INFRARED STANDARD STARS

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Received 1 March 1982; revised 13 April 1982

ABSTRACT

Lists of standard stars suitable for $JHKL$, H_2O, and CO photometry are given. These include stars faint enough for use on large telescopes. Most of the stars have estimated uncertainties in their magnitudes of ± 0.01 mag or less. The stars are accessible from both hemispheres, and cover a large enough range in color to permit definition of color transformations. The magnitudes are given on the "CIT" system.

I. INTRODUCTION

In the last several years, there has developed a need for a set of well established, faint near-infrared standards. It is important that these be faint enough to permit observations with the largest available telescopes—preferably not at the extreme bright limit of the detector dynamic range— and that they cover a sufficient range in color to permit adequate transformations between the numerous quasi-independent near-infrared photometric systems in use at different observatories. This latter point is particularly crucial now that observations in the near infrared at an accuracy of 1% are routinely made and effects of similar size are considered significant.

This paper describes the results of an observational program aimed at setting up a standard network of the required accuracy, covering both northern and southern hemispheres, which includes standards red enough to provide at least a limited check on color transformations. The standards have been set up at J (1.2 μm), H (1.6 μm), K (2.2 μm), and L (3.5 μm) and their H_2O and CO molecular absorption indices determined. The problem of color transformations between observatories is discussed briefly. All magnitudes presented are transformed to the natural system defined by the CIT observations.

II. METHODS

Faint stars whose K magnitudes were estimated to be about $+ 7$ mag were selected and calibrated with respect to a group of well measured bright standards (mostly about $K = +3 - +4$ mag). The faint standards

comprised two sets: the first, 26 A stars spaced at approximately 3-h intervals in right ascension, mainly at declinations of roughly $+ 40°$, $0°$, and $- 40°$; and the second, a collection of late-type dwarfs and giants at approximately 0° declination. The choice of A stars was dictated largely by a desire to make the bulk of the faint stars readily indentifiable at the telescope despite their faint infrared magnitudes; A stars are in addition not likely to be variable. The dwarfs were selected largely from the list of Veeder (1974), and were taken from those stars which are not known flare stars or emission-line stars (with the exception of Gl 406 = Wolf 359) and have approximately the desired magnitude and declination. The selection of giants was primarily from published spectral surveys of selected areas (McCuskey 1956; Upgren and Staron 1970); the stars were chosen to have spectral type K5III or M0III in order to diminish the probability of variability while getting sufficiently large colors and CO indices.

Measurements of the standards were made with the four broadband filters J (1.2 μm), H (1.6 μm), K (2.2 μm), and L (3.5 μm)* as well as colors for the H_2O and CO molecular absorption indices (Frogel *et al.* 1978; Aaronson, Frogel, and Persson 1978).

The stars were measured with respect to the set of well calibrated, bright near-infrared standards. These bright standards are listed in Table I, together with the magnitudes and colors adopted for them. A few stars are included which were not used for the program of faint standard measurements. The stars are from Frogel *et al.* (1978), Aaronson (1977), and the unpublished Caltech standards list. The values include considerable additional data and have been made internally consistent, so

*Bandpasses of the filters at operating temperature are listed below.

J 1.13 μm — 1.37 μm

H 1.50 μm — 1.80 μm

K 2.01 μm — 2.42 μm

L 3.22 μm — 3.76 μm

TABLE I. Bright standard Stars.

