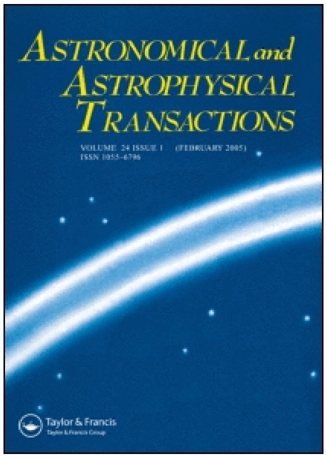

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

SPECTROPHOTOMETRIC AND PHOTOMETRIC STUDIES OF THE STARS

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Online Publication Date: 01 April 2003
To cite this Article: Knyazeva, L. N. and Kharitonov, A. V. (2003) 'SPECTROPHOTOMETRIC AND PHOTOMETRIC STUDIES OF THE STARS', Astronomical & Astrophysical Transactions, 22:2, 125 - 133
To link to this article: DOI: 10.1080/1055679031000084777
URL: http://dx.doi.org/10.1080/1055679031000084777

Astronomical and Astrophysical Transactions,
2003, Vol. 22(2), pp. 125–133

SPECTROPHOTOMETRIC AND PHOTOMETRIC STUDIES OF THE STARS

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(Received 29 May 2002)

We present here the use of the numerous spectrophotometric and photometric data to derive the different parameters of stars and Sun.

Keywords: Stars; Spectrophotometry; Photometry; Energy distribution; Standards

1 INTRODUCTION

This article is a review of studies on the use of the numerous spectrophotometric and photometric data to derive different parameters of the stars and the mean characteristics of spectral subclasses. The intrinsic energy distribution is one of the most important mean characteristics of a spectral subclass, which is needed for the theory of stellar photospheres and for analysis of different photometric systems. Intrinsic energy distributions have been studied in numerous publications. One of the most popular investigations is that of Sviderskiene (1988). It should be noted, however, that Sviderskiene used data from a number of literature sources and did not examine the homogeneity of the data obtained by different methods, with different techniques and with different binnings of the wavelengths. In his work, little attention was devoted to the problem of reliability of the results obtained. Also there was the problem related with the MK spectral classification which has been modified in the last few years.

Investigation of the Sun as the star, the search for its place among the stars, and the comparison of its photometric parameters with those of stars of the same spectral type are of interest. The colour indices are most appropriate for this aim, but observations of the Sun and the stars with the same equipment are difficult. There are some indirect methods for determinations of the solar colour indices. One of these is based on the solar energy distribution. The color indices of the Sun can be calculated using its energy distribution and the response curves of any photometric system.

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ISSN 1055-6796 print; ISSN 1476-3540 online
DOI: 10.1080/1055679031000084777

2 THE INTRINSIC ENERGY DISTRIBUTIONS

The intrinsic energy distributions were derived for 69 spectral subclasses in the wavelength region 3200–7600 Å in the following way.

(i) The sources for spectrophotometric data were three spectrophotometric catalogues (Glushniva, 1982; Kharitonov *et al.*, 1988; Alekseeva *et al.*, 1992) containing energy distributions for about 2000 stars of different spectral types. Two of these catalogues were created with the same method and are based on the same standard system. Comparisons of the data from these three catalogues showed sufficiently close agreement between them.

(ii) MK spectral classes were taken from *The Bright Star Catalogue* (Hoffleit, 1982). When analysing A0–A2V spectral types we took into account the paper by Gray and Garrison (1987) to examine the influence of errors in spectral classification.

(iii) *UBV* photometry for selected stars was taken from *The Bright Star Catalogue* (Hoffleit, 1997). We excluded from the investigation all known peculiar, double and variable stars.

(iv) The estimation that our list of stars with known spectrophotometric data in each subclass was sufficient to characterize the whole spectral subclass was made in the following way. We compared the mean $B - V$ and $U - B$ colour indices calculated from our lists with the mean values of the same colour indices obtained for very large lists of stars of the same spectral type from *The Bright Star Catalogue* with full *UBV* photometry. The differences does not exceed a magnitude of 0.01–0.02 in most cases. Unfortunately, it was not possible to make this comparison for O and early B spectral subclasses where some of stars are reddened. We assume that the most used stars are unreddened stars for the following reasons.

