.846	.0293	4.570	2.703	.6073	1.279
3.774	.0468	4.061	2.667	.6192	1.258
3.704	.0608	3.778	2.632	.5925	1.306
3.636	.0555	3.877	2.564	.5682	1.351
3.571	.0628	3.743	2.532	.6245	1.249
3.509	.0921	3.327	2.500	.8219	.951
3.448	.1459	2.828	2.469	1.029	.707
3.390	.1829	2.532	2.439	1.088	.646
3.333	.1831	2.581	2.410	1.103	.651
3.279	.2079	2.443	2.381	1.130	.605
3.226	.2436	2.271	2.353	1.139	.597
3.175	.2714	2.154	2.326	1.098	.636
3.125	.2903	2.080	2.299	1.149	.587
3.077	.3594	1.849	2.273	1.311	.444

*in units of 10^{-9} ergs $cm^{-2} sec^{-1} cps^{-1}$

TABLE I-7. Continued

Wavenumber (microns^{-1})	Irradiance*	Monochromatic Magnitude	Wavenumber (microns^{-1})	Irradiance*	Monochromatic Magnitude
2.247	1.420	.357	1.802	1.973	.000
2.222	1.486	.308	1.786	1.988	-.008
2.198	1.512	.289	1.770	2.013	-.022
2.174	1.525	.280	1.754	2.027	-.029
2.151	1.551	.261	1.739	2.062	-.048
2.128	1.599	.228	1.724	2.098	-.067
2.105	1.656	.190	1.709	2.112	-.074
2.083	1.660	.187	1.695	2.137	-.087
2.062	1.593	.232	1.681	2.161	-.099
2.041	1.594	.232	1.667	2.174	-.105
2.020	1.667	.183	1.639	2.197	-.117
2.000	1.651	.193	1.613	2.231	-.134
1.980	1.676	.177	1.587	2.251	-.143
1.961	1.701	.161	1.563	2.268	-.151
1.942	1.672	.180	1.538	2.283	-.159
1.923	1.687	.170	1.515	2.310	-.171
1.905	1.765	.121	1.493	2.321	.176
1.887	1.827	.083	1.471	2.329	-.180
1.869	1.881	.052	1.449	2.350	-.190
1.852	1.926	.026	1.429	2.354	-.192
1.835	1.962	.006	1.408	2.371	-.200
1.818	1.968	.003	1.389	2.369	-.199

*in units of 10^{-9} ergs cm^{-2} sec^{-1} cps^{-1}

TABLE I-7. Continued

Wavenumber (microns^{-1})	Irradiance*	Monochromatic Magnitude	Wavenumber (microns^{-1})	Irradiance*	Monochromatic Magnitude
1.370	2.382	-.205	.400	1.061	.673
1.351	2.375	-.201	.385	1.005	.734
1.333	2.383	-.205	.370	.9484	.795
1.250	2.406	-.216	.357	.8970	.856
1.176	2.417	-.221	.345	.8500	.914
1.111	2.418	-.221	.333	.8046	.974
1.053	2.418	-.221	.323	.7375	1.069
1.000	2.418	-.221	.313	.7310	1.078
.909	2.446	-.233	.303	.6938	1.135
.833	2.406	-.216	.294	.6594	1.190
.769	2.289	-.161	.286	.6252	1.248
.714	2.144	-.091	.278	.6009	1.291
.667	2.004	-.017	.270	.5708	1.346
.625	1.879	.053	.263	.5491	1.389
.588	1.754	.127	.256	.5226	1.442
.556	1.643	.199	.250	.5070	1.475
.526	1.534	.273	.244	.4878	1.517
.500	1.440	.342	.238	.4707	1.556
.476	1.349	.413	.233	.4502	1.604
.455	1.267	.480	.227	.4327	1.647
.435	1.193	.546	.222	.4120	1.700
.417	1.124	.611	.217	.3953	1.745

*in units of 10^{-9} ergs cm^{-2}sec^{-1}cps^{-1}

TABLE J-7. Continued

Wavenumber (microns^{-1})	Irradiance*	Monochromatic Magnitude			
.213	.3758	1.800	.200	.3502	1 877
.208	.3689	1.820	.167	.2522	2.233
.204	.3524	1.870			

*in units of 10^{-9} ergs cm^{-2} sec^{-1} cps^{-1}

7. REDUCTION OF THE INFRARED MAGNITUDES OF JOHNSON (1961), LUNEL (1960), AND MITCHELL AND HANIE (1961) TO MONOCHROMATIC MAGNITUDES

Recently three investigators have published measurements of the infrared magnitudes of stars obtained with relatively narrow bandpass filters. These are the K and L magnitudes of Johnson (1961), the m_x and m_y magnitudes of Mitchell and Hanie (1961, 1961a), and the m_{G+I} and m_{A+G} of Lunel (1960).

The K and L magnitudes were measured at McDonald Observatory with a refrigerated indium antimonide detector using square bandpass interference filters to isolate the two spectral regions. The m_x and m_y magnitudes were obtained at Mt. Wilson Observatory and Perkins Observatory using a cooled plumbide detector and bandpass interference filters. The m_{G+I} and m_{A+G} magnitudes were measured at the Haute-Provence Observatory using a cooled lead sulfide detector; for m_{G+I}, a long wave cut-off interference filter plus a filter composed of germanium, and, for m_{A+G}, a filter composed of alum and gelatin. The constant energy wavenumbers for these magnitudes are given in Table I-8.

TABLE I-8. Constant energy wavenumbers for infrared magnitudes

	K	L	m_x	m_y	m_{A+G}	m_{G+I}
n	.454	.270	.453	.268	.346	.445

The values for m_x, m_y, m_{A+G}, and m_{G+I} were calculated from Eq. I-9, while the values for K and L were obtained from Johnson (1961).

The above magnitudes are on a system such that $(K-L) = (m_x - m_y) = (m_{A+G} - m_{G+I}) = 0$ for an A0V star.

The K and L magnitudes have been reduced to monochromatic magnitudes by reduction to the Sun (Table I-7) and the mean colors of the stars HR 483, β Com, and ζ Her. β Com and ζ Her were considered usable since their effective temperatures, as given by Keenan and Morgan (1951), do not differ appreciably from those of HR 483.

Table I-9 presents this data.

