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ASTRONOMICAL MEASUREMENTS IN THE INFRARED[1]

By Harold L. Johnson

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona

Introduction

During recent years there has been more and more emphasis upon astronomical measurements in the infrared. To a great extent, this increased emphasis has been stimulated by recent detector developments, which have produced detectors capable of making the difficult long-wavelength observations. Baum (1) has reviewed the characteristics of photosensitive devices, including infrared detectors. He discussed the spectral responses and sensitivities of most of the available detectors and, rather than dissert upon this subject here, we refer the reader to Baum's article.

For the purposes of this discussion, we will divide the infrared spectrum as follows:

(*a*) The Near Infrared, from the visible region to approximately 1 μ. This region corresponds to the wavelength sensitivity range of photomultipliers having S-1 cathodes.

(*b*) The Intermediate Infrared, covering the range of wavelengths from 1 μ to 4 μ, approximately. This region corresponds to the wavelength range for optimum sensitivity of lead sulfide photoconductive cells, cooled by liquid nitrogen.

(*c*) The Far Infrared, covering the range of wavelengths from 4 μ to 22 μ, approximately. There are several newly developed detectors that are sensitive in this spectral region, but the most sensitive is the liquid helium-cooled germanium bolometer developed by F. J. Low (2).

Wavelengths longer than approximately 22 μ will not, for the purposes of the present discussion, be considered as belonging to the infrared, although Low (3) has used his germanium bolometer to make astronomical measurements at 1 mm.

A Survey of Infrared Astronomical Observations

Among the first observers to make astronomical infrared measurements were Pettit & Nicholson (4), whose thermoelectric observations included much stellar radiation in the Intermediate Infrared and a small contribution from the Far Infrared. Until very recently, their data were the observational basis of our knowledge of the bolometric corrections and effective temperatures of stars other than the Sun. About 1950, Fellgett (5) made stellar observations in the Intermediate Infrared, using a lead sulfide cell; Whitford (6, 7) used the same type of detector to make observations of the infrared characteristics of interstellar extinction.

[1] The survey of literature for this review was concluded January 1, 1966.

The year 1963 saw the first publication of photometric data confined entirely to Far Infrared wavelengths longer than 4 μ. Murray & Wildey (8) made stellar and planetary observations through the 8–14 μ atmospheric window and Johnson & Mitchell (9) published the first stellar observations through the 4.4–5.5 μ window. Two years later, the first stellar observations through the 20 μ window were published by Johnson, Low & Steinmetz (10).

While it certainly is not trivial, it will be mentioned only in passing that ground-based infrared astronomical measures can be made only through the several atmospheric windows. Some infrared spectral regions, such as those around 1.8 μ, 2.8 μ, 6.5 μ, and beyond 22 μ, are closed to ground-based observations because of the very great atmospheric absorption. Observations must be planned around this restriction, but it is now plain that probably 75 per cent of the astronomical infrared data that we would like to have can be obtained from good ground-based observing sites.

Observations in both the Intermediate and Far Infrared, bearing upon the problem of interstellar extinction, have been published by Johnson & Borgman (11) and Johnson (12, 13). Their interpretation of the long-wavelength data is not compatible with the earlier conclusion (7), based upon more limited data, that the interstellar extinction law is everywhere the same. Instead, the ratio of total-to-selective extinction, $R = A_V/E_{B-V}$, may be generally about 3.5 with regional excursions to much higher values, mostly (but not exclusively) in the vicinities of very hot stars. Furthermore, the details of the extinction curves in the infrared do not fit well with the computations of van de Hulst (14). Our current knowledge of the interstellar extinction problem has recently been summarized (13) and is not repeated here.

Another field of stellar astronomy to which modern infrared measures have made a significant contribution is that of bolometric corrections and effective temperatures; this is the field in which Pettit & Nicholson (4) made their classic contribution 37 years ago. Two analyses (15, 16) of modern infrared photometry in terms of the colors, bolometric corrections, and effective temperatures of stars have been published. At the University of Arizona, we have just this fall (1965) completed a large program of multicolor photometry of the brighter stars, and revision of the earlier work on bolometric corrections and effective temperatures is now in order. The new observational data, which cover the range of wavelength from 0.36 μ to 3.4 μ for nearly 1000 stars, are now being prepared for publication (17) and should be available by the time this chapter appears in print. The data are on the multicolor photometric system defined by Johnson (16); this system comprises ten wide-band magnitudes as follows: U (0.36 μ), B (0.44 μ), V (0.55 μ), R (0.70 μ), I (0.90 μ), J (1.25 μ), K (2.2 μ), L (3.4 μ), M (5.0 μ), and N (10.2 μ); the effective wavelength of each magnitude is indicated in parentheses following the letter-name of the band. The remainder of this chapter deals with the interpretation of the new data in terms of the intrinsic colors, bolometric corrections, and effective temperatures of stars.

The Intrinsic Colors

The first step in the computation of bolometric corrections and effective temperatures of stars of the various spectral types was the derivation of the mean intrinsic colors corresponding to these types. The procedures were much like those employed before (16), but they are nevertheless described here in some detail.