  (a) All stars are sufficiently bright (V less than a magnitude of 6.5). Trigonometric parallax occurs for most of them. They are in the neighbourhood of the Sun and far from the Galactic plane.

  (b) The records of spectra from the ultraviolet spectrophotometric catalogues OAO, TD-1 and IUE from CDS (Strasburg) were used. The absence of the $\lambda = 2200$ Å band in the spectrum of a star confirmed the absence of essential reddening.

  (c) For each subclass, the $B - V$ *versus* V relationships did not show a systematic trend of $B - V$ with V. This provided evidence that notable interstellar reddening is absent. The correction for interstellar reddening was made only for the O–B supergiants of early spectral subclasses using the relation

$$E_0(\lambda) = \frac{E(\lambda)}{\tau(\lambda)^{E(B-V)}},$$

where $E_0(\lambda)$ is the energy distribution distorted by interstellar reddening, $E(B - V)$ is the colour excess and $\tau(\lambda)$ is the optical depth per unit mass of interstellar matter according to Straizys (1992). These data were based on numerous observations of the stars. The interstellar reddening law depends only weakly on direction and therefore we used the same $\tau(\lambda)$ curve over the entire sky.

The comparison of our results with the those of Sviderskiene (1988) were made in spectral range 3200–7600 Å. The largest discrepancies from 4% to 14% are in region 3200–3800 Å for early spectral types. Our results can be found at http://cdsweb.u-strasbg.fr/catalogue/.

We compared the intrinsic colour indices calculated in the three photometric systems on the basis of our intrinsic energy distributions and the response curves of these systems with those derived from photometric observations in order to check the consistency between the intrinsic energy distributions and the intrinsic colour indices in these systems. Colour indices can be calculated in any photometric system provided that a reliable energy distribution and the response curves of system are available. The following formula modelling the photometric observations was used:

$$m_i - m_j = -2.5\log\frac{(E_{*,i}(\lambda)\phi_i(\lambda)\ d(\lambda)}{E_{*,j}(\lambda)\phi_j(\lambda)d(\lambda)} + C_{i,j}, \tag{1}$$

where $E_{*,i}(\lambda)$ and $E_{*,j}(\lambda)$ are the energy distributions of the star in the response curve band of the appropriate filters. $\phi_i(\lambda)$ and $\phi_j(\lambda)$ are the response curves of the photometric system; $C_{i,j} = (m_i - m_j)_{\mathrm{O}bs} - (m_i - m_j)_{\mathrm{C}alc}$ are the constants defining the zero point of the calculated colour indices. These constants are estimated with the help of a star having a reliable energy distribution and observed colour indices.

We compared the observed and calculated colour indices for numerous stars in the three photometric systems (*WBVR* (Kornilov *et al.*, 1991), *uvby* (Crawford and Barnes, 1970) and Vilnius (Straizys and Kazlauskas, 1993)) to estimate the errors in the calculated colour indices (Knyazeva and Kharitonov, 2000). For this purpose the lists of single non-variable stars of different spectral subclasses were selected from *The Spectrophotometric Catalogue of Stars* published by Kharitonov *et al.* (1988). The accuracy of the energy distributions of these stars is 1.5–2% in spectral region 4000–6000 Å and 2–3% at the violet and red edges. The response curves were taken from the work of Kodaira (1975) (*uvby*), Kornilov *et al.* (1991) (*WBVR*), Straizys, Zdanavichus (1970) (Vilnius). To define the zero point the primary spectrophotometric standard Vega was used. The energy distribution of Vega was taken from the data of Kharitonov *et al.* (1988). The absolute scale of this catalogue is based on the absolute energy distribution of Vega derived by Hayes (1985). One can exclude the errors of the absolute calibration from the calculated colour indices using these data for Vega. In Table I the results of the comparison of the observed and calculated colour indices in three photometric systems are presented. Δ is the mean difference between the observed and calculated colour indices and σ is the mean square error. This table shows that the differences between the calculated and observed colour indices are within the limits of the discrepancies of the observed colour indices obtained by different workers in the various photometric systems used. Good agreement between the calculated and observed colour indices for the same stars in the three photometric systems confirms the reliability of these response curves. The close agreement of the calculated and observed colour indices is due to the reliable spectrophotometric data, the reliable response curves and the correct definition of zero point.