TABLE I-9. Data for reduction of K and L

Star	Spect.	K	K-V	K-L	L-V	T_e(°K)
HR 483	G2 V	3.39	-1.55	-	-	5730
β Com	G0 IV	2.77	-1.53	+.22	-1.75	5750
ζ Her	G0 IV	1.32	-1.50	+.16	-1.66	5750
Mean	-	-	-1.53	+.19	-1.70	-

The reduction equation for K is

$$(K-V) = -2.5 \log \frac{H(.454)}{H(1.80)} + 2.5 \log \frac{H(.454)(A0V)}{H(1.80)(A0V)}, \qquad (I-44)$$

which for a star of solar type becomes

$$2.5 \log \frac{H(.454)(A0V)}{H(1.80)(A0V)} = (K-V)_{\odot} - m(.454)_{\odot} = -2.01.$$

Thus Eq. I-44 becomes

$$m(.454) = (K-V) + 2.01 \qquad (I-45)$$

and similarly for the L magnitude we have

$$m(.270) = (L-V) + 3.05. \qquad (I-46)$$

Examination of Table I-8 reveals that the wavenumbers of m_x, K, and m_{G+I} are very nearly the same, that is, $\bar{n}_0 = 0.450 \pm .005$. Plots of m_x and m_{G+I} versus K, shown in Figures I-7 and I-8, show m_x and m_{G+I} to be linearly related to K. Thus, reduction equations for m_x and m_{G+I} can be derived from Eq. I-45,

$$m(.445) = 0.912 m_{G+I} - V + 2.01 \qquad (I-47)$$

and

$$m(.453) = (m_x - V) + 2.01 \qquad (I-48)$$

for the observations made at Perkins, and

$$m(.453) = (m_x - V) + 2.18 \qquad (I-49)$$

for those made at Mt. Wilson.

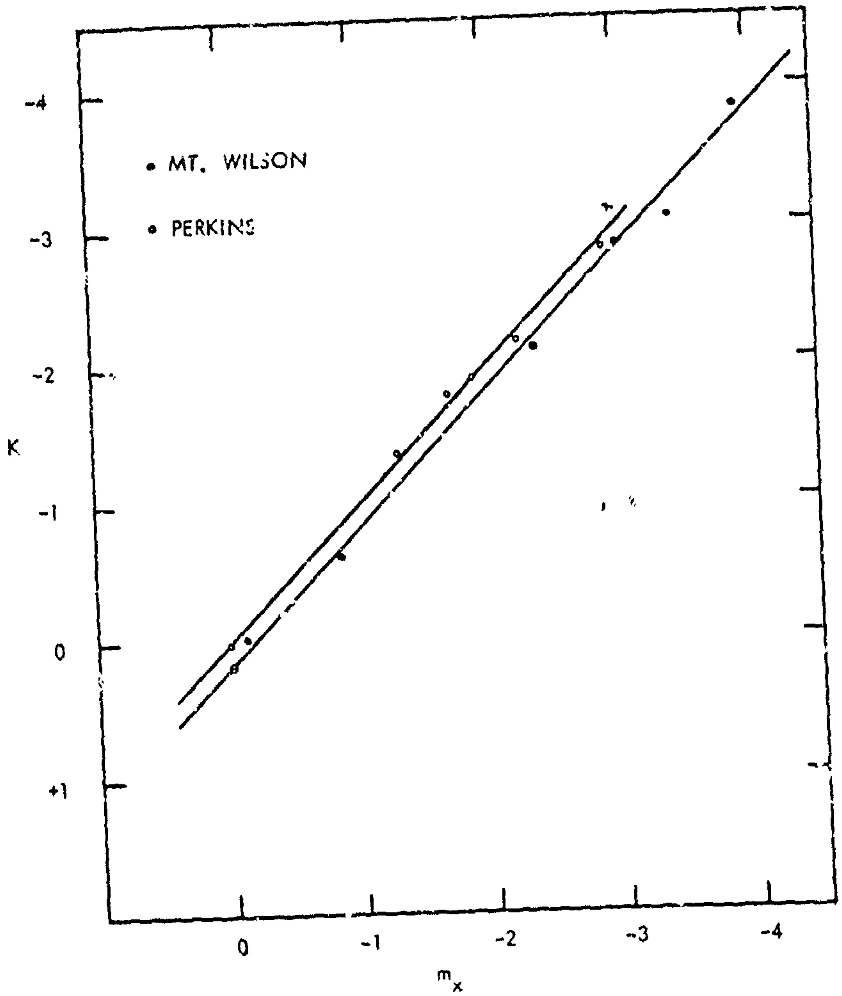

Figure I-7. Comparison of m_x of Mitchell and Hayme with the K Magnitude of Johnson.

In a similar manner, the magnitudes L and m_y may be related (see Table I-8 and Figure I-9), and the following reductions derived for the Mt. Wilson data

$$m\,(.268) = 1.08 m_y - V + 3.20. \tag{I-50}$$

and for the Perkins data

$$m\,(.268) = 0.728 m_y \cdot V + 2.18. \tag{I-51}$$

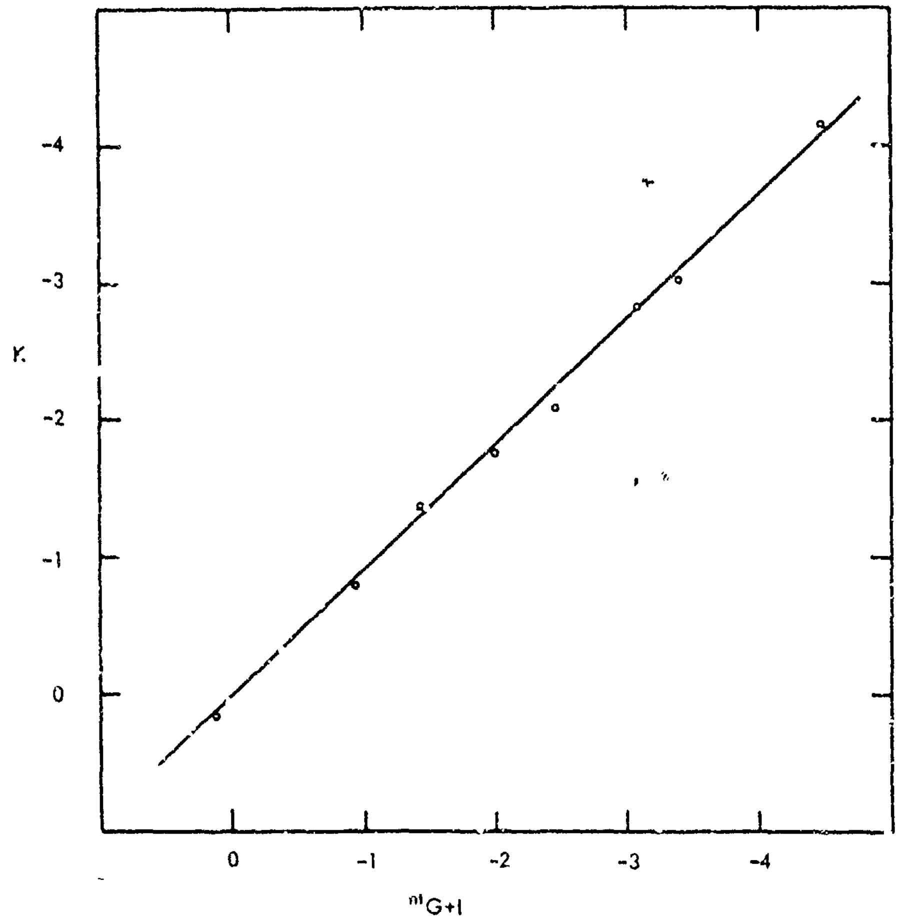

Figure I-8. Comparison of the K Magnitude of Johnson with m_{G+I} of Lu[illegible]

In the case of those stars for which no V magnitude is available on Johnson's system, the V magnitude of Eggen has been used in the reduction equations. Figure I 10 is a plot of V_J versus V_E for the stars considered in this paper. For practical purposes the correlation is one to one.