The lists of Johnson, Mitchell & Iriarte (17) contain 225 stars of luminosity class III with spectral types ranging from G5 to M6. These data were examined carefully to see whether there is a significant correlation of the observed colors with apparent magnitude (and therefore distance). With the exception of a few of the faintest stars, there is no indication that these giants of class III are significantly affected by interstellar reddening. For example, the stars of each spectral type were divided into two groups: those for which V is brighter than 4.1, and those fainter than this magnitude. For some spectral types (K1, K2, K3), the mean colors of the fainter group were slightly redder than those of the brighter group; on the other hand, for other types (K5, M0, M3), the fainter group was slightly bluer. The remaining types showed no significant difference in color between the two groups, and the mean difference for all giant types was zero. From this and other analyses, it was concluded that the stars used in forming the mean giant colors are all reddened by the same amount, regardless of distance, and that this reddening is most likely zero.

This result accords with that of Eggen (18), who showed that, for the B- and A-type stars he investigated, there is no evidence of interstellar reddening out to distances of 50 to 100 parsecs from the Sun. Kron (19) has also noted the evidence that these giants are not significantly reddened; he also pointed out that the fact that Stebbins & Kron (20) found the Sun to have the same color as much more distant stars of the same spectral type makes it unlikely that the Sun is enclosed in a small ball of reddening material. We assumed that simple averages of the observed colors are satisfactory for the giants; the mean values, smoothed somewhat for the later types, are given in Table I. The first column gives the spectral type and the second through eighth columns, the mean data derived as described above.

We do not have enough observational data to apply this procedure to magnitudes M and N. Instead, the data published by Low & Johnson (21), Wildey & Murray (22), and Mendoza & Johnson (23, 24), plus additional unpublished data, were used to derive the mean relationships between $K-M$ and $V-K$ and between $K-N$ and $V-K$. The $K-M$ diagram is quite good with relatively little scatter ($\pm$.08 mag, maximum range) but $K-N$ has more scatter, undoubtedly as a result of the much greater difficulty of making observations at N. In neither $K-M$ nor $K-N$ is there evidence for intrinsic differences among stars of luminosity class III, and values derived from the mean curves, added to $V-K$, have been entered in columns 9 and 10 of Table I. The bolometric corrections and effective temperatures in the last two columns of this table will be explained later.

The mean colors of main-sequence stars later than A0 may be derived by similar procedures since they are nearer to the Sun than are the giants and are therefore unlikely to be appreciably reddened. The Hyades main-sequence stars have been adopted by several investigators as "standard" stars of their types and it was convenient to start with them in this analysis. The photometry of Johnson & Knuckles (25) and Mendoza (26), and the new spectral classifications of Morgan & Hiltner (27), provide accurate spectral types and *UBVRI* photometry for Hyades main-sequence stars from A3 to K4. The mean intrinsic *UBVRI* colors for spectral types A5 to K2, given in Table II, depend upon the Hyades data; except for *U–V*, the listed values do not differ significantly from those for the general field dwarfs. The principal cause of the difference in *U–V* between the Hyades and the general field dwarfs is differing stellar chemical compositions, and investigations of the composition of individual stars should be possible using our data.

The mean values of *V–J*, *V–K*, *V–M*, and *V–N* for main-sequence stars were derived from the data for the general field stars, since very few Hyades dwarfs have been observed at the longer wavelengths. The tabulated values were derived from plots of *V–J*, for example, against *V–I* for the field stars; they also depend upon plots of the color indices against spectral types. Thus, the *JKLMN* means were not derived from the same stars as the *UBVRI* data, but the fact that *B–V*, *V–R*, and *V–I* are practically identical for the Hyades and the field stars indicates that the longer-wavelength mean values should apply also to the Hyades stars. It should be noted here, however, that a few well-observed stars (for example, α CMa) deviate significantly from the mean values in Table II. This is a point that should be kept in mind —while, generally speaking, most stars of a given spectral type are similar over the wide range of wavelength, there is good evidence of differences from the mean values for individual stars.

TABLE I

GIANT STARS

Sp (III)	*U–V*	*B–V*	*V–R*	*V–I*	*V–J*	*V–K*	*V–L*	*V–M*	*V–N*	B.C.	T_e (°K)
G5	+1.55	+0.92	+0.69	+1.17	+1.52	+2.08	+2.18	+2.02	+2.05	−0.20	5010
G8	+1.64	+0.95	+0.70	+1.18	+1.56	+2.16	+2.27	+2.09	+2.12	−0.21	4870
K0	+1.93	+1.04	+0.77	+1.30	+1.71	+2.35	+2.47	+2.25	+2.28	−0.30	4720
K1	+2.13	+1.10	+0.81	+1.37	+1.80	+2.48	+2.61	+2.36	+2.39	−0.36	4580
K2	+2.32	+1.16	+0.84	+1.42	+1.87	+2.59	+2.73	+2.45	+2.48	−0.42	4460
K3	+2.74	+1.30	+0.96	+1.61	+2.12	+2.92	+3.07	+2.75	+2.80	−0.59	4210
K4	+3.07	+1.41	+1.06	+1.81	+2.36	+3.24	+3.39	+3.05	+3.11	−0.79	4010
K5	+3.34	+1.54	+1.20	+2.10	+2.71	+3.67	+3.83	+3.47	+3.54	−1.08	3780
M0	+3.43	+1.55	+1.23	+2.17	+2.82	+3.79	+3.96	+3.59	+3.65	−1.17	3660
M1	+3.48	+1.56	+1.28	+2.27	+2.90	+3.92	+4.09	+3.72	+3.78	−1.25	3600
M2	+3.51	+1.59	+1.34	+2.44	+3.08	+4.11	+4.29	+3.91	+3.97	−1.41	3500
M3	+3.51	+1.60	+1.48	+2.79	+3.51	+4.58	+4.77	+4.39	+4.45	−1.80	3300
M4	+3.32	+1.59	+1.74	+3.39	+4.26	+5.24	+5.44	+5.10	+5.14	−2.44	3100
M5	+3.00	+1.55	+2.18	+4.14	+5.04	+6.06	+6.31	+6.00	+6.00	−3.23	2950
M6	+2.43	+1.54	+2.80	+5.06	+5.86	+7.01	+7.39			−4.15	2800