For the reasons given above, one can use a comparison of the intrinsic calculated colour indices and those derived from photometric observations to check our intrinsic energy

TABLE I The Results of the Comparison of the Calculated and Observed Colour Indices in the Three Photometric Systems.

UPXYZVS, $n=35$	*uvby*, $n=17$	*WBVR*, $n=61$
$\Delta(U-P)=0.015$	$\Delta(b-y)=-0.006$	$\Delta(W-B)=0.014$
$\sigma(\Delta(U-P))=0.031$	$\sigma(\Delta(b-y))=0.013$	$\sigma(\Delta(W-B))=0.034$
$\Delta(P-X)=0.003$	$\Delta(v-b)=0.001$	$\Delta(B-V)=-0.009$
$\sigma(\Delta(P-X))=0.030$	$\sigma(\Delta(v-b))=0.012$	$\sigma(\Delta(B-V))=0.015$
$\Delta(X-Y)=0.000$	$\Delta m_1=0.007$	
$\sigma(\Delta(X-Y))=0.018$	$\sigma(\Delta m_1)=0.019$	
$\Delta(Y-Z)=0.011$		

distributions. We made these comparisons in the three photometric systems to find, firstly, the possible errors of the intrinsic colour indices derived from photometric observations in these systems and, secondly, the location of the P and X bands of the Vilnius photometric system and the B band of the *WBVR* system involving the spectral region near the Balmer discontinuity where there is the same uncertainty in the spectrophotometric data due to the difficulty in determining the continuum level in the spectra of standard stars. The *u* and *v* bands of the *uvby* system do not involve this problematic region and can be used to check this important spectral region before and after the Balmer discontinuity. The reliability of our intrinsic energy distributions at $\lambda > 6000$ Å could be estimated only using the *B* and *V* bands of the *WBVR* system. Unfortunately, the intrinsic colour indices derived from photometric observations were available only in the Vilnius system. We derived the intrinsic colour indices from photometric observations in the *WBVR* and *uvby* systems using the data from Kornilov *et al.* (1991) and Hauck and Mermilliod (1998).

A comparison of the intrinsic calculated and observed colour indices in the three photometric systems is given in Table II. This table presents the characteristic of the consistency of our intrinsic energy distributions and the intrinsic colour indices. Moreover this table allows us to estimate the reliability of the intrinsic colour indices derived from the photometric observations in these systems.

3 THE SOLAR COLOUR INDICES AND POSSIBLE SOLAR ANALOGUES

On the basis of the above-mentioned comparisons we believe that one can calculate the colour indices of the Sun using the energy distribution in its spectrum and the response curves of the any photometric system. Until recently we used the mean solar energy distribution obtained by Makarova *et al.* (1991) on the basis of corrected observations. It was found that these data could not be used to calculate the colour indices. The absolute energy distribution of the Sun is obtained from comparing it with reference sources, which are calibrated with the primary standard model of a black body. The procedure of calibration of the Sun is difficult. The reliability of results depends to a large degree on how precisely the observer has transferred the temperature scale from the standard source to the Sun. In their calibrations of the Sun different researchers have used various reference sources calibrated in different laboratories and no cross-comparisons were made. Most known data about the energy distribution in a spectrum of the Sun (Arvesen *et al.*, 1969; Neckel and Labs, 1984; Lockwood *et al.*, 1992; Burlov-Vasilijev *et al.*, 1992) have the differences in the ultraviolet of up to 10% and in the near infrared of up to 6%, which may be caused by the above-mentioned reasons. It is possible to exclude the errors of the absolute calibration in the calculations of colour indices if constants are calculated by defining the zero point of the calculated indices using a star calibrated with the same reference source as the Sun. Taking that into account we used, in our calculations of colour indices, only the data obtained by Lockwood *et al.* (1992). These workers have calibrated the solar spectrum with reference to Vega, using for it the absolute energy distribution that they obtained earlier (Tug *et al.*, 1977). We transformed our data for the integral spectrum of Vega into the absolute calibration made by these workers and used the results obtained for calculation of the fixed zero-point constants. Thus we eliminate the absolute calibration as it enters both the addend of the formula for calculation of the colour indices but with different signs. The solar colour indices were calculated in the *UBV* (only $B - V$), *WBVR*, *uvby* and Vilnius photometric systems. The results are listed in Table III.

