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The *Hipparcos* and *Tycho* Photometric System Passbands

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ABSTRACT. *Hipparcos* and *Tycho* magnitudes have been extracted for many of the E-region standard stars. Differences between *B*, *V*, and the *Hipparcos* and *Tycho* magnitudes have been derived and regressed against color. Fiducial lines and polynomial fits have been derived and compared with values in the *Hipparcos* and *Tycho* Catalogues. Synthetic photometry has been made using the Vilnius spectra and compared with the observations. As a result, it has been necessary to modify some of the published bandpasses.

1. INTRODUCTION

The *Hipparcos* mission of the European Space Agency was a remarkable achievement. As well as providing parallaxes of unprecedented precision and accuracy for the nearby stars, it also produced exceedingly precise magnitudes for hundreds of thousands of stars. All this is described in the *Hipparcos* and *Tycho* Catalogues (Perryman et al. 1997, hereafter HTC). It is these magnitudes and the photometric system that they define that are the subject of this paper. The main *Hipparcos* detector was an unfiltered S20 image dissector scanner which provided the H_P magnitudes. Most stars brighter than 8.5 were measured with a precision of a few tenths of a millimagnitude. In addition, light from the star mapper area was divided by a dichroic beam splitter onto two photomultiplier tubes, providing simultaneously measured B_T and V_T magnitudes. The *Tycho* catalog provides magnitudes for a larger number of stars, but for the fainter stars the precision is lower than the *Hipparcos* catalog. For the brighter stars it is comparable. Never before has such a wealth of accurately calibrated and precisely measured photometric data been obtained, data covering the whole sky, north and south of the equator. This enables intercomparison of many of the ground-based standard photometric systems and a search to be made for systematic differences.

Amongst the most precisely defined ground-based standard systems are the *UBVRI* E-region standards set up originally by Cousins (1974, 1976) and continued by Menzies et al. (1989). These standards comprise samples of stars with spectral types between B and early M and apparent magnitudes between $m_V = 4$ and 9 in 10 regions with a declination of about S35° and at roughly 3 hour intervals around the sky. Additional very blue and red standards on the same system have been provided by Kilkenny et al. (1998).

During an investigation of the zero points of the various sets of *UBVRI* standard-star photometry (Cousins & Bessell 2000), it became apparent that the differences between the South African Astronomical Observatory (SAAO) *B* and *V* magnitudes (E-region: Menzies et al. 1989; E-region second 10 year means: J. W. Menzies 1999, private communication; supplementary blue and red stars: Kilkenny et al. 1998) and the H_P, B_T, and V_T magnitudes (HTC) differed slightly from those described in tables and equations provided in the HTC. These precisely defined differences are interesting in that they indicate qualitatively and quantitatively the differences to be expected when different passbands are used, differences that have been masked in the past by the lower precision of most ground-based photometry systems. Such systematic differences are important to consider also in the context of new magnitude data from new and broader band photometric systems of the gravitational lensing programs.[1]

In addition, when synthetic photometry was carried out on the Vilnius spectra (Straizys & Sviderskiene 1972) using the published H_P, B_T, and V_T passbands (HTC) and the standard *BV* passbands (Bessell 1990), some of the synthetic relations did not agree well with the observed relations. It is important that the passbands of the HTC and other new systems be well understood so that calibrations of tem-

[1] MACHO (http://wwwmacho.anu.edu.au), EROS (http://www.lal.in2p3.fr/recherche/eros/), and OGLE (http://www.astrouw.edu.pl/~ftp/ogle/)—monitoring the LMC Bar and Galactic bulge—and wide-field surveys, such as the Sloan Digital Sky Survey (http://www.sdss.org).