BS	K	J − K	H − K	K − L	H₂O	CO	Useᵃ
			Standard Magnitudes and Colors				
696	5.440	0.145	0.055	(0.09)ᵇ	—	—	N
718	4.390	− 0.025	− 0.025	− 0.025	− 0.001	+ 0.004	N,S
1552	4.140	− 0.100	− 0.045	− 0.025	− 0.001	+ 0.013	N,S
1953	2.655	0.620	0.100	0.075	+ 0.034	+ 0.084	S
3888	2.990	0.145	0.030	—	—	—	—
4167	3.100	0.150	0.025	0.020	+ 0.004	− 0.010	S
4550	4.385	0.485	0.070	0.045	(+ 0.02)ᵇ	(+ 0.005)ᵇ	N
4689	3.765	0.025	0.010	0.010	+ 0.001	− 0.004	N,S
5447	3.485	0.195	0.025	0.050	—	—	N
6092	4.300	− 0.100	− 0.035	—	(− 0.01)ᵇ	(+ 0.010)ᵇ	N
6136	2.020	0.810	0.140	0.150	+ 0.030	+ 0.144	S
6707	3.205	0.245	0.040	—	—	—	
7615	1.630	0.525	0.070	0.110	—	—	
8143	3.795	0.075	0.030	0.085	—	—	N
8541	4.250	0.050	0.015	0.020	—	—	N
8551	2.295	0.610	0.075	0.075	+ 0.034	+ 0.085	N,S

ᵃ "Use" column indicates whether the standard was used for reduction of faint standard observations in the northern (N) or southern (S) hemisphere.
ᵇ Values given in parentheses are of lower accuracy.

they differ slightly from previously published values, though there is no significant systematic difference between the revised values and those previously published. These are referred to α Lyr, which is defined as having a magnitude of 0.00 at all wavelengths, as well as zero CO and H₂O indices. In practice, the standards in Table I may be considered as defining the system used.

Several of the bright equatorial standards were used extensively for measurements in both hemispheres. The relative accuracy of the values in Table I is about ± 0.01 mag for the K magnitudes and $K − L$ colors, about ± 0.005 mag for the $J − K$ and $H − K$ colors and the H₂O indices, and about ± 0.003 mag for the CO indices. All values tabulated are on the "CIT system" defined by Frogel *et al*. (1978) and Aaronson, Frogel, and Persson (1978) (see Sec. IV below). Measurements were made in the north with the Mount Wilson 2.5-m, 1.5-m, and 0.6-m telescopes and the 5-m Hale telescope; measurements in the south were made with the CTIO 4-m, 1.5-m, and 0.9-m telescopes and the Las Campanas 2.5-m DuPont telescopes.

The faint standards were usually measured with respect to the bright standards during nights primarily devoted to other programs. Measurements were used in determining the magnitudes of the faint standards only if the photometric residual of the bright standards were acceptably small. Typical residuals for measurements on good nights are ± 0.02 mag or less; residuals greater than twice typical values were considered unacceptable. A few nights on the smaller telescopes were devoted exclusively to measurements of standards. The data were supplemented by reductions relative to the best-established faint standards. The observations were made between 1978 and 1982.

The northern measurements were made only at J, H, and K. The Las Campanas measurements were made in all filters except L, and the CTIO measurements were made at all wavelengths, though sometimes L was omitted. Hence the northern (+ 40°) standards have no $K − L$ colors or H₂O and CO indices, and these indices for the equatorial standards are derived entirely from the southern-hemisphere measurements. Roughly 75% of the J, H, and K observations were made at CTIO, 10% at Las Campanas, and 15% at Mount Wilson or Palomar.

Because three different detector systems were used in the measurements (at Mount Wilson and Palomar, at Las Campanas, and at CTIO), color transformations between them were determined, using standards and redder objects. The transformations are discussed in Sec. IV.

III. RESULTS

The faint standard values are listed in Table II. Coordinates and annual proper motions are given for epoch and equinox 1950. These have been mainly taken from the GC (Boss 1937) and Gliese (1969). References for finding charts are also given for the fainter stars to aid in location.

The magnitudes and colors in Tables I and II have been given to 0.005 mag (0.001 mag for H₂O and CO) primarily to avoid round-off errors in making transformations. The estimated uncertainties for the faint standards are indicated by the quality column in Table II and the corresponding uncertainties tabulated in the notes. These uncertainty estimates are based on comparisons of measurements made on different nights, with different telescopes, detectors, and electronics, and thus should exclude only systematic effects common to all measurements. Measurements made at the four observatories were carefully compared with one another; these were made with different detector systems, elec-

TABLE II. Faint standard stars.