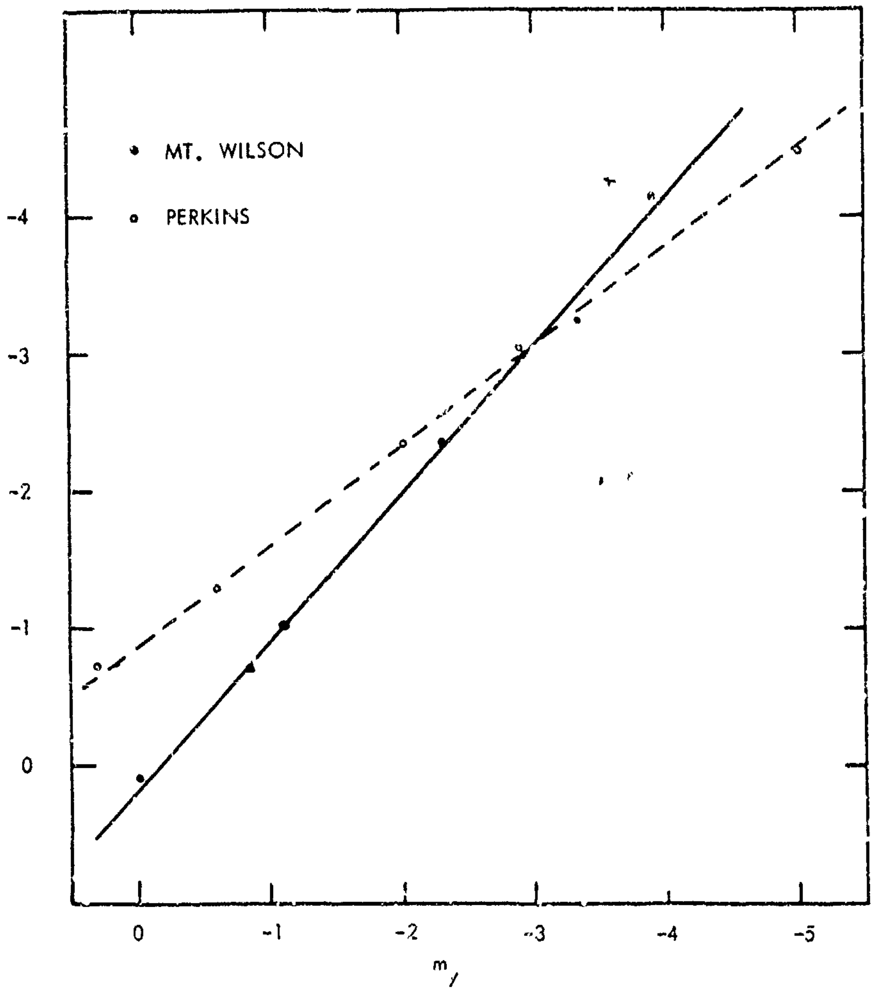

Figure I-9. Comparison of the L Magnitude of Johnson with the m_y Magnitude of Mitchell and Haynie.

The magnitude m_{A+G} may be reduced to a monochromatic magnitude from

$$(m_{A+G} - V) = m(.846) - m(1.80) + \text{Constant} \qquad \text{(I-52)}$$

where the constant may be evaluated from

$$\text{Constant} = (m_{A+G} - V)_{\odot} - m(.846)_{\odot} \qquad \text{(I-53)}$$

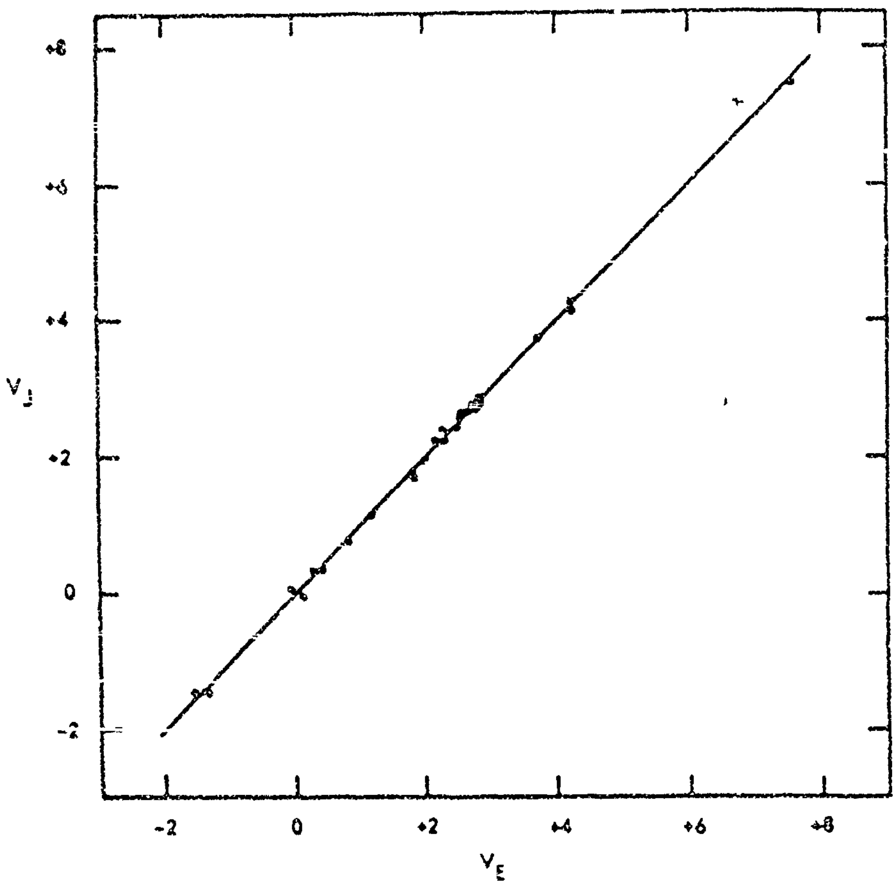

Figure I-10. Comparison of the V Magnitude of Johnson and Morgan with that of Eggen.

The value of the index $(m_{A+G} - V)_{\odot}$ was obtained from Figure 17 of Lunel (1960) and m $(.846)_{\odot}$ was read from Table I-7. The resulting reduction equation is

$$m\,(.846) = (m_{A+G} - V) + 0.776. \qquad \text{(I-54)}$$

As a check on the accuracy of the reductions the same procedure was used for m (.445) to give

$$m\,(.445) = (m_{G+I} - V) + 2.17. \qquad \text{(I-55)}$$

Values of m (.445) calculated from Eq. I-55 agree with those calculated from I-47 to within ± 0.1 magnitude.

Monochromatic magnitudes calculated from the equations developed in this section (Section 7) may be expected to have larger uncertainties than those derived in the previous sections. This is because there are few stars available for transformation of the zero point, thus requiring one to rely heavily on the measured values of one or two stars rather than on mean values. An additional factor contributing to the uncertainty arises through the inability to derive empirical corrections to the flux due to color terms of the type $\frac{\Delta H}{H}$. To properly evaluate the effect of such terms, one will need data taken with a spectrum scanner operating in the infrared region.