TABLE II

THE MAIN SEQUENCE

Sp (V)	U–V	B–V	V–R	V–I	V–J	V–K	V–L	V–M	V–N	B.C.	T_e (°K)
O5–7	−1.46	−0.32	−0.15	−0.47	−0.73	−0.94	−1.01	—	—	—	—
O8–9	−1.44	−0.31	−0.15	−0.47	−0.73	−0.94	−1.01	—	—	—	—
O9.5	−1.40	−0.30	−0.14	−0.46	−0.73	−0.94	−1.00	—	—	—	—
B0	−1.38	−0.30	−0.13	−0.42	−0.70	−0.93	−0.99	—	—	−2.27	26500
B0.5	−1.29	−0.28	−0.12	−0.39	−0.66	−0.88	−0.93	—	—	−1.92	24500
B1	−1.19	−0.26	−0.11	−0.36	−0.61	−0.81	−0.86	—	—	−1.59	21500
B2	−1.10	−0.24	−0.10	−0.32	−0.55	−0.74	−0.77	—	—	−1.31	18000
B3	−0.91	−0.20	−0.08	−0.27	−0.45	−0.61	−0.63	—	—	−1.00	15500
B5	−0.72	−0.16	−0.06	−0.22	−0.35	−0.47	−0.48	—	—	−0.70	13800
B6	−0.63	−0.14	−0.06	−0.19	−0.30	−0.41	−0.41	—	—	−0.56	12900
B7	−0.54	−0.12	−0.04	−0.17	−0.25	−0.35	−0.34	—	—	−0.48	12200
B8	−0.39	−0.09	−0.02	−0.12	−0.17	−0.24	−0.22	—	—	−0.30	11300
B9	−0.25	−0.06	0.00	−0.06	−0.09	−0.14	−0.11	—	—	−0.14	10600
A0	0.00	0.00	+0.02	0.00	−0.01	−0.03	0.00	−0.03	−0.03	−0.01	9850
A2	+0.12	+0.06	+0.08	+0.09	+0.11	+0.13	+0.16	+0.13	+0.13	+0.08	9120
A5	+0.25	+0.14	+0.16	+0.22	+0.27	+0.36	+0.40	+0.36	+0.36	+0.13	8260
A7	+0.30	+0.19	+0.19	+0.28	+0.35	+0.46	+0.52	+0.46	+0.46	+0.13	7880
F0	+0.37	+0.31	+0.30	+0.47	+0.58	+0.79	+0.86	+0.79	+0.79	+0.11	7030
F2	+0.39	+0.36	+0.35	+0.55	+0.68	+0.93	+1.07	+0.93	+0.93	+0.09	6700
F5	+0.43	+0.43	+0.40	+0.64	+0.79	+1.07	+1.25	+1.07	+1.07	+0.06	6400
F8	+0.60	+0.54	+0.47	+0.76	+0.96	+1.27	+1.45	+1.27	+1.27	+0.04	6000
G0	+0.70	+0.59	+0.50	+0.81	+1.03	+1.35	+1.53	+1.35	+1.35	0.00	5900
G2	+0.79	+0.63	+0.53	+0.86	+1.10	+1.44	+1.61	+1.44	+1.44	0.00	5770
G5	+0.86	+0.66	+0.54	+0.89	+1.14	+1.49	+1.67	—	—	−0.02	5660
G8	+1.06	+0.74	+0.58	+0.96	+1.24	+1.63	+1.85	—	—	−0.06	5440
K0	+1.29	+0.82	+0.64	+1.06	+1.38	+1.83	+2.00	—	—	−0.12	5240
K2	+1.60	+0.92	+0.74	+1.22	+1.57	+2.15	+2.24	—	—	−0.23	4960
K5	+2.18	+1.15	+0.99	+1.62	+2.04	+2.75	+2.84	—	—	−0.55	4400
K7	+2.52	+1.30	+1.15	+1.93	+2.36	+3.21	+3.40	—	—	−0.82	4000
M0	+2.67	+1.41	+1.28	+2.19	+2.71	+3.60	+3.78	—	—	−1.10	3750
M1	+2.70	+1.48	+1.40	+2.45	+3.06	+3.95	+4.15	—	—	−1.38	3600
M2	+2.69	+1.52	+1.50	+2.69	+3.37	+4.27	+4.47	—	—	−1.64	3400
M3	+2.70	+1.55	+1.60	+2.94	+3.66	+4.57	+4.79	—	—	−1.85	3300
M4	+2.70	+1.56	+1.70	+3.19	+3.97	+4.87	+5.20	—	—	−2.17	3200
M5	+2.80	+1.61	+1.80	+3.47	+4.28	+5.17	(+5.54)	—	—	−2.48	3100
M6	+2.99	+1.72	+1.93	+3.76	+4.63	+5.58	(+6.03)	—	—	−2.82	2950
M7	+3.24	+1.84	+2.20	+4.20	+5.20	+6.18	—	—	—	−3.35	(2850)
M8	(+3.50)	(+2.00)	(+2.50)	(+4.70)	(+5.80)	(+6.75)	—	—	—	−3.9	(2750)