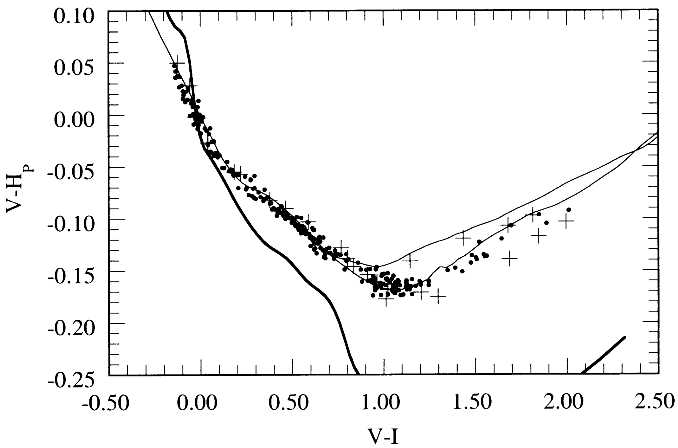

FIG. 1.—The $V-H_P$ vs. $V-I$ regression for individual E-region stars (10 year mean data). The thin lines represent the empirical relations for main-sequence stars and for red giants given in the HTC. The plus signs are the synthetic photometry derived from the set of Vilnius spectra using the new *Hipparcos* passband. The thick line is the locus of the synthetic photometry derived from the Vilnius spectra using the original *Hipparcos* passband given in the HTC.

perature and luminosity can be made from model atmosphere fluxes for stars, such as metal-deficient stars and supergiants, that are poorly represented in standard-star photometry lists and spectrophotometric atlases.

In this paper are presented some mean empirical relations between the Cousins-Johnson B and V magnitudes and *Hipparcos-Tycho* H_P, B_T, and V_T magnitudes as defined by the E-region stars and the sample of bluer sdOB stars and redder K–M dwarf stars of Kilkenny et al. (1998) together with modified H_P, B_T, and V_T bandpasses that better match the observed interrelations.

2. DISCUSSION

A list of HD numbers for the E-region stars was submitted to the VizieR Catalogue interface to the HTC provided by the Centre de Données Astronomiques de Strasbourg. Where available the HTC data were returned and combined with the *UBVRI* data. The two sets of *UBVRI* data used were the original E- and F-region 1975–1989 data set and an "independent" subset of E-region 1989–1999 data. There was no systematic difference between the two data sets, but the 10 year (1989–1999) set had a higher internal precision of a few millimagnitudes and was mainly for stars fainter than $V=6$. There were 419 stars in the first list and 275 in the second. After rejecting some more highly reddened stars, some "fliers," and those few stars with HTC errors exceeding 0.02 mag, there remained 389 stars in the first list and 253 (230 for *Tycho*) in the second.

Tables 14.1–14.4 in HTC volume 3 list relationships between $V-I$ and H_P-V, and $V-I$ and $B-V$, for giants and dwarfs. The H_P, B_T, and V_T passbands are given in § 1.3 of volume 1.

The number of photons counted in passband R_X for a star with flux $f(\lambda)$ is given by

$$\int [f(\lambda)/h\nu]R_X(\lambda)d\lambda = (1/hc)\int f(\lambda)[\lambda R_X(\lambda)]d\lambda \, .$$