8. CONVERSION OF SPECTRAL SCANS TO THE SYSTEM OF CODE

Reduction of the spectral scans of Bonsack and Stock (1957) to that of Code was accomplished by the addition of the magnitudes Δm listed in Table I-10. These values were taken from Table 3, page 111 of the above referenced paper.

TABLE I-10. Corrections to convert the spectral scans of Bonsack and Stock to monochromatic magnitudes of Code

n	Δm	n	Δm	n	Δm
2.04	-.02	2.36	-.22	2.63	-.25
2.08	-.05	2.40	-.22	2.72	-.43
2.12	-.08	2.44	-.23	2.76	-.44
2.16	-.11	2.48	-.24	2.80	-.45
2.20	-.12	2.52	-.27	2.84	-.55
2.24	-.15	2.56	-.25	2.88	-.74
2.28	-.17	2.60	-.26		
2.32	-.19	2.64	-.27		

Reduction of the scanner data of Hall was accomplished by the addition of the magnitudes Δm listed in Table I-11 for each wavelength and reduction by the V magnitude of Johnson. These values were taken from Table 9, page 84 of Code (1960).

The spectral data of Oke (1960) requires no correction, as it is presented on the system of Code.

TABLE I-11. Corrections to convert the spectral scans of Hall to monochromatic magnitudes of Code

Amherst Data			Sproul Data		
λ	n	Δm	λ	n	Δm
.450	2.22	-.12	.456	2.19	-.11
.500	2.00	-.06	.505	1.98	-.06
.550	1.82	-.01	.553	1.81	.00
.600	1.67	+.03	.601	1.66	+.14
.650	1.54	+.22	.649	1.55	+.22
.701	1.43	+.20	.696	1.44	+.29
.751	1.33	+.38	.745	1.34	+.36
.801	1.25	+.50	.794	1.26	+.48
.851	1.18	+.52	.840	1.19	+.51
.881	1.14	+.53	.889	1.12	+.53
			.935	1.02	+.60
			1.032	0.97	+.66

9. COMPUTER PROGRAM FOR THE REDUCTION OF PHOTOELECTRIC COLORS TO MONOCHROMATIC MAGNITUDES

The purpose of the computer program is to facilitate the reduction of the colors and magnitudes, measured on the various photoelectric color systems, to a common system--the monochromatic magnitudes of Code (1960).

Magnitudes and colors are entered on one or more cards for each color system. The cards are coded by placing an integer from 1 to 11 in the second column of the data card, or in the first and second columns if the integer is ten or greater. This integer identifies the color system and determines the type of conversion to be performed. A list of the eleven data codes are as follows:

Code 1. U, B, V data of Johnson and Morgan. Data to be entered in the order U, (B-V), (U-B), K, (K-L)

Code 2. Data of Lunel to be entered in the order m_{A+G}, m_{G+I}

Code 3. Data of Mitchell and Hanie to be entered in the order m_x, m_y

Code 4. Six Color Photometry of Stebbins and Whitford to be entered in the order U, V, B, G, R, I

Code 5. P, V Photometry of Eggen to be entered in the order V. (P-V)

Code 6. R, I Photometry of Kron, and others, to be entered in the order R, (R-I)

Code 7. Amherst data of Hall to be entered in order of decreasing wavenumber

Code 8. Sproul data of Hall to be entered in order of decreasing wavenumber

Code 9. Scanner data of Oke - in order of increasing wavenumber

Code 10. Scanner data of Bonsack and Stock - in order of increasing wavenumber

Code 11. Scanner data of Code - in order of decreasing wavenumber.

Preceeding each set of coded data cards must be a card which identifies the star and the number of magnitude systems (N) to be considered in the calculation for that star. The information entered on this card, the star name, catalogue number, and spectral type is read alphanumerically and stored in BCD for use as page headings in the output record. Any number of stars up to 999 may be included in the input data; however, the first card in the input deck must bear a single integer (NSTARS) equal to the number included.

Any number of combination of data codes may be included for each star; however, if a V magnitude is not entered in either Code 1 or Code 5 no conversion is possible for data of Codes 2, 3, 7, and 8 since these require a V magnitude in the calculation. An additional restriction imposed on the data cards is that the data within each code group be complete. If a magnitude or color is missing or not available, then the value 10.0 must be entered in its place, otherwise the missing magnitude will be interpreted as m = 0.0 and thus an error will result.

Upon reading a data card, the program executes the branch indicated by the data code. The magnitudes are reduced according to the appropriate equations (as previously derived), the corresponding wavenumbers supplied, and the results stored in order of increasing wavenumber. After all the data on a given star have been reduced the monochromatic flux relative to that at n = 1.80 is calculated. The absloute value of the irradiance (ergs cm^{-2} sec^{-1} cps^{-1}) according to Code's (1960) calibration of the V magnitude is also calculated.