Star	Coordinates (1950)				Magnitudes and Colors						Quality[a]	N[b]	Remarks
	α	μ_α	δ	μ_δ	K	J–K	H–K	K–L	H$_2$O	CO			
HD 225023	0^h 0^m 11^{s}8	+0^{s}0000	+35°32'14"	−0."004	6.960	+0.105	+0.025	...	...	...	b	16, 0, 0	
G158-27	0 4 12.	−0.056	− 7 47 54	−1.85	7.430	+0.875	+0.325	...	+0.317	−0.015	b	14, 1,12	*
HD 1160	0 13 23.1	+0.0 6	+ 3 58 24	−0.013	7.040	+0.015	+0.005	+0.015	−0.006	−0.004	a	27, 6,11	
HD 2811	0 28 53.0	−0.0015	−43 52 58	−0.024	7.065	+0.105	+0.025	+0.025	−0.003	−0.006	a+	71,31,65	
HD 3029	0 31 02.3	−0.0001	+20 09 30	+0.011	7.090	+0.160	+0.030	...	...	...	b	10, 0, 0	
Gℓ 105.5	2 38 07.6	+0.0187	+ 0 58 57	+0.242	6.525	+0.715	+0.110	+0.065	+0.058	+0.051	a	22,12,20	*
HD 18881	3 00 20.5	+0.0001	+38 12 53	−0.030	7.140	−0.015	−0.010	...	...	...	c	9, 0, 0	
HD 19904	3 08 49.1	−0.0042	−39 14 24	+0.010	6.640	+0.080	+0.020	+0.020	−0.003	−0.004	a+	59,33,57	
G77-31	3 10 40.5	+0.112	+ 4 35 12	+0.15	7.840	+0.900	+0.320	+0.290	+0.257	−0.016	b	12, 5,11	*
HD 22686	3 36 18.7	+0.0017	+ 2 36 07	−0.010	7.185	+0.010	+0.005	−0.010	+0.001	−0.005	a	28, 9,21	
HD 38921	5 45 41.0	−0.0007	−38 14 51	−0.025	7.535	+0.035	+0.015	+0.010	−0.004	−0.006	a+	86,49,85	
HD 40335	5 55 37.6	−0.0005	+ 1 51 09	−0.018	6.450	+0.090	+0.020	+0.035	+0.000	−0.008	a	41,16,32	
HD 44612	6 21 09.7	+0.0002	+43 34 35	−0.032	7.040	+0.020	−0.005	...	...	...	c	15, 0, 0	
BD+0°1694	6 52 07.3	...	+ 0 0 52	...	4.585	+1.055	+0.225	+0.170	+0.065	+0.212	a+	27,19,30	*
Gℓ 299	8 09 11.	+0.080	+ 8 59 42	−5.10	7.640	+0.740	+0.275	+0.280	+0.269	−0.046	a+	31,17,30	*
HD 75223	8 45 29.8	−0.0017	−39 36 54	+0.021	7.280	+0.045	+0.015	+0.020	−0.002	−0.004	a+	90,48,81	
HD 77281	8 59 05.4	−0.0024	− 1 16 45	−0.034	7.030	+0.075	+0.020	+0.035	+0.003	−0.004	a+	47,15,39	
Gℓ 347a	9 26 25.	−0.009	− 7 8 30	−0.70	7.630	+0.780	+0.230	+0.205	+0.193	−0.014	b	10, 7,13	*
HD 84800	9 45 35.9	−0.0048	+43 53 56	−0.007	7.530	+0.030	+0.000	...	...	...	c	17, 0, 0	