The mean values for stars later than K2 V were derived from stars of the general field (28) by the same procedures used for the earlier types.

The intrinsic colors of stars earlier than about A0 were derived by the method used by Johnson & Borgman (11) and illustrated in Figure 1, in which are plotted the observed *V–I* and *B–V* colors for O and B0 stars. As Johnson & Borgman remarked, the wedge-shaped distributions of the points in such diagrams must be due to variations of the interstellar reddening law; they imply also that the intrinsic colors of the stars are identical and equal to the values at the apices of the wedges. We did not have sufficient data to perform this analysis for each individual early spectral type but, when we assumed that the intrinsic colors vary smoothly with spectral

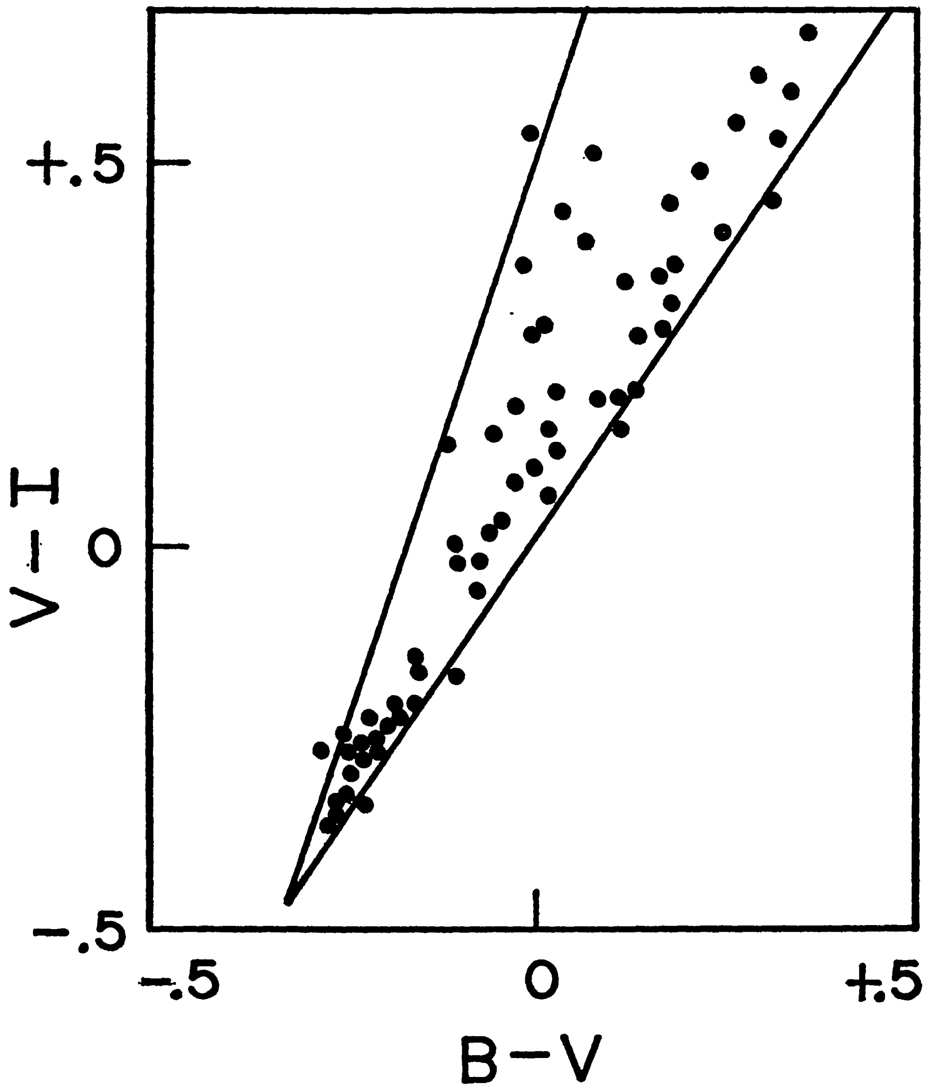

FIG. 1. $V-I$ versus $B-V$ for O and B0 stars.

type, we obtained the mean intrinsic colors listed in Table II. The values of $V-L$ in this table are smaller (more negative) than those given earlier (12, 13) but the new values were indicated by the plot of $K-L$ versus $B-V$, analyzed like Figure 1; they also are in accord with those expected from black bodies of the appropriate temperatures. The bolometric corrections and effective temperatures in the last two columns are discussed below.