The following pages are a listing of the Fortran coded program, which, although compiled in Altac and run on a Philco 2000 computer, is fully compatible with the IBM 7090 with the addition of the appropriate Monitor control cards. Following the program listing is a listing of typical input data cards.

```
C     PROGRAM FOR CONVERSION OF COLORS TO MONOCHROMATIC MAGNITUDES
      DIMENSION XMAG(28),GNU(103),XMON(103),FLX(103),STAR(18),FFLX(103),
     1GGNU(103),NUM(103),V(2),XIR(6),MM(11),ABFLX(103),XXMON(103),
     2AFLX(103)
      READ INPUT TAPE 11,100,NSTARS
  100 FORMAT(I3)
   12 READ INPUT TAPE 11,101,(STAR(I),I=1,3),HD,SPEC,N
  101 FORMAT(3A6,F7.0,1A6,I2)
      NN=N
      K=0
      DO 14 I=1,103
      XXMON(I)=0.0
      FFLX(I)=0.0
      FLX(I)=0.0
      XMON(I)=0.0
      ABFLX(I)=0.0
      AFLX(I)=0.0
   14 NUM(I)=0
      DO 255 I=1,6
  255 XIR(I)=0.0
      DO 32 I=1,2
   32 V(I)=10.0
      JJ=0
      JH=0
      JL=0
      JU=0
   13 DO 256 I=1,28
  256 XMAG(I)=0.0
      READ INPUT TAPE 11,102,M,(XMAG(I),I=1,14)
  102 FORMAT(I2,14F5.2)
      K=K+1
      MM(K)=M
      N=N-1
      GO TO (1,2,3,4,5,6,7,8,9,10,11),M
C     UBV DATA
    1 XMON(41)=0.0
      NUM(41)=1
      XMON(65)=XMAG(2)-0.102
      IF(XMAG(2)-9.0)15,15,16
   15 NUM(65)=1
   16 GNU(65)=2.29
      GNU(41)=1.83
      XMON(100)=1.049*(XMAG(2)+XMAG(3))+0.881
      IF(XMAG(3)-9.0) 17,17,18
   17 NUM(100)=1
   18 GNU(100)=2.89
      V(1)=XMAG(1)
      IF(V(1)-9.0)19,19,20
   20 XIR(1)=XMAG(4)
      JJ=1
```

```
C     JU=1
      XIR(2)=XMAG(5)
      GO TO 200
   19 XMON(5)=(XMAG(4)-XMAG(1))+2.01
      IF(XMAG(4)-9.0)21,21,22
   21 NUM(5)=1
   22 GNU(5)=0.454
      XMON(2)=3.05-(XMAG(5)-XMAG(1)-XMAG(4))
      IF(XMAG(5)-9.0)23,23,24
   23 NUM(2)=1
 24   GNU(2)=0.270
  200 IF(N)201,201,13
C     LUNEL CONVERSION
    2 IF(V(1)-9.0)30,30,31
   31 XIR(3)=XMAG(2)
      JJ=1
      JL=1
      XIR(4)=XMAG(1)
      GO TO 200
   30 XMON(3)=0.912*XMAG(2)+2.01-V(1)
      IF(XMAG(2)-9.0)33,33,34
   33 NUM(3)=1
   34 GNU(3)=0.445
      XMON(6)=(XMAG(1)-V(1))+0.776
      IF(XMAG(1)-9.0)35,35,36
   35 NUM(6)=1
   36 GNU(6)=0.846
      IF(N)201,201,13
C     HANIE CONVERSION
    3 IF(V(1)-9.0)40,40,41
   41 XIR(5)=XMAG(1)
      JJ=1
      JH=1
      XIR(6)=XMAG(2)
      GO TO 200
   40 XMON(4)=(XMAG(1)-V(1))+2.18
      IF(XMON(4)-9.0)42,42,43
   42 NUM(4)=1
   43 GNU(4)=0.453
      XMON(1)=1.08*XMAG(2)+3.20-V(1)
      IF(XMAG(2)-9,0)44,44,45
   44 NUM(1)=_
   45 GNU(1)=0.268
      IF(N)201,201,13
C     6 COLOR CONVERSION
    4 X=0.176*XMAG(3)+0.824*XMAG(4)
      XMON(97)=XMAG(1)+0.15-X+1.523
      IF(XMAG(1)-9.0)50,50,51
   50 NUM(97)=1
   51 GNU(97)=2.84
      XMON(75)=XMAG(2)+0.08-X+0.698
      IF(XMAG(2)-9.0)52,52,53
   52 NUM(75)=1
   53 GNU(75)=2.45
      XMON(52)=XMAG(3)+0.01-X+0.187
      NUM(52)=1
      GNU(52)=2.08
      XMON(36)=XMAG(4)+0.03-X-0.048
      NUM(36)=1
      GNU(36)=1.74
```

```
      XMON(26)=XMAG(5)-0.04-X-0.178
      NUM(26)=1
      GNU(26)=1.48
      XMON(10)=XMAG(6)-0.19-X-0.221
      IF(XMAG(6)-9.0)54,54,55
   54 NUM(10)=1
   55 GNU(10)=1.09
      IF(N)201,201,13
C     P,V DATA,EGGEN CONVERSION
    5 V(2)=XMAG(1)
      IF(XMAG(2)-9.0)57,57,56
    7 XMON(42)=0.195*XMAG(2)-0.003
      NUM(42)=1
      GNU(42)  .89
      XMON(67)=1.163*XMAG(2)-0.014
      NUM(67)=1
      GNU(67)=2.31
   56 IF(N)201,201,13
C     R,I KRON CONVERSION
    6 XMON(17)=0.308-2.23*XMAG(2)
      NUM(17)=1
      GNU(17)=1.21
      XMON(27)=0.106-1.208*XMAG(2)
      NUM(27)=1
      GNU(27)=1.49
      IF(N)201,201,13
C     HALL AMHERST DATA
    7 IF(V(1)-9.0)300,300,301
  301 VV=V(2)
      GO TO 304
  300 VV=V(1)
  304 DO 302 I=1,14
  302 XMAG(I)=XMAG(I)-VV
      XMON(61)=XMAG(I)-0.12
      NUM(61)=1
      GNU(61)=2.22
      XMON(47)=XMAG(2)-0.06
      NUM(47)=2.00
      XMON(40)=XMAG(3)-0.01
      NUM(40)=1
      GNU(40)=1.82
      XMON(33)=XMAG(4)+0.03
      NUM(33)=1
      GNU(33)=1.67
      XMON(29)=XMAG(5)+0.22
      NUM(29)=1
      GNU(29)=1.54
      XMON(24)=XMAG(6)+0.29
      NUM(24)=1
      GNU(24)=1.43
      XMON(21)=XMAG(7)+0.38
      NUM(21)=1
      GNU(21)=1.33
      XMON(18)=XMAG(8)+0.50
      NUM(18)=1
      GNU(18)=1.25
      XMON(15)=XMAG(9)+0.52
      NUM(15)=1
      GNU(15)=1.18
      XMON(13)=XMAG(10)+0.53
```

```
      NUM(13)=1
      GNU(13)=1.14
      IF(N)201,201,13
C     HALL SPROUL DATA
    8 IF(V(1)-9.0)305,305,306
  306 VV=V(2)