TABLE 1

RELATION BETWEEN $V-I$, $B-V$, AND *Hipparcos/Tycho* DATA FOR MAIN-SEQUENCE B–G STARS AND K–M GIANTS

$V-I$	$V-H_P$	$B-V$	$\Delta(B-V)$
−0.250	0.089	−0.244	0.021
−0.200	0.068	−0.198	0.016
−0.150	0.046	−0.152	0.010
−0.100	0.026	−0.104	0.006
−0.050	0.006	−0.050	0.003
−0.000	−0.015	0.009	−0.004
0.050	−0.030	0.060	−0.013
0.100	−0.041	0.102	−0.019
0.150	−0.051	0.145	−0.021
0.200	−0.059	0.185	−0.020
0.250	−0.067	0.223	−0.022
0.300	−0.075	0.262	−0.025
0.350	−0.082	0.300	−0.026
0.400	−0.089	0.339	−0.026
0.450	−0.095	0.381	−0.028
0.500	−0.101	0.425	−0.030
0.550	−0.110	0.476	−0.038
0.600	−0.116	0.535	−0.049
0.650	−0.125	0.595	−0.061
0.700	−0.132	0.654	−0.072
0.750	−0.135	0.704	−0.081
0.800	−0.140	0.761	−0.096
0.850	−0.146	0.825	−0.111
0.900	−0.153	0.893	−0.128
0.950	−0.160	0.957	−0.142
1.000	−0.160	1.007	−0.157
1.050	−0.163	1.076	−0.181
1.100	−0.166	1.133	−0.194
1.150	−0.165	1.192	−0.210
1.200	−0.163	1.238	−0.225
1.250	−0.160	1.285	−0.241
1.300	−0.156	1.326	−0.253
1.350	−0.152	1.364	−0.263
1.400	−0.147	1.401	−0.273
1.450	−0.143	1.437	−0.283
1.500	−0.138	1.468	−0.291
1.600	−0.127	1.504	−0.300
1.700	−0.116	1.522	−0.305
1.800	−0.106	1.545	−0.311
1.900	−0.097	1.569	−0.318
2.000	−0.086	1.592	−0.324
2.100	−0.076	1.615	−0.330
2.200	−0.066	1.638	−0.336
2.300	−0.056	1.661	−0.342
2.400	−0.046	1.684	−0.348
2.500	−0.036	1.707	−0.354

TABLE 2

Relation between $B_T - V_T$ and *Hipparcos*/*Tycho* Data for B–G Main-Sequence Stars and K–M Giants

$B_T - V_T$	$V - V_T$	$\Delta(B-V)$	$V - H_P$
−0.250	0.038	0.031	0.066
−0.200	0.030	0.021	0.051
−0.150	0.022	0.011	0.036
−0.100	0.015	0.005	0.021
−0.050	0.008	0.002	0.006
−0.000	0.001	−0.005	−0.011
0.050	−0.005	−0.010	−0.025
0.100	−0.012	−0.017	−0.038
0.150	−0.018	−0.020	−0.048
0.200	−0.024	−0.021	−0.058
0.250	−0.029	−0.023	−0.069
0.300	−0.035	−0.025	−0.079
0.350	−0.040	−0.025	−0.087
0.400	−0.045	−0.026	−0.094
0.450	−0.050	−0.030	−0.101
0.500	−0.054	−0.035	−0.108
0.550	−0.059	−0.045	−0.114
0.600	−0.064	−0.051	−0.120
0.650	−0.068	−0.060	−0.127
0.700	−0.072	−0.068	−0.131
0.750	−0.077	−0.076	−0.134
0.800	−0.081	−0.085	−0.137
0.850	−0.085	−0.094	−0.142
0.900	−0.089	−0.104	−0.147
0.950	−0.093	−0.113	−0.151
1.000	−0.098	−0.122	−0.155
1.050	−0.102	−0.131	−0.158
1.100	−0.106	−0.142	−0.157
1.150	−0.110	−0.154	−0.160
1.200	−0.115	−0.166	−0.162
1.250	−0.119	−0.178	−0.164
1.300	−0.124	−0.189	−0.166
1.350	−0.128	−0.199	−0.166
1.400	−0.133	−0.210	−0.165
1.450	−0.138	−0.222	−0.164
1.500	−0.143	−0.234	−0.161
1.550	−0.148	−0.245	−0.157
1.600	−0.154	−0.256	−0.153
1.650	−0.160	−0.266	−0.148
1.700	−0.165	−0.277	−0.143
1.750	−0.172	−0.288	−0.137
1.800	−0.178	−0.299	−0.131
1.850	−0.185	−0.309	−0.125
1.900	−0.191	−0.320	−0.119
1.950	−0.199	−0.331	−0.112
2.000	−0.206	−0.342	−0.106