TABLE II The Results of the Comparison Between the Intrinsic Calculated and Observed Colour Indices.

Sp	$\delta(U-V)$	$\delta(P-V)$	$\delta(X-V)$	$\delta(Y-V)$	$\delta(Z-V)$	$\delta(V-S)$	$\delta(W-V)$	$\delta(B-V)$	$\delta(b-y)$	δm_1	δc_1
B1V	0.015	0.047	0.045	0.026	0.013	−0.032	0.108	0.067	—	—	—
B2V	−0.068	−0.019	0.005	0.001	0.003	−0.033	0.066	0.045	—	—	—
B3V	−0.077	−0.040	−0.015	0.016	0.009	−0.025	−0.017	0.012	—	—	—
B5V	0.011	0.014	0.008	0.022	0.009	−0.047	0.026	0.016	0.004	−0.002	0.030
B7V	0.031	0.012	0.022	0.032	0.022	−0.037	−0.022	0.005	0.017	−0.002	−0.037
B8V	0.030	0.037	0.029	0.017	0.007	−0.064	−0.001	0.008	−0.002	0.011	−0.034
B9B	0.179	0.150	0.061	0.031	0.021	−0.026	0.003	−0.002	0.000	0.011	0.054
B9.5V	—	—	—	—	—	—	—	—	−0.002	0.004	0.006
A0V	0.024	0.043	0.010	0.014	0.007	−0.019	−0.018	−0.018	−0.019	0.011	−0.037
A1V	0.033	0.056	0.040	0.025	0.014	−0.030	−0.014	−0.009	−0.008	0.012	−0.022
A2V	0.011	0.039	0.042	0.020	0.009	−0.027	−0.018	−0.013	−0.017	0.026	−0.025
A3V	0.014	0.058	0.058	0.029	0.009	−0.038	0.017	0.004	−0.009	0.011	−0.019
A4V	—	—	—	—	—	—	0.037	0.013	0.010	0.003	−0.019
A5V	0.016	0.050	0.065	0.023	0.019	−0.051	0.017	0.012	−0.003	0.012	−0.005
A7V	−0.053	0.039	0.061	0.021	0.012	−0.023	0.012	−0.013	−0.006	0.029	−0.072
F0V	−0.049	0.001	0.038	0.023	0.008	−0.036	−0.013	−0.028	−0.018	0.017	0.003
F5V	0.009	0.021	0.037	0.016	0.000	−0.014	−0.003	−0.008	−0.005	0.016	−0.012
F6V	—	—	—	—	—	—	0.014	−0.033	−0.013	0.010	0.035
F7V		—	—	—	—	—	0.041	−0.011	−0.013	0.009	0.053
F8V	0.023	0.022	0.013	0.006	−0.002	−0.049	0.042	−0.014	−0.013	0.013	0.000
G0V	0.069	0.065	0.027	0.015	−0.005	−0.019	0.003	−0.021	−0.013	0.010	0.041
G2V	−0.025	−0.029	−0.006	0.023	0.012	−0.029	0.003	−0.006	−0.006	−0.006	0.009
G5V	−0.028	0.002	−0.006	0.002	−0.007	−0.018	—	—	−0.025	0.012	−0.033
G8V	0.057	0.061	−0.010	0.003	0.001	−0.034	−0.079	−0.047	−0.018	−0.022	0.014
B2IV	0.039	0.042	0.012	−0.002	0.009	−0.051	0.031	0.013	0.000	0.024	−0.007
B3IV	−0.070	−0.060	−0.029	−0.018	−0.010	−0.067	−0.004	0.024	0.015	0.019	−0.049
B5IV	0.080	0.065	0.016	0.006	0.001	−0.036	0.028	0.024	0.015	0.012	−0.031
B9IV	0.224	0.133	0.048	0.021	0.012	−0.004	−0.101	−0.020	−0.011	0.012	−0.049
A3IV	0.039	0.020	0.012	0.011	0.003	−0.048	−0.015	−0.022	0.007	0.008	−0.010
A7IV	0.010	0.013	0.040	0.026	0.011	−0.010	0.002	−0.034	−0.014	0.014	−0.006
F0IV	−0.024	0.015	0.078	0.051	0.018	−0.013	−0.045	0.014	0.005	0.010	−0.098
F2IV	−0.018	0.016	0.021	0.017	0.005	−0.061	0.005	−0.009	0.000	0.014	−0.029
F5IV	0.066	0.048	0.069	0.037	0.013	−0.043	0.012	0.008	0.012	0.004	−0.002
B2III	0.041	0.040	0.053	0.020	0.025	−0.069	—	—	—	—	—
B5III	−0.107	−0.040	0.005	−0.005	0.001	−0.066	−0.065	0.002	0.002	0.041	−0.166
B6III	−0.035	−0.041	−0.025	−0.022	−0.005	−0.052	0.026	−0.013	—	—	—