Next, we turn to the supergiants of luminosity class I. Unfortunately, almost all supergiants are affected by interstellar reddening, and the simple procedure that was adopted for luminosity class III cannot be used. Nevertheless, it was possible to derive reasonably accurate intrinsic colors for these stars by taking advantage of the facts that "temperature reddening" and interstellar reddening have different effects upon the several color indices [this was the method used by Kron (19) to derive his supergiant and

Cepheid intrinsic colors], and that the law of interstellar reddening is not everywhere the same (see Figure 1). The procedures are, by now, fairly standard and we do not discuss the matter further here; the results of the computations are given in Table III. Because of the uncertainty introduced by the corrections for interstellar reddening, the intrinsic colors for supergiants are less accurate than those for the lower luminosity classes. Since the values in Table III have been smoothed, there might be systematic errors affecting several adjacent tabular values. The derivation of the bolometric corrections and effective temperatures is described in the next two sections of this chapter.

Bolometric Corrections

The next step in the determination of bolometric corrections was the establishment of an absolute calibration of the photometric system. The most recent and most reliable calibration (29) is reproduced in Table IV. The effective wavelengths are those defined by Strömgren (30) and King (31); photometry through the wide-band filters approximates the results of narrow-band filters centered at these effective wavelengths.

If we assume that there are no unknown or unusually strong spectral features, such as water-vapor bands, in the spectral regions inaccessible because of atmospheric absorption, we can integrate numerically under the derived absolute energy curves and obtain the total fluxes reaching the Earth. However, water-vapor bands have been observed (32) in the spectra of late-type stars and their influence upon the integrations cannot be neglected. Furthermore, a "transparency peak" occurs in late-type stars at about 1.6 μ. The corrections to be made to the simple numerical integrations to account for the effects of these infrared spectral features were evaluated by planimetric integrations of the observed infrared spectra (32). The corrections required are small, typically 0.1 mag or less, and their application results in total fluxes that probably are accurate within 2 or 3 per cent.

The bolometric correction B.C. is defined as $m_{\text{bol}} - V$, and is the correction to be applied to the V magnitude to obtain the apparent bolometric magnitude. The zero-point has been set so that B.C. = 0.00 for the Sun. For stars cooler than the Sun, the values of B.C. were computed as indicated and are listed in the next-to-last columns of Tables I, II, and III. This procedure is valid for these stars, which radiate a negligible portion of their output at wavelengths shorter than 0.3 μ, the atmospheric limit.

Before we could compute the bolometric corrections for the hot stars, it was necessary to estimate the amount of energy they radiate shortward of the atmospheric limit. There are now enough far-ultraviolet rocket observations to permit us to estimate, albeit rather crudely, the amount of stellar ultraviolet energy for stars as early as B0. Since this chapter is concerned with "infrared measurements," we merely refer to that estimate (cf. 17), and say that all of the bolometric corrections listed in the tables of this chapter are based upon actual observational data. The necessity of bringing