Gℓ 390	10 22 44.	−0.048	− 9 58 36	+0.10	6.045	+0.825	+0.205	+0.165	+0.133	+0.018	a	11,11,13	*
Gℓ 406	10 54 06.	−0.259	+ 7 19 12	−2.70	6.080	+0.980	+0.360	+0.350	+0.352	+0.020	b	7, 5, 7	*
HD 101452	11 37 45.1	−0.0016	−38 52 09	−0.037	6.845	+0.160	+0.040	+0.035	+0.006	−0.008	a+	74,53,69	
HD 105601	12 06 56.1	−0.0034	+38 54 39	−0.068	6.685	+0.125	+0.030	...	...	...	c	14, 0, 0	
HD 106965	12 15 24.0	−0.0030	+ 1 51 10	−0.016	7.315	+0.060	+0.020	+0.020	+0.008	−0.002	a+	37,20,27	
HD 129653	14 40 38.2	+0.0029	+36 58 07	−0.018	6.920	+0.060	+0.020	...	...	...	b	23, 0, 0	
HD 129655	14 41 11.0	−0.0018	− 2 17 38	−0.030	6.690	+0.125	+0.030	+0.025	+0.005	−0.008	a	35,18,20	
HD 130115	14 44 36.2	−0.0057	−39 43 04	−0.012	6.835	+0.020	+0.010	+0.025	−0.006	−0.008	a+	55,50,56	
BD+3°2954	14 52 23.2	−0.0028	+ 3 11 33	−0.010	4.805	+1.035	+0.190	+0.155	+0.057	+0.190	b	8, 7,10	
HD 136754	15 19 24.3	−0.0019	+24 31 19	−0.015	7.135	+0.015	−0.005	...	...	...	b	17, 0, 0	
BD+2°2957	15 22 29.0	−0.0002	+ 1 41 06	−0.023	4.245	+0.955	+0.180	+0.150	+0.038	+0.182	b	8, 7, 9	
S–R 3	16 23 7.7	...	−24 27 26	...	6.520	+1.185	+0.445	...	+0.104	−0.072	c	5, 4, 3	*
Oph S1	16 23 32.8	...	−24 16 44	...	6.330	+2.470	+0.940	+0.560	...	−0.135	c	8, 7, 3	*
HD 161743	17 45 31.8	+0.0013	−38 06 11	−0.013	7.615	+0.005	+0.005	+0.010	−0.005	−0.004	a+	33,25,32	
HD 161903	17 45 43.3	+0.0003	− 1 47 34	−0.002	7.020	+0.150	+0.035	+0.035	+0.007	−0.008	a	35,19,22	
HD 162208	17 46 20.7	−0.0018	+39 59 40	+0.122	7.110	+0.105	+0.035	+0.035	...	...	b	20, 0, 0	
Gℓ 748	19 09 38.	+0.118	+ 2 48 36	−0.45	6.305	+0.770	+0.240	...	+0.217	−0.020	c	4, 3, 3	*
Gℓ 811.1	20 54 04.	−0.005	−10 37 36	−1.14	6.930	+0.825	+0.220	+0.190	+0.168	+0.013	c	8, 4, 5	*
HD 201941	21 10 13.6	−0.0020	+ 2 26 12	−0.008	6.625	+0.075	+0.015	+0.015	−0.002	−0.005	a	33,10,14	
HD 203856	21 21 37.1	+0.0040	+39 48 12	+0.027	6.860	+0.065	+0.020	...	...	...	b	22, 0, 0	
HD 205772	21 35 33.6	+0.0047	−41 16 26	+0.004	7.655	+0.110	+0.030	+0.020	−0.002	−0.009	a+	24,12,21	