TABLE II *(Continued)*.

Sp	$\delta(U-V)$	$\delta(P-V)$	$\delta(X-V)$	$\delta(Y-V)$	$\delta(Z-V)$	$\delta(V-S)$	$\delta(W-V)$	$\delta(B-V)$	$\delta(b-y)$	δm_1	δc_1
B7III	0.095	0.067	0.021	0.014	0.015	−0.046	−0.002	0.015	0.016	0.001	−0.040
B8III	0.157	0.104	0.021	0.010	0.013	−0.033	−0.019	0.021	−0.003	0.048	−0.142
B9III	0.166	0.077	−0.003	0.007	0.007	−0.030	−0.038	−0.017	−0.010	0.008	−0.030
A0III	0.173	0.105	0.070	0.034	0.026	0.029	−0.016	0.003	0.002	0.016	−0.037
A3III	0.006	−0.002	−0.005	0.000	0.002	−0.029	0.011	−0.011	−0.005	0.025	−0.006
A5III	0.125	0.050	0.052	0.017	0.008	0.000	0.046	0.008	0.001	0.023	−0.021
A7III	0.064	0.044	0.072	0.036	0.021	−0.036	0.015	0.003	0.001	0.018	−0.037
F0III	−0.057	−0.010	0.067	0.027	0.015	−0.023	−0.047	0.011	0.013	0.049	−0.269
G7III	—	—	—	—	—	—	—	0.055	—	—	—
G8III	—	0.061	0.027	0.007	0.000	−0.025	—	−0.017	—	—	—
G9III	—	—	—	—	—	—	—	−0.029	—	—	—
K0III	—	0.122	0.058	0.024	0.010	−0.026	—	0.004	—	—	—
K1III	—	0.183	0.108	0.044	0.023	−0.014	—	0.002	—	—	—
K2III	—	0.100	0.049	0.026	0.009	−0.033	—	−0.017	—	—	—
K3III	—	0.014	−0.028	−0.023	−0.014	−0.057	—	−0.013	—	—	—
K4III	—	−0.075	−0.072	−0.050	−0.015	−0.055	—	−0.026	—	—	—
K5III	—	0.044	0.033	0.012	0.013	−0.063	—	−0.016	—		—
M0III	—	0.068	0.049	0.017	0.017	−0.035	—	−0.021	—	—	—
M1III	—	0.204	0.103	0.031	0.015	−0.023	—	0.005	—	—	—
M2III	—	0.220	0.076	0.030	0.022	−0.003	—	−0.015	—	—	—
M3III	—	0.121	0.044	0.020	0.002	−0.007	—	−0.005	—	—	—
M4III	—	0.071	−0.030	0.020	−0.015	−0.007	—	−0.001	—	—	—
M5III	—	0.108	0.025	0.092	0.042	−0.022	—	0.013	—	—	—
B1Iab	−0.123	−0.045	0.011	−0.012	0.002	−0.039	—	—	—	—	—
B2Iab	−0.003	0.006	0.017	−0.000	−0.009	−0.062	—	—	—	—	—
B5Iab	0.036	−0.004	0.022	0.008	−0.002	−0.049	—	—	—	—	—
B9Iab	0.007	−0.013	0.029	0.025	0.005	−0.082	—	—	—	—	—
G2Iab	−0.150	−0.098	−0.068	−0.049	−0.015	−0.061	—	—	—	—	—