This rearrangement shows how one can then use the same fluxes with the $\lambda R_X(\lambda)$ responses to compute the synthetic photometry. That is, in order to convert quantum efficiency (QE) based passbands into photon-counting passbands, the QE-based passbands are multiplied by the wavelength, then renormalized. This has the effect of weighting the flux by the wavelength and essentially shifts the passbands slightly to

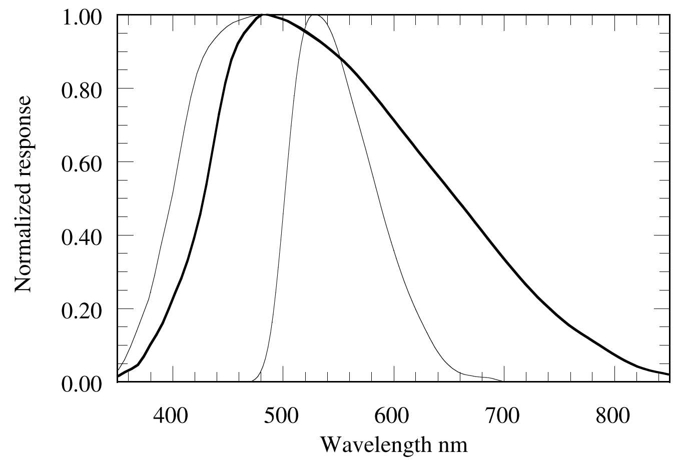

Fig. 2.—The new adopted $\lambda R(\lambda)$ response for H_P (*thick line*) compared with the original passband (*medium line*) and the standard V passband (*thin line*).

the red. This can be better understood in terms of its requiring more red photons than blue photons to yield the same (energy) flux. The $B-V$ versus $V-I$ relation for early-type stars and red giants given below was derived from the less reddened E-region stars.

2.1. The H_P and V Magnitudes

Figure 1 plots the $V-H_P$ versus $V-I$ relation from the 10 year E-region data. Note the extremely small scatter for the hotter stars and the increasing scatter for the redder stars where presumably the metal-line differences become more obvious. However, it is very interesting that the scatter is so small given the large difference in the width of the V and H_P passbands. The fiducial lines from HTC

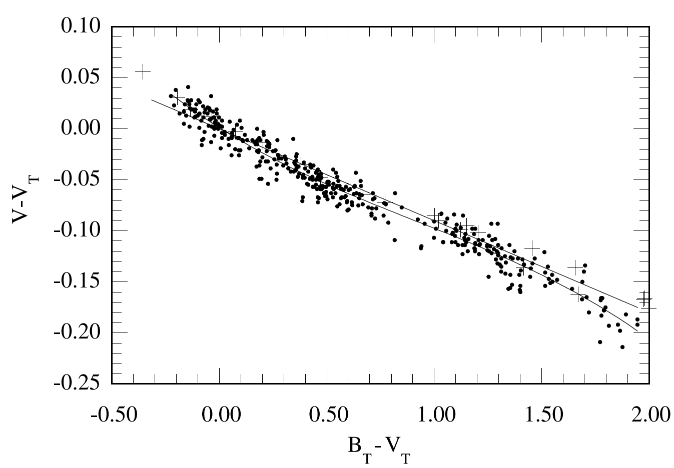

Fig. 3.—The $V-V_T$ vs. B_T-V_T regression for the E-region stars. The straight line is the suggested approximate empirical relation given in the HTC; the curve is a polynomial that better fits the data. The plus signs are the synthetic photometry derived from the Vilnius spectra using the new passband.