NOTES to Table II

[a] Quality defined as:

Quality	Estimated Uncertainties (mag)		
	K,J–K,H–K,H$_2$O	K–L	CO
a+	<0.005	<0.007	<0.003
a	<0.007	<0.010	<0.004
b	<0.010	<0.015	<0.006
c	<0.015	<0.020	<0.010

[b] N is number of nights with acceptable measurements at K, L, and H$_2$O respectively. Number of measurements at J–K, H–K will be comparable with number of K measures; number of CO measurements will be comparable with number of H$_2$O measurements.

Remarks

G158-27: Chart in Giclas, Burnham, and Thomas (1964a).

Gℓ 105.5 = G75-34: Chart in Giclas, Burnham, and Thomas (1961).

G77-31: Chart in Giclas, Burnham, and Thomas (1961).

BD+0°1694: Chart in McCuskey (1956).

Gℓ 299 = G50-22: Chart in Giclas, Slaughter, and Burnham (1959).

Gℓ 347a = G161-33 = Chart in Giclas, Burnham,and Thomas (1964b).

Gℓ 390 = G162-52 = Chart in Giclas, Burnham, and Thomas (1964b).

Gℓ 406 = Wolf 359 = G45-20: Flare star, chart in Giclas, Slaughter, and Burnham (1959).

S–R 3: Chart in Grasdalen, Strom, and Strom (1973).

Oph S1: Chart in Grasdalen, Strom, and Strom (1973).

Gℓ 748 = G22-18 = Chart in Giclas, Slaughter, and Burnham (1959).

Gℓ 811.1 = LFT 1586: Chart in Rodgers and Eggen (1974).

tronics, and from both hemispheres, so we expect that errors owing to nonlinearities in electronics, small amplifier miscalibrations, or other similar effects would have been both identified and largely averaged out. Any such effects appear to be at most at the 1% level for measurements at any single telescope, and must be still smaller for color measurements, as these are largely differential. We believe, therefore, that *systematic* errors in the final standard values are less than 0.01 mag in the magnitudes relative to the bright standards and 0.005 mag in the colors and indices relative to the bright standards. The uncertainties in the magnitudes of the bright standards relative to α Lyr are also less than 0.01 mag.

Comparison of values obtained at different observatories indicates that the estimates of the accuracies given in Table II are valid down to about the 0.005-mag level. The comparisons involve dividing the data into subsets of necessarily reduced accuracy. Thus comparison of the values for the equatorial standards derived from the northern-hemisphere observations with those derived from the southern hemisphere yields rms differences in the range 0.01–0.02 mag for the broadband magnitudes and colors because the nothern data are rather sparse. Though these rms differences are consistent with the internal uncertainties for the individual determinations, one cannot be sure that a similar consistency would be present for measurements with very small internal uncertainties.

IV. TRANSFORMATIONS

Until recently, infrared photometric systems at different observatories were largely independent, and little attempt was made to make detailed comparisons between them—usually establishment of a common zero point was considered sufficient. The precision now obtainable has made determination of color terms necessary as well, and such transformations have begun to abound in the literature (e.g., Persson, Aaronson, and Frogel 1977; Frogel *et al.* 1978; Jones and Hyland 1980). Unfortunately, the system most often used for reference is the Johnson system (Johnson 1965, 1966), which in its original form does not even include the H (1.6 μm) filter, and is in any case based on measurements of less accuracy than is now routine.

The strong absorptions present in late-type stars, and the differences between stars of different spectral type (including heavily reddened early-type stars), means that any transformation must be viewed with some caution, and cannot be used or extrapolated blindly. To illustrate this, some examples of the transformations found between the various observatories where the standard measurements were made are given.