      GO TO 307
  305 VV=V(1)
  307 DO 308 I=1,14
  308 XMAG(I)=XMAG(I)-VV
      XMON(58)=XMAG(1)-0.11
      NUM(58)=1
      GNU(58)=2.19
      XMON(46)=XMAG(2)-0.06
      NUM(46)=1
      GNU(46)=1.98
      XMON(39)=XMAG(3)
      NUM(39)=1
      GNU(39)=1.81
      XMON(32)=XMAG(4)+0.14
      NUM(32)=1
      GNU(32)=1.66
      XMON(30)=XMAG(5)+0.22
      NUM(30)=1
      GNU(30)=1.55
      XMON(25)=XMAG(6)+0.29
      NUM(25)=1
      GNU(25)=1.44
      XMON(22)=XMAG(7)+0.36
      NUM(22)=1
      GNU(22)=1.34
      XMON(20)=XMAG(8)+0.48
      NUM(20)=1
      GNU(20)=1.26
      XMON(16)=XMAG(9)+0.51
      NUM(16)=1
      GNU(16)=1.19
      XMON(12)=XMAC(10)+0.53
      NUM(12)=1
      GNU(12)=1.12
      XMON(9)=XMAG(11)+0.60
      NUM(9)=1
      GNU(9)=1.02
      XMON(7)=XMAG(12)+0.66
      NUM(7)=1
      GNU(7)=0.970
      IF(N)201,201,13
C     OKE SCANNER DATA
    9 XMON(34)=XMAG(1)
      NUM(34)=1.
      GNU(34)=1.70
      XMON(37)=XMAG(2)
      NUM(37)=1
      GNU(37)=1.80
      XMON(43)=XMAG(3)
      NUM(43)=1
      GNU(43)=1.90
      XMON(44)=XMAG(4)
      NUM(44)=1
      GNU(44)=1.95
```

```
      XMON(48)=XMAG(5)
      NUM(48)=1
      GNU(48)=2.00
      XMON(50)=XMAG(6)
      NUM(50)=1
      GNU(50)=2.04
      XMON(53)=XMAG(7)
      NUM(53)=1
      GNU(53)=2.09
      XMON(55)=XMAG(8)
      NUM(55)=1
      GNU(55)=2.14
      XMON(59)=XMAG(9)
      NUM(59)=1
      GNU(59)=2.19
      XMON(63)=XMAG(10)
      NUM(63)=1
      GNU(63)=2.24
      XMON(66)=XMAG(11)
      NUM(66)=1
      GNU(66)=2.29
      XMON(69)=XMAG(12)
      NUM(69)=1
      GNU(69)=2.35
      XMON(72)=XMAG(13)
      NUM(72)=1
      GNU(72)=2.40
      XMON(76)=XMAG(14)
      NUM(76)=1
      GNU(76)=2.45
      READ INPUT TAPE 11,102,M,(XMAG(I),I=15,28)
      XMON(79)=XMAG(15)
      NUM(79)=1
      GNU(79)=2.48
      XMON(82)=XMAG(16)
      NUM(82)=1
      GNU(82)=2.56
      XMON(84) XMAG(17)
      NUM(84)=1
      GNU(84)=2.60
      XMON(87)=XMAG(18)
      NUM(87)=1
      GNU(87)=2.65
      XMON(89)=XMAG(19)
      NUM(89)=1
      GNU(89)=2.70
      XMON(92)=XMAG(20)
      NUM(92)=1
      GNU(92)=2.75
      XMON(95)=XMAG(21)
      NUM(95)=1
      GNU(95)=2.80
      XMON(98)=XMAG(22)
      NUM(98)=1
      GNU(98)=2.85
      XMON(101)=XMAG(23)
      NUM(101)=1
      GNU(101)=2.90
      XMON(103)=XMAG(24)
      NUM(103)=1
```

```
      GNU(103)=2.95
      IF(N)201,201,13
C     BONSACK DATA
   10 READ INPUT TAPE 11,102,M,(XMAG(I),I=15,28)
      XMON(49)=XMAG(1)-0.02
      NUM(49)=1
      GNU(49)=2.04
      XMON(51)=XMAG(2)-0.05
      NUM(51)=1
      GNU(51)=2.08
      XMON(54)=XMAG(3)-0.08
      NUM(54)=1
      GNU(54)=2.12
      XMON(56)=XMAG(4)-0.11
      NUM(56)=1
      GNU(56)=2.16
      XMON(60)=XMAG(5)-0.12
      NUM(60)=1
      GNU(60)=2.20
      XMON(62)=XMAG(6)-0.15
      NUM(62)=1
      GNU(62)=2.24
      XMON(64)=XMAG(7)-0.17
      NUM(64)=1
      GNU(64)=2.28
      XMON(68)=XMAG(8)-0.19
      NUM(68)=1
      GNU(68)=2.32
      XMON(70)=XMAG(9)-0.22
      NUM(70)=1
      GNU(70)=2.36
      XMON(73)=XMAG(10)-0.22
      NUM(73)=1
      GNU(73)=2.40
      XMON(74)=XMAG(11)-0.23
      NUM(74)=1
      GNU(74)=2.44
      XMON(77)=XMAG(12)-0.24
      NUM(77)=1
      GNU(77)=2.48
      XMON(80)=XMAG(13)-0.27
      NUM(80)=1
      GNU(80)=2.52
      XMON(81)=XMAG(14)-0.25
      NUM(81)=1
      GNU(81)=2.56
      XMON(85)=XMAG(15)-0.26
      NUM(85)=1
      GNU(85)=2.60
      XMON(86)=XMAG(16)-0.27
      NUM(86)=1
      GNU(86)=2.64
      XMON(88)=XMAG(17)-0.25
      NUM(88)=1
      GNU(88)=2.68
      XMON(90)=XMAG(18)-0.43
      NUM(90)=1
      GNU(90)=2.72
      XMON(93)=XMAG(19)-0.44
      NUM(93)=1
```

```
      GNU(93)=2.76
      XMON(94)=XMAG(20)-0.45
      NUM(94)=1
      GNU(94)=2.80
      XMON(96)=XMAG(21)-0.55
      NUM(96)=1
      GNU(96)=2.84
      XMON(99)=XMAG(22)-0.74
      NUM(99)=1
      GNU(99)=2.88
      IF(N)201,201,13
C     CODES DATA SCANNER
   11 READ INPUT TAPE 11,102,M,(XMAG(I),I=15,28)
      XMON(102)=XMAG(1)
      NUM(102)=1
      GNU(102)=2.94
      XMON(91)=XMAG(2)
      NUM(91)=1
      GNU(91)=2.74
      XMON(83)=XMAG(3)
      NUM(83)=1
      GNU(83)=2.59
      XMON(78)=XMAG(4)
      NUM(78)=1
      GNU(78)=2.48
      XMON(71)=XMAG(5)
      NUM(71)=1
      GNU(71)=2.39
      XMON(57)=XMAG(6)
      NUM(57)=1
      GNU(57)=2.18
      XMON(45)=XMAG(7)
      NUM(45)=1
      GNU(45)=1.98
      XMON(38)=XMAG(8)