TABLE 3

NORMALIZED $\lambda R_X(\lambda)$ RESPONSES

λ	H_P	λ	B_T	λ	V_T
340......	0.000	350......	0.000	455......	0.000
350......	0.015	355......	0.011	460......	0.020
360......	0.032	360......	0.048	465......	0.106
370......	0.052	365......	0.103	470......	0.280
380......	0.103	370......	0.175	475......	0.498
390......	0.155	375......	0.262	480......	0.700
400......	0.227	380......	0.363	485......	0.835
410......	0.300	385......	0.468	490......	0.912
420......	0.400	390......	0.569	495......	0.953
430......	0.530	395......	0.656	500......	0.980
440......	0.700	400......	0.722	505......	0.996
450......	0.845	405......	0.771	510......	1.000
460......	0.928	410......	0.810	515......	0.994
470......	0.970	415......	0.846	520......	0.977
480......	1.000	420......	0.886	525......	0.952
490......	0.997	425......	0.929	530......	0.921
500......	0.988	430......	0.968	535......	0.886
510......	0.973	435......	1.000	540......	0.849
520......	0.956	440......	0.985	545......	0.808
530......	0.935	445......	0.879	550......	0.766
540......	0.911	450......	0.707	555......	0.723
550......	0.887	455......	0.510	560......	0.678
560......	0.858	460......	0.334	565......	0.632
570......	0.825	465......	0.215	570......	0.584
580......	0.789	470......	0.147	575......	0.536
590......	0.752	475......	0.110	580......	0.487
600......	0.714	480......	0.088	585......	0.439
610......	0.675	485......	0.066	590......	0.391
620......	0.637	490......	0.040	595......	0.345
630......	0.599	495......	0.018	600......	0.302
640......	0.562	500......	0.003	605......	0.261
650......	0.525	505......	0.000	610......	0.225
660......	0.487			615......	0.194
670......	0.449			620......	0.166
680......	0.411			625......	0.141
690......	0.372			630......	0.121
700......	0.335			635......	0.103
710......	0.299			640......	0.087
720......	0.264			645......	0.074
730......	0.232			650......	0.060
740......	0.203			655......	0.049
750......	0.176			660......	0.037
760......	0.152			665......	0.024
770......	0.131			670......	0.011
780......	0.112			675......	0.000
790......	0.093				
800......	0.074				
810......	0.057				
820......	0.043				
830......	0.033				
840......	0.026				
850......	0.020				
860......	0.013				
870......	0.005				
880......	0.000				

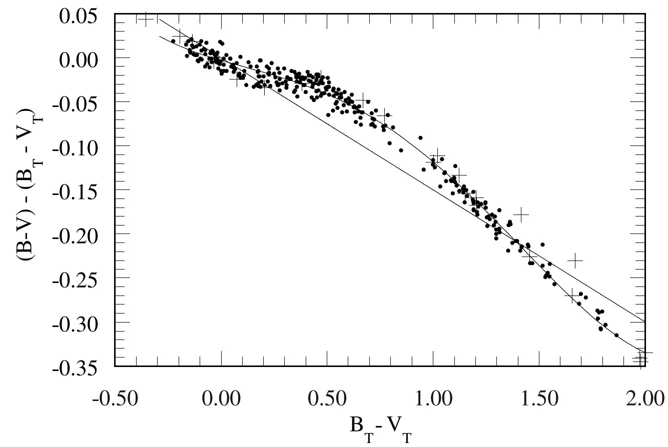

FIG. 4.—The $(B-V)-(B_T-V_T)$ vs. B_T-V_T regression for the E-region stars. The straight line is the suggested approximate empirical relation given in the HTC; the curve is a polynomial that better fits the data. The plus signs are the synthetic photometry derived from the Vilnius spectra using the new passband.

volume 3 Tables 14.1 and 14.2 are also plotted; the line for early-type stars and red giants lies within 0.01 mag of the E-region observations. In Table 1 are given the mean observational lines from the E-region data together with the interpolated $B-V$ values from the mean $B-V$ versus $V-I$ relation defined by the E-region stars.