TABLE III The Calculated and Observed Solar Colour Indices in Different Photometric Systems.

Calculated	*Observed*	*Calculated*	*Observed*
UBV		*UPXYZVS*	
$B-V=0.634$	0.62–0.68	$U-P=0.466$	$Z-V=0.213$
WBVR		$P-X=0.656$	$V-S=0.501$
$W-B=-0.06$	−0.05	$X-Y=0.832$	
$B-V=0.66$	0.67	$Y-Z=0.333$	
uvby			
$b-y=0.404$			
$m_1=0.217$			
$c_1=0.373$			

The solar colour indices were obtained from a direct comparison of the Sun with stars in the *WBVR* photometric system (Mironov *et al.*, 1998). The observations were made at the Tjan-Shan station (altitude, 2800 m) together with the collaborators from the Moscow State University. The results are given in Table III. There is close agreement for the calculated and observed colour indices.

We compared the solar colour indices with those for the single non-variable G2V stars. Figure 1 presents a diagram of $b-y$ *versus* $v-b$. It was plotted on the basis of the *uvby* observations of the stars in the solar neighbourhood. In the *uvby* system the $m_1=(v-b)-(b-y)$ index may be used to estimate the metal abundance of the F8V–G5V stars. Comparison of the of $b-y$ *versus* m_1 and $b-y$ *versus* $v-b$ diagrams shows identical m_1 and $v-b$ dependences on the $b-y$ colour indices. Therefore we used the diagram of $b-y$ *versus* $v-b$ to make a rough estimation of the metallicity of selected stars. The main sequence of the stars of Hyades serves as the standard. Most G2V stars are metal-poor stars because they lie lower than the Hyades stars. The calculated solar colour indices are locate the Sun as among Hyades. The photometric system *uvby* is of interest to search for solar analogues because the *uvby* catalogue contains numerous stars of spectral subclasses close to the solar type. We have selected from this catalogue all stars having $b-y$ values of magnitudes from 0.398 to 0.410. Accepted limits for the $b-y$ index are based on its value for the Sun and the observational errors of this index. Thus 250 stars were selected on this basis. All known variable and double stars were excluded from this review. Taking account of the observational errors of the m_1 and c_1 indices we selected

TABLE IV The List of Possible Solar Analogues.

HD	*V*	$b-y$	m_1	c_1	*Sp*
6 517	8.15	0.407	0.215	0.374	
9 175	7.80	0.407	0.210	0.373	G0V(G5IV)
15 064	6.17	0.405	0.217	0.378	
18 993	8.23	0.404	0.227	0.384	
44 594	6.60	0.408	0.214	0.370	G0V(G4V)
45 289	6.67	0.409	0.213	0.373	(G5V)
45 701	6.46	0.406	0.224	0.374	G0V(G3III-IV)
79 985	7.5	0.405	0.217	0.380	G5IV(G1V)
80 332	7.0	0.405	0.211	0.367	G0V(G3III-IV)
111 513	7.35	0.406	0.211	0.364	G1V(G1V)
158 783	6.8	0.407	0.210	0.378	G5IV
159 222	6.56	0.406	0.216	0.364	G5V(G5V)
184 525	7.9	0.402	0.217	0.360	G0V