      NUM(38)=1
      GNU(38)=1.80
      XMON(35)=XMAG(9)
      NUM(35)=1
      GNU(35)=1.72
      XMON(31)=XMAG(10)
      NUM(31)=1
      GNU(31)=1.65
      XMON(28)=XMAG(11)
      NUM(28)=1
      GNU(28)=1.50
      XMON(23)=XMAG(12)
      NUM(23)=1
      GNU(23)=1.34
      XMON(19)=XMAG(13)
      NUM(19)=1
      GNU(19)=1.25
      XMON(14)=XMAG(14)
      NUM(14)=1
      GNU(14)=1.14
      XMON(11)=XMAG(15)
      NUM(11)=1
      GNU(11)=1.09
      XMON(8)=XMAG(16)
      NUM(8)=1
```

```
      GNU(8)=1.00
      IF(N)201,201,13
  201 CONTINUE
      IF(JJ)70,70,71
   71 IF(V(1)-9.0)64,64,65
   64 V(2)=V(1)
   65 IF(JU)290,290,291
  291 XMON(5)=(XIR(1)-V(2))+2.01
      IF(XIR(1)-9.0)60,60,61
   60 NUM(5)=1
   61 GNU(5)=0.454
      XMON(2)=3.05-(XIR(2)+V(2)-XIR(1))
      IF(XIR(2)-9.0)62,62,63
   62 NUM(2)=1
   63 GNU(2)=0.270
  290 IF(JL)292,292,293
  293 CONTINUE
      XMON(3)=0.912*XIR(3)+2.01-V(2)
      IF(XIR(3)-9.0)66,66,67
   66 NUM(3)=1
   67 GNU(3)=0.445
      XMON(6)=(XIR(4)-V(2))+0.776
      IF(XIR(4)-9.0)68,68,69
   68 NUM(6)=1
   69 GNU(6)=0.846
  292 IF(JH)70,70,295
  295 CONTINUE
      XMON(4)=(XIR(5)-V(2))+2.18
      IF(XIR(5)-9.0)72,72,73
   72 NUM(4)=1
   73 GNU(4)=0.453
      XMON(1)=1.08*XIR(6)+3.20-V(2)
      IF(XIR(6)-9.0)74,74,75
   74 NUM(1)=1
   75 GNU(1)=0.268
   70 CONTINUE
      C=-0.40/0.43429448
      IF(V(1)-9.0)82,82,81
   81 IF(V(2)-9.0)85,85,86
   85 V(1)=V(2)
   82 A=EXPF(C*V(1))
      DO 80 I=1,103
      FLX(I)=EXPF(C*XMON(I))
   80 ABFLX(I)=FLX(I)*3.91E-20*A
      GO TO 87
   86 CONTINUE
      DO 88 I=1,103
   88 FLX(I)=EXPF(C*XMON(I))
   87 CONTINUE
C     SORT ROUTINE
      J=0
      DO 93 I=1,103
      IND=NUM(I)
      IF(IND)93,93,92
   92 J=J+1
      L=J
      XXMON(J)=XMON(I)
      FFLX(J)=FLX(I)
      GGNU(J)=GNU(I)
      AFLX(J)=ABFLX(I)
```

```
   93 CONTINUE
      WRITE OUTPUT TAPE 5,103,(STAR(I),I=1,3),HD,SPEC,(MM(K),K=1,NN)
  103 FORMAT(1H1,10X,3A6,3X,3HHD ,F7.0,3X,1A6,5X,10HDATA CODE ,1114////)
      WRITE OUTPUT TAPE 5,104,(GGNU(I),FFLX(I),XXMON(I),AFLX(I),I=1,L)
 104  FORMAT(//2X,10HWAVENUMBER,16H  FLUX/FLUX(1.8),16H  MONO MAGNITUDE,
     12X,13HH-E/CM2/S/CPS,5X,10HWAVENUMBER,2X,14HFLUX/FLUX(1.8),2X,
     214HMONO MAGNITUDE,2X,13HH-E/CM2/S/CPS///(3X,F5.3,8X,F6.3,10X,F6.3,
     38X E9.3,10X,F5.3,8X,F6.3,10X,F6.3,8X,E9.3))
      NSTARS=NSTARS-1
      IF(NSTARS)95,95,12
   95 CONTINUE
      START TAC
                RUNOUT   $
                JMP      5$
                END TAC  $
      END(
```

```
                    JOB       RUN MAGNCON3  WALKER  C4904X2?5
                    HLT       SCRATCH ON 11
                    REWIND    11
                    RPL       1,DATA,GO
                    TAPE      11
75
ALPHA AND              358. AOF    5
110.0 10.0 10.0 +2.4610.0
4-1.44-1.00-0.48-0.05+0.53+1.11
5 2.13-.235
8 2.04 2.06 2.14 2.12 2.17 2.15 2.23 2.21 2.23 2.29 2.32 2.35 2.40
10 0.00 0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.07 0.07 0.06 0.10 0.13
10 0.26 0.48 0.59 0.80 0.81 0.82 0.37 1.02
BETA AND              6860.MO III 5
2-0.62-2.00
3-1.8 -2.0
410.0 +1.26 0.59 0.01-0.06-1.30
5 2.06 1.51
8 3.30 2.68 2.03 1.62 1.26 0.98 0.57 0.34 0.22 0.03-0.09-0.22-0.39
GAMMA AND           12533.K2 III 3
3-0.8 -1.0
4 1.36 0.61 0.34-0.02-0.32-0.69
5 2.3010.0
DELTA AND             3627.K3 III 3
3 0.6  0.7
410.0  0.83 0.35-0.02-0.33-0.68
5 3.25 1.20
ALPHA AQL           187642.A7 IV  6
1  .75  .23  .07 0.25  .06
310.0 -0.9
4-0.54-0.62-0.30-0.01 0.31 0.68
5 0.82 0.10
6 0.76 0.02
8 1.01 0.88 0.78 0.73 0.69 0.65 0.61 0.54 0.54 0.54 0.52 0.54 0.45
GAMMA AQL           186791. K3 II 4
3-1.0 -0.9
410.0  1.17 0.47-0.01-0.46-0.91
5 2.64 1.44
8 4.07 3.22 2.71 2.3. 1.99 1.75 1.55 1.35 1.24 1.06 1.02 0.92 0.74
ALPHA ARI             12929.K2 III 5
1 1.99 1.15 1.12-0.61 0.12
3-0.6 -0.8
4 1.40 0.64 0.25 0.00-0.25-0.52
8 2.85 2.39 1.97 1.67 1.42 1.24 1.11 0.91 0.06 0.75 0.66 0.54 0.40
5 2.00 1.08
ALPHA AUR           34029.G8 III 6
1 0.09 0.80 0.49-1.78 0.06
2-1.24-2.00
3-1.7 -2.2
4 0.37 0.14 0.08-0.03-0.05-0.08
6-2.5  0.28
8 0.21 0.38 0.10-0.15-0.30-0.47-0.57-0.71-0.75-0.81-0.86-0.80-1.03
BETA AUR            40183. A2 IV 4
1 1.90 0.03 0.06 1.94100
4-0.72-0.84-0.40-0.06 0.45 0.91
 7 1.96 1.97 1.92 1.94 1.91 1.89 1.90 1.87 1.90 1.89
10 0.00 0.01 0.01 0.02 0.06 0.07 0.06 0.08 0.10 0.12 0.13 0.13 0.17 0.28
10 0.47 0.84 1.34 1.51 1.61 1.63 1.76 2.00
```