There is no evidence for night-to-night effects on colors, largely because the extinction in the near infrared is small and relatively constant. The most likely exception to this would be the H_2O index, where the airmass coef-
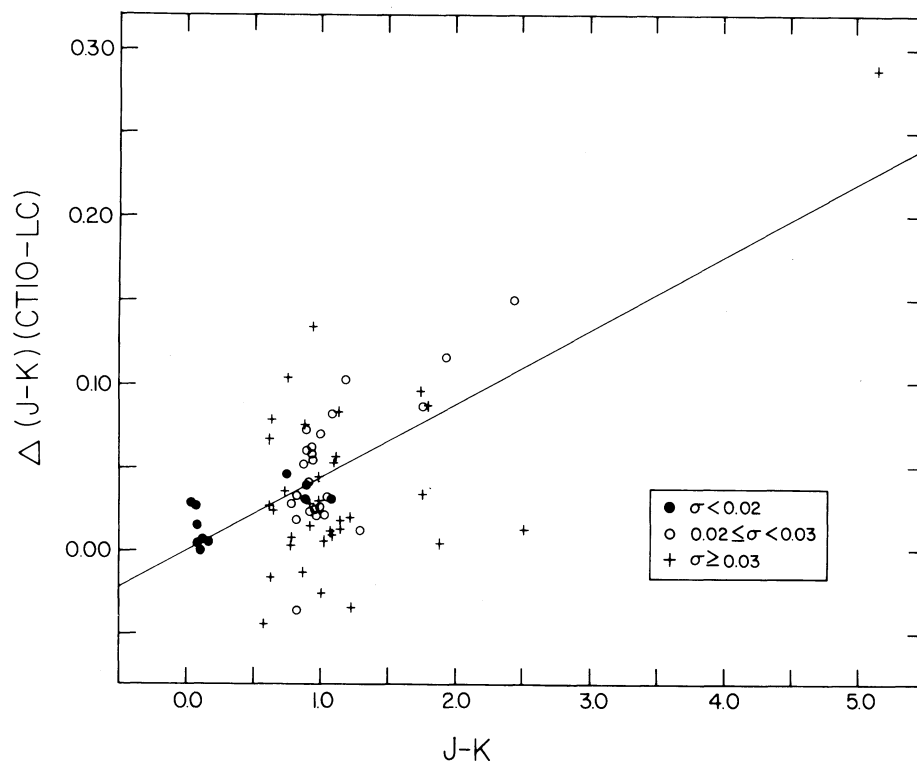

FIG. 1. Example of a color transformation: differences in $J - K$ measured at CTIO and Las Campanas. The line is a best-forced fit through the origin (because the data are reduced with a common zero point). Some of the scatter in the redder objects may be due to small variations between the times of the two measurements. The symbols indicate the accuracy to which the individual differences are known.
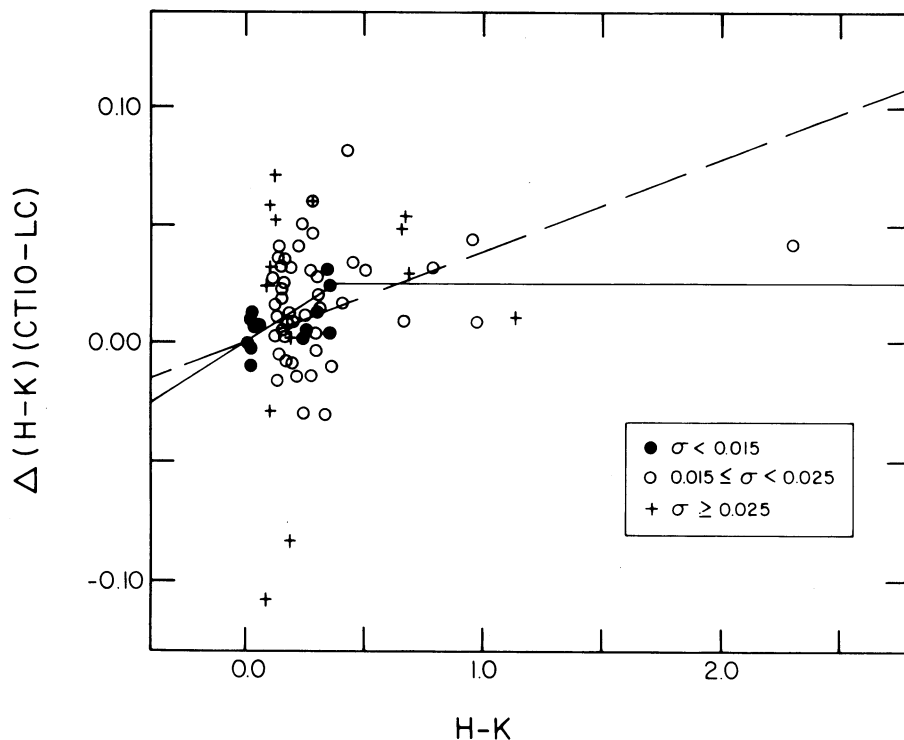
FIG. 2. Example of a color transformation: differences in $H - K$ measured at CTIO and Las Campanas. The dashed line is a best forced fit through the origin; the solid lines are the transformation adopted (see text).