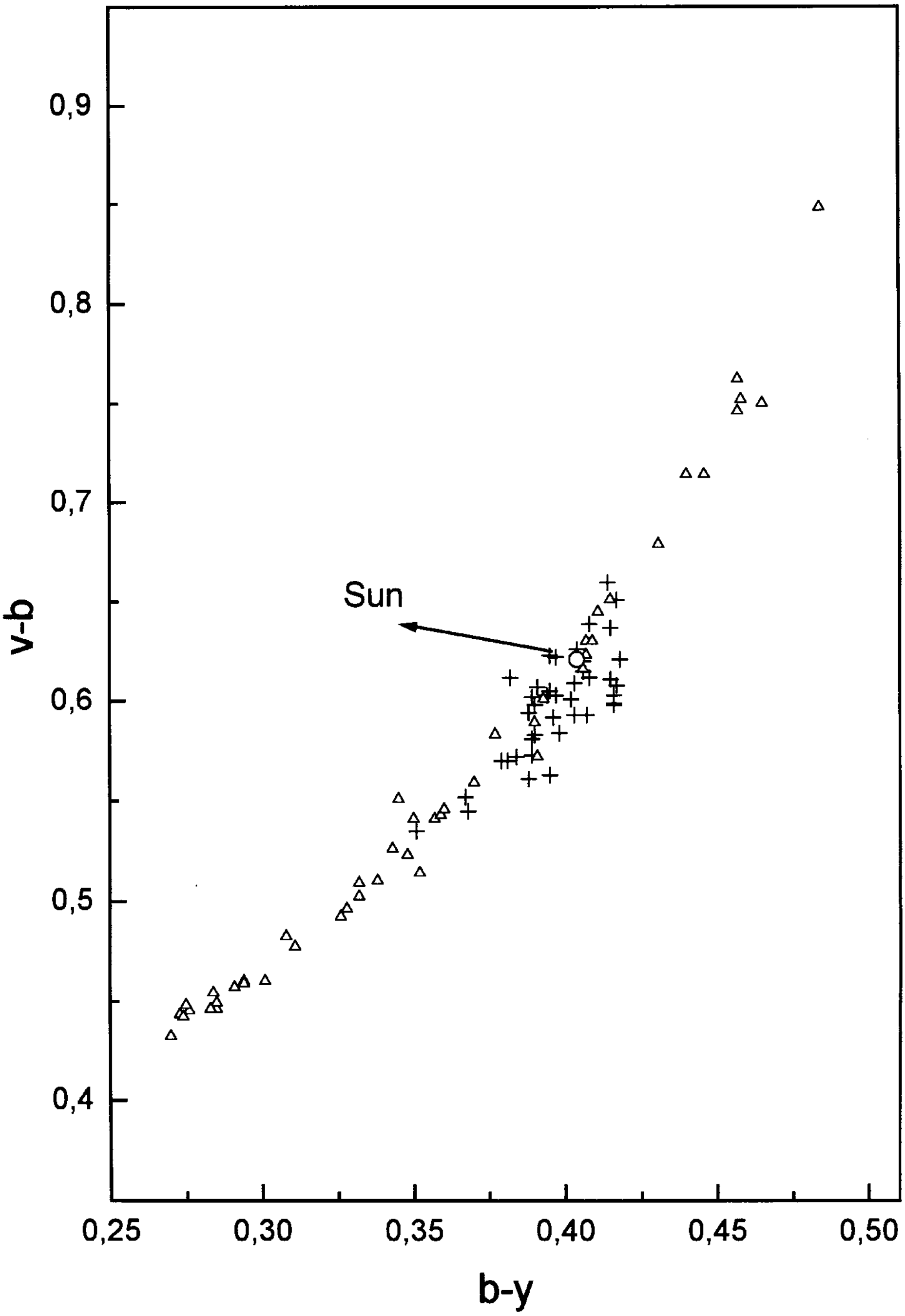

FIGURE 1 A plot of $b-y$ *versus* $v-b$. Open triangles – Hyades stars; plus signs – G2V stars.

from this list, stars having m_1 and c_1 close to the solar values. The list of these stars together with their photometric data are given in Table IV.

Currently we are deriving the effective temperatures of the solar analogues and their locations on the ZAMS (Zero Age Main Sequence).

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