The H_P passband, modified as described above, was used with the Vilnius spectra (Straizys & Sviderskiene 1972) to compute synthetic H_P magnitudes. When combined with the synthetic V magnitude and plotted against the synthetic $V-I$ colors for early-type dwarfs and late-type giants, it differed greatly from the observed relation as seen in Figure 1 (*thick line*). The passband was adjusted in various ways, and eventually a passband with the original red edge but with a blue edge shifted redward by about 30 nm gave quite good agreement with the observations. The colors computed for the individual Vilnius spectra using the revised *Hipparcos* passband are shown in Figure 1 as plus signs; the three upper plus signs redward of $V-I=1.0$ are for K-dwarf spectra. Although the agreement is not perfect, given the uncertainties involved, it is not really worthwhile to attempt further modifications of the band on the basis of these data. As it stands, the adopted passband is adequate to produce useful synthetic magnitudes from grids of model atmosphere fluxes. Such computations are being done by Bessell & Castelli (2000). In Figure 2 the original and revised H_P passbands are shown with the standard V for comparison.

2.2. The V_T and V Magnitudes

In Figure 3 are plotted the observed differences between standard V and *Tycho* V_T for the E- and F-region standards. Also shown is the straight line suggested in the HTC

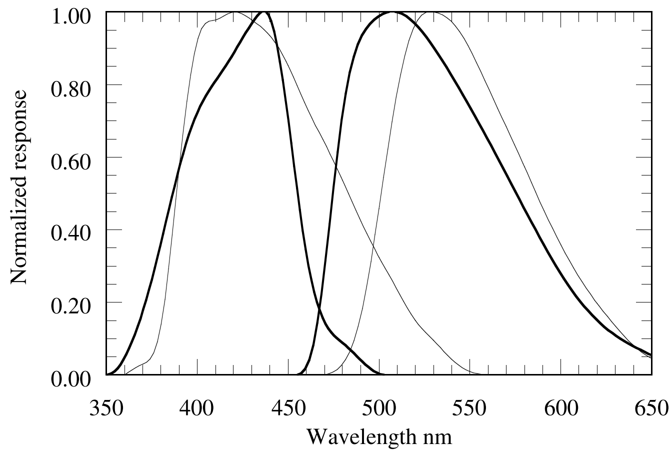

FIG. 5.—$\lambda R(\lambda)$ responses of the B_T and V_T passbands (*thick lines*) compared with the B and V passbands (*thin lines*).

as approximating the relationship, namely, $V - V_T = -0.09$ $(B_T - V_T)$, and a cubic that better fits the data.

Although a cubic is better than a straight line, the data deviate systematically from the cubic and are best represented by a spline. In Table 2 the observed mean relation between $V - V_T$ and $B_T - V_T$ is listed.

The $V - V_T$ and $B_T - V_T$ colors were synthesized from the Vilnius spectra and compared with the observations. Here the agreement was much better. The modified (photon counting) B_T and V_T passbands reproduced the observed relations quite well. The synthetic data are plotted in Figure 3 as plus signs. They fit well except for the late M giants.

Figure 4 shows the difference between $B - V$ and $B_T - V_T$ as a function of $B_T - V_T$ color. The straight line is the approximate relation suggested in the HTC for stars other than M stars. The curve is a fourth-order polynomial fit. Although better than the straight line, there are still systematic deviations from the curve resulting mainly from the Balmer jump and the confluence of the hydrogen lines. The mean empirical relation has been derived and is given in Table 2. The heading $\Delta(B - V)$ in Tables 1 and 2 refers to $(B - V) - (B_T - V_T)$. The plus signs show the synthetic photometry which now agrees well. In Figure 5 are shown the adopted B_T and V_T passbands in comparison with the standard B and V passbands. Table 3 lists the adopted passbands for H_P, B_T, and V_T.

3. SUMMARY

Comparison between the E-region standard *UBVRI* magnitudes and the H_P, B_T, and V_T magnitudes from the *Hipparcos* and *Tycho* Catalogues for the same stars has yielded improved relations between the systems. Synthetic photometry carried out with the Vilnius spectra for H_P, B_T, V_T, B, and V were also compared with the observations, and as a result a large modification was necessary to the H_P bandpass. The revised relations and passbands are shown in a series of figures and tables. These should permit better calibration of the *Hipparcos* and *Tycho* photometry using model atmosphere fluxes.

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