SUPERGIANTS

Sp (I)	U−V Ia	U−V Ib	B−V	V−R	V−I	V−J	V−K	V−L	V−M	V−N	B.C.	T_e (°K)
O9	−1.46	−1.46	−0.31	−0.15	−0.47	−0.73	−0.94	−1.00	—	—	—	—
O9.5	−1.44	−1.44	−0.30	−0.13	−0.45	−0.70	−0.90	−0.96	—	—	—	—
B0	−1.38	−1.37	−0.27	−0.11	−0.38	−0.62	−0.79	−0.84	—	—	−2.29	21000
B0.5	−1.32	−1.30	−0.25	−0.09	−0.32	−0.54	−0.70	−0.74	—	—	−1.99	18500
B1	−1.26	−1.24	−0.22	−0.08	−0.27	−0.47	−0.60	−0.62	—	—	−1.82	16000
B2	−1.15	−1.10	−0.18	−0.05	−0.20	−0.36	−0.45	−0.46	—	—	−1.53	14000
B3	−1.03	−0.98	−0.14	−0.02	−0.14	−0.29	−0.36	−0.36	—	—	−1.27	12800
B5	−0.86	−0.78	−0.10	+0.02	−0.05	−0.20	−0.22	−0.20	—	—	−0.91	11500
B6	−0.80	−0.74	−0.08	+0.02	−0.03	−0.16	−0.16	−0.13	—	—	−0.85	11000
B7	−0.73	−0.67	−0.06	+0.02	−0.01	−0.12	−0.10	−0.06	−0.10	−0.10	−0.75	10500
B8	−0.64	−0.57	−0.03	+0.02	+0.02	−0.08	−0.03	+0.01	−0.03	−0.03	−0.64	10000
B9	−0.58	−0.50	−0.01	+0.02	+0.05	−0.03	+0.03	+0.08	+0.03	+0.03	−0.52	9700
A0	−0.47	−0.40	+0.01	+0.03	+0.08	+0.01	+0.10	+0.15	+0.10	+0.10	−0.38	9400
A1	−0.35	−0.29	+0.03	+0.05	+0.11	+0.06	+0.16	+0.21	+0.16	+0.16	−0.30	9100
A2	−0.22	—	+0.05	+0.07	+0.14	+0.10	+0.22	+0.27	+0.22	+0.22	−0.21	8900
	I											
A5	+0.05		+0.11	+0.12	+0.25	+0.23	+0.37	+0.42	+0.37	+0.37	+0.01	8300
F0	+0.45		+0.19	+0.21	+0.41	+0.45	+0.63	+0.68	+0.63	+0.63	+0.14	7500
F2	+0.55		+0.25	+0.26	+0.47	+0.54	+0.75	+0.80	+0.75	+0.75	+0.13	7200
F5	+0.66		+0.37	+0.35	+0.58	+0.67	+0.93	+0.98	+0.93	+0.93	+0.11	6800
F8	+1.01		+0.55	+0.45	+0.72	+0.85	+1.21	+1.27	+1.21	+1.21	+0.08	6150
G0	+1.24		+0.70	+0.51	+0.84	+1.03	+1.44	+1.51	+1.44	+1.44	+0.04	5800
G2	+1.47		+0.85	+0.58	+0.98	+1.20	+1.67	+1.75	+1.67	+1.67	−0.04	5500
G5	+1.83		+1.01	+0.67	+1.11	+1.43	+1.95	+2.04	+1.91	+1.94	−0.13	5100
G8	+2.07		+1.03	+0.69	+1.15	+1.45	+1.99	+2.10	+1.95	+1.97	−0.15	5050
K0	+2.38		+1.12	+0.76	+1.24	+1.58	+2.16	+2.28	+2.09	+2.12	−0.22	4900
K1	+2.60		+1.18	+0.80	+1.32	+1.67	+2.29	+2.42	+2.20	+2.23	−0.28	4700
K2	+2.83		+1.25	+0.85	+1.40	+1.78	+2.44	+2.58	+2.32	+2.36	−0.35	4500
K3	+3.10		+1.38	+0.94	+1.57	+2.00	+2.72	+2.86	+2.57	+2.61	−0.50	4300
K4	+3.35		+1.49	+1.04	+1.75	+2.25	+3.00	+3.15	+2.82	+2.88	−0.68	4100
K5	+3.51		+1.62	+1.20	+2.10	+2.71	+3.70	+3.85	+3.50	+3.57	−1.10	3750
M0	+3.57		+1.63	+1.23	+2.17	+2.82	+3.79	+3.96	+3.59	+3.66[a]	−1.17	3660
M1	+3.61		+1.63	+1.28	+2.27	+2.90	+3.92	+4.09	+3.72[a]	+3.79[a]	−1.26	3600
M2	+3.62		+1.64	+1.34	+2.44	+3.08	+4.11	+4.29	+3.91[a]	+3.98[a]	−1.39	3500
M3	+3.60		+1.64	+1.48	+2.79	+3.51	+4.58	+4.77	+4.39[a]	+4.46[a]	−1.80	3300
M4	+3.36		+1.64	+1.74	+3.39	+4.26	+5.24	+5.44	+5.10[a]	+5.13[a]	−2.44	3100
M5	(+3.00)		+1.62	+2.18	+4.14	+5.04	+6.06	+6.31	+6.00[a]	+6.00[a]	−3.23	2950

[a] Luminosity classes Ib and II. Probably do not apply to luminosity classes Ia and Iab.

TABLE IV

THE ABSOLUTE CALIBRATION OF THE PHOTOMETRY

Filter band	λ_0	Absolute flux density for mag=0.00 F_λ	F_ν
U	0.36 μ	4.35×10^{-12} W/cm² μ	1.88×10^{-23} W/m² Hz
B	0.44 μ	7.20×10^{-12} W/cm² μ	4.44×10^{-23} W/m² Hz
V	0.55 μ	3.92×10^{-12} W/cm² μ	3.81×10^{-23} W/m² Hz
R	0.70 μ	1.76×10^{-12} W/cm² μ	3.01×10^{-23} W/m² Hz
I	0.90 μ	8.3×10^{-13} W/cm² μ	2.43×10^{-23} W/m² Hz
J	1.25 μ	3.4×10^{-13} W/cm² μ	1.77×10^{-23} W/m² Hz
K	2.2 μ	3.9×10^{-14} W/cm² μ	6.3×10^{-24} W/m² Hz
L	3.4 μ	8.1×10^{-15} W/cm² μ	3.1×10^{-24} W/m² Hz
M	5.0 μ	2.2×10^{-15} W/cm² μ	1.8×10^{-24} W/m² Hz
N	10.2 μ	1.23×10^{-16} W/cm² μ	4.3×10^{-25} W/m² Hz

ultraviolet measures into a discussion of infrared measures does, however, emphasize the impracticability of strict segregation of astronomical measures by wavelength. As we will see from the discussion of effective temperatures, which follows below, photometric measures in the Intermediate Infrared can be used in the determination of the temperatures of hot stars, whose radiation is concentrated in the far ultraviolet.