Appendix II: Definition of Terms and Reduction of Some Astronomical Quantities to Absolute Energy Units

The monochromatic flux F_ν at the surface of a star is the amount of radiant energy passing through a unit area of stellar surface in unit time and per unit frequency interval. The flux then has the dimensions of ergs cm^{-2} sec^{-1} cps^{-1} or watts cm^{-2} cps^{-1}. The total flux or integrated flux F is then defined

$$F = \int_0^\infty F_\nu \, d\nu \qquad \text{(II-1)}$$

For the case of a blackbody radiator at a temperature T (°K) the flux F_{BB} is given by Stefan's law

$$F_{BB} = \sigma T^4 \qquad \text{(II-2)}$$

where σ is the Stefan - Boltzman constant.

The effective temperature T_e of a star is defined as the temperature of a blackbody which radiates the same amount of integrated flux as the star, that is

$$F = \sigma T_e{}^4 \qquad \text{(II-3)}$$

The luminosity L of a star is the total amount of energy radiated by the star and is obtained from integration of the flux over the area of the star. L has the dimensions, ergs per second or watts. For the case of a spherical star of radius R_* the luminosity is given by

$$L = 4\pi R_*^2 F = 4\pi R_*^2 \sigma T_e^4 \qquad \text{(II-4)}$$

The monochromatic irradiance H_ν of a surface by stellar radiation is the flux at a distance R from the star. For $R >> R_*$, H_ν is given by

$$H_\nu = F_\nu \left(\frac{R_*}{R}\right)^2 \qquad \text{(II-5)}$$

and the integrated or total irradiance is

$$H = \int_0^\infty H_\nu \, d\nu = \left(\frac{R_*}{R}\right)^2 \int_0^\infty F_\nu \, d\nu \qquad \text{(II-6)}$$

Substituting Eq. II-6 into Eq. II-4, one obtains the luminosity in terms of the irradiance

$$L = 4\pi R^2 \int_0^\infty H_\nu \, d\nu \qquad \text{(II-7)}$$

The apparent bolometric magnitude m_{bol} is just the integrated irradiance expressed on a magnitude scale, that is

$$m_{bol} = -2.5 \log \int_0^\infty H_\nu \, d\nu + C_1 \qquad \text{(II-8)}$$

where C_1 is a constant establishing the zero point of the magnitude system.

The absolute bolometric magnitude M_{bol} is the apparent bolometric magnitude of the star at a distance of 10 parsecs from the star (1 pc = 3.0857×10^{18} cm) and may be found from the relation

$$M_{bol} = m_{bol} - 5 \log R + 5 \qquad \text{(II-9)}$$

where here R is the distance to the star in parsecs. Thus,

$$M_{bol} = -2.5 \log \int_0^\infty H_\nu \, d\nu - 5 \log R + 5 + C_1 \qquad \text{(II-10)}$$

Direct observation of m_{bol} with earth-fixed instrumentation is not possible since a determination of m_{bol} requires the measurement of the monochromatic irradiance at all frequencies. The earth's atmosphere is opaque to radiation of all but a few narrow frequency bands. Oxygen and ozone strongly absorb radiation at wavelengths shorter than about 3000 Å, while water vapor and carbon dioxide obscure large regions in the infrared region of the spectrum.

Consider now a magnitude measured in a finite frequency interval and, in particular, consider the frequency interval and detector response which defines the V magnitude of Johnson and Morgan (see Appendix I) ,

$$V = -2.5 \log \int_0^\infty S_\nu H_\nu d\nu + C_2 \qquad \text{(II-11)}$$

where S_ν is the normalized response of the system as given by Johnson and Morgan (1953) and C_2 is a constant which determines the zero point of the system. Let us now define the bolometric correction B. C. by the following relation

$$B.C. = m_{bol} - V \qquad \text{(II-12)}$$

then by substitution of Eq. II-8 and II-11 into Eq. II-12 and setting $C_3 = C_1 - C_2$ we have

$$B.C. = -2.5 \log \left[\frac{\int_0^\infty H_\nu \, d\nu}{\int_0^\infty S_\nu H_\nu \, d\nu} \right] + C_3 \qquad \text{(II-13)}$$

Thus, the bolometric correction is the ratio of the total irradiance to that measured with the response S_ν expressed on a magnitude scale.

With the aid of well-determined data on the sun we may now determine the values of the constants C_1, C_2, and C_3. The bolometric correction for the sun, B. C. $(\odot)$, has been arbitrarily set at -0.07 (see text) . The V magnitude of the sun, $V_\odot$, has been determined by Martynov (1959) from the data of Stebbins and Kron (1957) to be -26.80 $\pm$ 0.03. By substituting these values into Eq. I-12 we obtain the apparent bolometric magnitude of the sun $m_{bol}(\odot) = -26.87$.

For the sun

$$\int_0^\infty H_\nu \, d\nu = \text{solar constant} = 0.135 \text{ watts/cm}^2 \qquad \text{(II-14)}$$

and by substitution into Eq. II-8 we obtain $C_1' = -29.04$. From Eq. II-9 we may obtain $M_{bol}(\odot) = +4.70$, where the quantity 5-5 log R = 31.57.

The constant C_2 may be evaluated from Eq. II-13, that is

$$C_2 = 2.5 \log \int_0^\infty S_\nu H_\nu d\nu - 2.5 \log \int_0^\infty H_\nu d\nu - 29.04 - B.C.(\odot) \quad \text{(II-15)}$$

expanding $\int_0^\infty S_\nu H_\nu d\nu$ about the effective frequency $H_{\nu o}$ as in Appendix I and converting the wavelength units by the relation $H_\lambda = \frac{c}{\lambda^2} H$ (where c is the velocity of light) one obtains

$$C_2 = 2.5 \log \frac{H_{\lambda o}}{\int_0^\infty H_\lambda d\lambda} + 2.5 \log \int_0^\infty S_\lambda d\lambda - 28.97 \quad \text{(II-16)}$$

From the solar spectrum of Goldberg and Pierce (1959) we obtain $H_{\lambda o} = 0.1916$ watts cm^{-2} $microns^{-1}$ where $\lambda_o = 0.556$ microns, and from graphical integration of the response curve given by Johnson and Morgan (1953) and Johnson (1955) we obtain

$$\int_0^\infty S_\lambda d\lambda = 0.0866 \text{ microns.} \quad \text{(II-17)}$$

Substitution of these values into Eq. II-16 yields $C_2 = -31.22$ and $C_3 = 2.18$ Thus, the relations between Eqs. II-8, II-10, II-11, and II-13 become

$$m_{bol} = -2.5 \log \int_0^\infty H_\nu d\nu - 29.04$$

$$M_{bol} = -2.5 \log \int_0^\infty H_\nu d\nu - 5 \log R - 24.04$$

$$B.C. = 2.5 \log \frac{\int_0^\infty H_\nu d\nu}{\int_0^\infty S_\nu H_\nu d\nu} + 2.18$$

$$V = -2.5 \log \int_0^\infty S_\nu H_\nu d\nu - 31.22$$

and in terms of the monochromatic irradiance at $\lambda_o = 0.556$ microns

$$V = -2.5 \log H_{\lambda o} - 28.59 \quad \text{(II-18)}$$

where $H_{\lambda o}$ has the units watts cm^{-2} $microns^{-1}$, and the integrated quantities, the units of watts cm^{-2}.

Willstrop (1958) obtained a calibration of the V magnitude from comparison of the monochromatic irradiance at λ 5400 Å from a large number of stars to that from a calibrated standard lamp. His measurements indicated that for a star of V = 0.0, $H_{\lambda o} = 3.8 \times 10^{-12}$ watts cm^{-2} $micron^{-1}$. From Eq. II-18 we calculate for

$V = 0.0$, $H_{\lambda o} = 3.72 \times 10^{-12}$ watts cm^{-2} $microns^{-1}$, a value 2 percent smaller. This difference reflects the uncertainty in the value of $V_{\odot}$ and the solar constant.

From a rearrangement of the above equations, a number of useful relations may be derived:

$$\log H_{\lambda o} = -0.4 V - 11.43 \tag{II-19}$$

$$\log \int_0^\infty H_\nu \, d\nu = -11.62 - 0.4 (V + B.C.) \tag{II-20}$$

$$\log \int_0^\infty S_\nu H_\nu \, d\nu = -0.4 V - 12.49 \tag{II-21}$$

and for $m_{bol} = 0.0$,

$$\int_0^\infty H_\nu \, d\nu = 2.46 \times 10^{-12} \text{ watts cm}^{-2} \tag{II-22}$$

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