ficient* can approach 0.30 mag/airmass, and where the transmission through the H_2O filter varies by up to 30% from night to night. The data are not extensive enough to preclude effects of the order of a few percent of the index under extreme conditions.

The first example is the transformation in $J - K$ between Las Campanas and CTIO for the J filter in the use at CTIO through early 1980. Figure 1 shows the differences between $J - K$ values for individual objects measured at both observatories, when they have been corrected to a common zero point for zero-color standards, plotted as a function for $J - K_{CIT}$. These include measurements of variable stars (carbon stars and Miras) made nearly simultaneously at both observatories. It can be seen that the observations match a simple linear fit rather well, though there is more scatter than should be due to the internal errors in the photometry, possibly owing to variations in the stars' colors between the times of the CTIO and Las Campanas measurements. Some of the scatter may be intrinsic, in which case the transformation for the reddest stars may be accurate to no more than 0.02 mag.

A more instructive example is the comparison of the $H - K$ observations at the two observatories, shown in

Fig. 2. Magnitude differences for individual objects are plotted against $H - K_{CIT}$. Here it is obvious that a simple linear fit is not optimal, and that better accuracy is provided by a two-part fit. Without the redder objects one might have accepted a linear fit, which would have led to incorrect transformation of colors of very red objects. Such nonlinear transformations can be produced by small differences in properties of the filter, detector, or field optics used at different observatories; in the case of the narrowband H_2O and CO indices the properties of the molecular absorptions themselves may also have a substantial effect.

APPENDIX A

a) Tabulated Color Transformations

We tabulate here the transformations between the natural systems in use presently or recently at CTIO, Las Campanas, and CIT (Palomar and Mount Wilson Observatories). The magnitudes tabulated in this paper are defined as being on the natural system in use at CIT so no transformations are needed from that system to the standard systems. In addition, we have found no differ-

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*A simple exponential form of the extinction law was used, rather than the more complex law required in principle because the extinction in the filters in nonuniform. The difference between the simple law and a correct law is negligible for *relative* photometry— generally of the order of 0.002 mag, or smaller than the effects of uncertainty in the airmass coefficient (cf. Manduca and Bell 1979).

ences between magnitudes and colors at Las Campanas and at CIT, nor any differences in measurements at K,

L, or in the CO index between all three systems. The remaining differences are as follows.

$$J - K_{CIT} = 0.96\, J - K_{CTIO}$$
$$J - K_{CIT} = 1.00\, J - K_{CTIO}$$
$$H - K_{CIT} = 0.94\, H - K_{CTIO}$$
$$H - K_{CIT} = H - K_{CTIO} - 0.025$$
$$H_2O_{CIT} = 0.80\, H_2O_{CTIO}$$
$$H_2O_{CIT} = 0.958\, H_2O_{CTIO} - 0.011$$

(prior to June 1980) $(-0.2 < J - K_{CTIO} < 3.0)$
(after June 1980) $(-0.2 < J - K_{CTIO} < 3.0)$
$(H - K_{CTIO} < 0.40)$
$(0.40 < H - K_{CTIO} < 1.0)$
$(H_2O_{CTIO} < 0.07)$
$(H_2O_{CTIO} < 0.07)$.

The H_2O transformation is valid primarily for stars where the index is due to H_2O absorption rather than a steep continuum, although we find no differences for stars with indices up to about 0.3 owing to red continuum.

None of the transformations are necessarily correct outside the indicated range in color.

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