EFFECTIVE TEMPERATURES

The effective temperature T_e of a star is defined as the temperature of a black body that produces the same total energy per unit surface area as does the star. Therefore, in order to compute the effective temperature of a star, we must know both its apparent angular diameter and the total flux of energy received from the star per unit area on the Earth; only for the Sun is the diameter known with sufficient precision that an accurate effective temperature (5800°K) can be computed. Several other stars have had their angular diameters measured, however, and when these diameters are combined with the total energies computed according to the procedures outlined above, their effective temperatures can be determined. These stars and their derived bolometric corrections and effective temperatures, are listed in the first three columns of Table V. The diameter of α CMa that was used is that of Brown & Twiss (33) as rediscussed by Popper (34); that of β Aur also follows from Popper's discussion. The diameter of α Lyr was that of Brown (35). The diameter of the mean component of YY Gem was taken from Kron's (36) investigation, and combined with the trigonometric parallax of 0.″072 (37). The diameter of β Per A (Algol) was derived from Eggen's (38) discussion and the trigonometric parallax of 0.″031 (37). The diameter of μ^1 Sco was derived from the linear diameter given by Harris, Strand & Worley (39) and the moving-cluster distance of Bertiau (40); the star is

TABLE V

THE EFFECTIVE TEMPERATURE CALIBRATION

Star	B.C.	T_e (°K)		Comparison T_e (°K)			
		(diam.)	$(I-L)_{BB}$	Kuiper (41)	Harris (51)	Popper (34)	BB fit
μ^1 Sco	−1.45	19200	22500	15800	27500	—	—
β Per A	−0.30	11500	11700	—	—	—	—
α CMa	−0.05	9000	11700	—	9350	9350	—
β Aur	+0.06	10000	10000	9800	10500	10500	—
α Lyr	−0.08	8950	9000	—	—	—	—
Sun	0.00	5800	5800	5713	5784	—	5800
α Boo	−0.62	4250	4250	4075	4090	—	4200
α Tau	−1.09	3860	3830	3800	3780	—	3600
YY Gem	−1.31	3720	3850	3550	3650	3650	3400
β Peg	−1.82	3130	3650	3090	3080	—	3100
α Ori	−1.41	3790	3600	3460	3460	—	3400
α Sco	−1.41	3520	3600	3240	3230	—	3400
α Her	−3.55	3400	3000	—	—	—	2700
o Cet (max)	−3.5	2600	3000	2400	2360±	—	—

slightly reddened and an extinction correction of 0.10 mag was made to the observed V magnitude. For the other stars, the diameters were those given by Kuiper (41); with the exception of α Ori, these diameters are the same as those given by Pettit & Nicholson (4) and all were derived from the interferometric observations of Michelson & Pease. α Her has been included here although Kuiper rejected it from his discussion; its diameter seems as well determined as that of o Cet. The corrections for limb darkening computed by Kuiper (41) were used. α Ori and α Sco are affected by interstellar extinction; for these two stars, the visual magnitude used was the observed magnitude corrected by the color excess in $V-N$ (it was assumed that the extinction in N is zero and that the extinction in V is equal to E_{V-N}), and the bolometric corrections were read from Table III for their spectral types. Effective temperatures used by other investigators are listed in the fifth, sixth, and seventh columns of Table V; they differ from those derived here (third column) principally because of changes in the bolometric corrections.

There are only 14 stars for which direct determinations of the effective temperatures can be made. We must, therefore, find some means of interpolating between these data if we are to determine the effective temperatures of other stars. The usual procedure is to select a suitable color index as the interpolation parameter; an earlier analysis of mine (16) used $(R+I)-(J+K)$. $I-L$ seems even better, as is shown by the temperatures listed in the fourth column of Table V. These temperatures were obtained by computation of black-body radiation passing through the I and L filters, with

TABLE VI

INFRARED STARS

Star	T_e (°K) (BB fit)
o Cet (min)	2300
χ Cyg (min)	2000
TX Cam (min)	1350
NML (Cyg)	800
NML (Tau)	1700
HC-1	1500
HC-2	1650
Hetzler 1-1	1700
Hetzler 4-1	1900
Hetzler 4-2	2200

the zero-point of the computed $I-L$ colors set so that a 5800° black body has the same $I-L$ as the Sun (29). It is interesting that the black-body temperatures so closely approximate the observed ones over the whole temperature range. Note the large discrepancy for α CMa; this star is too blue in infrared wavelengths for both its spectral type and its diameter-temperature.

The last column of Table V, labeled "BB fit," contains temperatures obtained by fitting black-body curves ocularly to the observed data. The BB fit temperatures agree well with the others at solar temperatures, but are lower for the cooler stars. The BB fit method is, at present, the only way to estimate the temperatures of very cool "infrared" stars, such as those that have recently been found and observed (10, 42–44). Some of these stars, and their temperatures by the BB fit method, are listed in Table VI.

Selected effective temperatures from theoretical stellar model computations are listed in Table VII. The sources of these temperatures are indi-

TABLE VII

THEORETICAL TEMPERATURES

Star	T_e (°K) (theoretical)	Reference
B1.5 V	21900	45
α Gru (B5 V)	13700	46
A3 V	8900	47
A9 V	7560	47
σ Boo (F2 V)	6800	48
α CMi (F5 IV–V)	6570	49
M4 V	3150	50
M6 V	2950	50

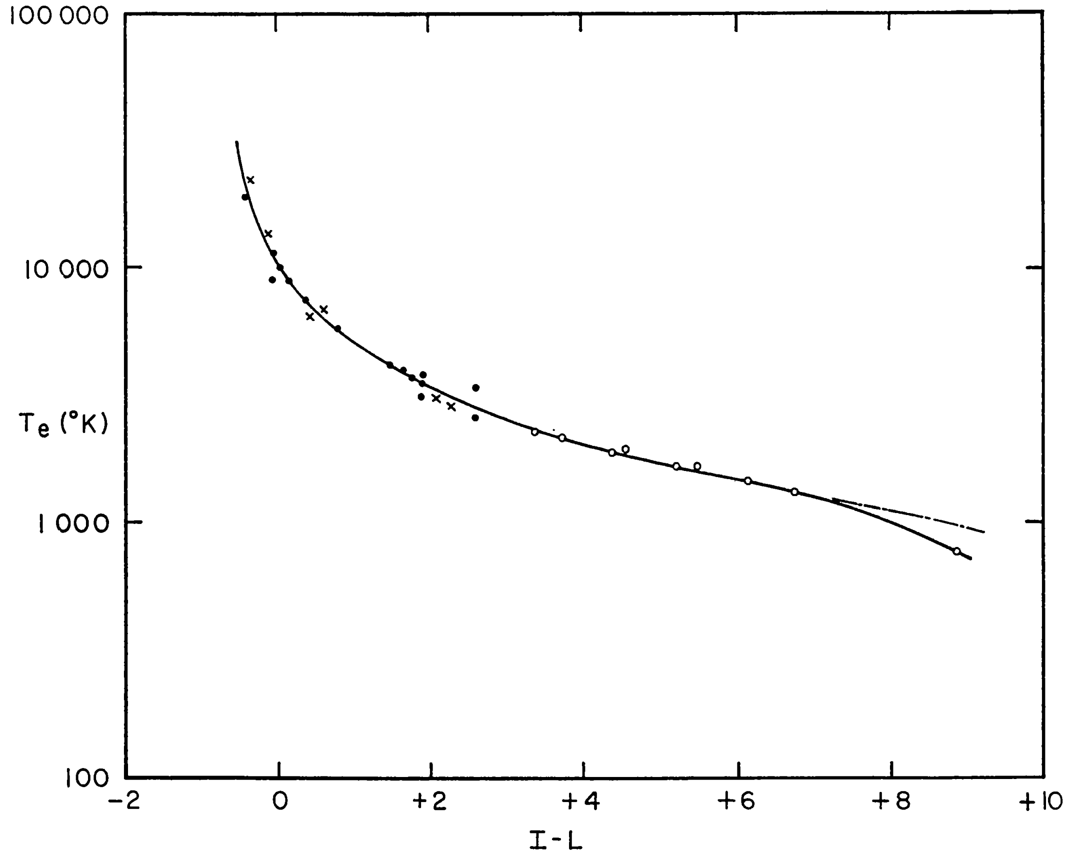

FIG. 2. The relationship between effective temperature and I–L. The spots designate the diameter-based temperatures of Table V; the open circles, the temperatures from Table VI; the crosses, those from Table VII.

cated in the third column of the table. In some cases, the calculated temperatures were partly based upon observational data in the visible and Near Infrared spectral regions. The close agreement of these temperatures with those determined from angular diameters will become apparent immediately.

The relationship between the effective temperatures of Tables V, VI, and VII is shown in Figure 2. The spots designate the temperatures in the third column of Table V; the open circles, the temperatures in Table VI; and the crosses, those from Table VII. The solid curve represents the mean relationship; for stars warmer than about 3200°K it is practically identical with the one computed from black-body radiation. For the cooler stars, the black-body curve has been modified to fit the open circles (the dashed line indicates a possible alternative curve for the very coolest stars). The discordant point at I–$L = -0.1$ is α CMa; the peculiarity of this star's colors can bear further investigation.

Diagrams similar to Figure 2 were constructed for five other color indices, including $(R+I)-(J+K)$. The effective temperatures listed in the last columns of Tables I, II, and III were derived from these diagrams, giving higher weight to the I–L diagram than to the others. Color indices ranging from B–I to I–L were used to insure that as much as possible of the radiation curves of the stars was taken into account. For the latest spectral types (later than M0), the BB fit temperatures were included in the means.

I believe that the effective temperatures given in Tables I, II, and III are the best that can be obtained from the observational data available at the present time and that they will not be improved significantly until many more observations of stellar apparent diameters have been made, or until detailed comparisons of the results of stellar model computations have been made with observational data over the large range of wavelength now available. Such observations, or theoretical computations, are particularly important for the very cool stars so that we will know whether the very low temperatures obtained from the BB fit method are correct.

Conclusion

This discussion of astronomical measurements in the infrared is deliberately incomplete, for it would have been impossible in the space available to have examined more than a fragment of the expansive field of infrared astronomy in any detail. Practically no mention has been made of the instrumentation for these wavelengths, although some formidable problems had to be solved before the astronomical data could be obtained. The large field of infrared spectrophotometry, from which some very interesting results have been obtained, has been entered only to the extent necessary for the purposes at hand. I believe, however, that the discussion of bolometric corrections and effective temperatures not only has summarized this part of the field, but also has provided an indication of the kinds of results which may be obtained from infrared observations. Furthermore, if the reader wishes to consult them, the references cited can lead him to other corners of the field of infrared astronomy not emphasized in this chapter.

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