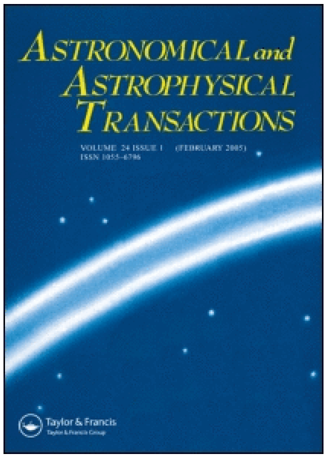

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I. N. Glushneva [a]; V. I. Shenavrin [a]
[a] Sternberg State Astronomical Institute, University of Moscow, Moscow, Russia

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BRIGHT SPECTROPHOTOMETRIC STANDARDS: ENERGY DISTRIBUTION AND PHYSICAL PARAMETERS OF ATMOSPHERES

I. N. GLUSHNEVA and V. I. SHENAVRIN

Sternberg State Astronomical Institute, University of Moscow, 13 Universitetskij Prospect, 119899, Moscow, Russia

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Eleven stars of B and A spectral types were chosen from the catalogue of 238 spectrophotometric standards, based on the Moscow and Alma-Ata catalogues. These stars are not variable or suspected variable and monochromatic flux measurements in the near IR range obtained at the Sternberg Institute Crimean station are available for them. Comparison of the synthetic and photometric system indices observed in the $WBVR$ demonstrates good agreement for $B - V$ indices and statisfactory agreement for $V - R$ indices. For those stars of 3–4 mag proposed as spectrophotometric standards, effective temperature, bolometric correction, radius, angular diameter and luminosity have been obtained by means of the infrared flux method.

KEY WORDS Spectrophotometry, effective temperature, infrared flux method

1 INTRODUCTION

In the process of the creation of two large spectrophotometric catalogues – the Moscow and Alma-Ata catalogues eight bright standards of 0–2 mag were used: α Lyr, α Aql, α Peg, α Leo, β Ari, β Tau, γ Ori, η UMa (Voloshina *et al.*, 1982; Kharitonov *et al.*, 1988). Each of these catalogues includes energy distribution data for about 1000 stars obtained on the basis of comparison with one or several standard stars.

The programme of observations of spectrophotometric standards of 7–8 mag were begun at the Sternberg Institute Crimean Station as part of the preparation for the space project Lomonosov. The results, including energy distribution data for 60 stars in the range 3400–7500Å, are presented in the paper by Biryukov *et al.* (in press).

In the catalogue of 238 secondary spectrophotometric standards (Glushneva *et al.*, 1992) the energy distribution is characterized by the mean monochromatic flux in the range 3200–7600Å obtained independently at the Sternberg State Astronomical Institute and the Fessenkov Astrophysical Institute, Alma-Ata. Furthermore, this catalogue also contains near-infrared (6300–10 800Å) energy distribution data for 99 stars, obtained at the Crimean Station of the Sternberg Institute. This catalogue provides a homogeneous spectrophotometric data set for a rather wide range from 3200 to 10 800Å which may be used for the total flux determination and therefore calculation of bolometric correction, effective temperature and angular diameters of stars.

This catalogue makes it possible to choose standard stars of 3–4 mag with reliable energy distribution data.

2 CHOICE OF STARS

The catalogue of 238 spectrophotometric standards includes stars of different spectral types and luminosities common to the Moscow and Alma-Ata catalogues with differences of monochromatic fluxes less than 5% in the range 3200–7600Å. It is necessary to stress that these sets of spectrophotometric observations are fully independent. True independence and the good agreement of results obtained are evidence of the reliability of the energy distribution data presented in the catalogues. Three criteria were used in the choice of stars from the catalogue of 238 spectrophotometric standards.

(1) B and A type stars were chosen with energy distribution data available in the range 3200–7600Å and in the near-infrared (6300–10 800Å).

(2) These stars are not variable or suspected variable, i.e. they are not members of the General Catalogue of Variable Stars (fourth edition), New Catalogue of Suspected Variable Stars and Name Lists 67–71.

(3) Differences of monochromatic fluxes in the range 6300–7600Å common to the mean of the Moscow and Alma-Ata data (Glushneva *et al.*, 1992, Table 3) and near-infrared data, obtained at the Sternberg Institute Crimean Station (Glushneva *et al.*, 1992, Table 5), do not exceed 5%.

The 11 stars presented in Table 1 satisfy all of these criteria.

The list of stars contains the BS and HD numbers of stars, their magnitude and colour index $B - V$, spectral type and parallax taken from The Bright Star Catalogue (Hoffleit, 1982). Parallaxes marked by an asterisk were obtained on the basis of distances taken for stars when parallaxes are absent or negative in the Bright Star Catalogue, as in the case of the star BS 8335.

Additional evidence for the absence of significant brightness variations of these stars is the so-called class of accuracy presented in the Catalogue of WBVR magnitudes of bright northern sky stars (Kornilov *et al.*, 1991). This catalogue contains photoelectric magnitudes of 13 586 stars in four colours WBVR. The observations were done at the Sternberg Institute High-Mountain Station located near Alma-Ata, Kazakhstan at an altitude about 3000 m. All of our stars are members of this catalogue and their class of accuracy varies between 2 and 6. This means that the

Table 1. The list of stars

BS	*HD*	*V* (*mag*)	*B − V* (*mag*)	*Spectral type*	π''
269	5448	3.87	0.13	A5V	0.039
580	12216	3.98	-0.01	A2V	0.028*
1520	30211	4.02	-0.15	B5IV	0.008*
2540	50019	3.60	0.10	A3III	0.021
3690	80081	3.82	0.06	A3V	0.042
5107	118098	3.37	0.11	A3V	0.044
6396	155763	3.17	-0.12	B6III	0.023
7236	177756	3.44	-0.09	B9V$_n$	0.032
8335	207330	4.23	-0.12	B3III	0.004*
8597	213998	4.02	-0.09	B9IV-V	0.025
8634	214923	3.40	-0.09	B8V	0.023

mean square error calculated on the basis of all the measurements in all spectral bands expressed in thousandths of a magnitude for the stars from Table 1 does not exceed 0.006 mag.

3 ENERGY DISTRIBUTION IN THE RANGE 6300–7600Å

To obtain energy distribution data in the wide spectral range 3200–10 800Å it is necessary to combine monochoromatic fluxes in two ranges: 3200–7600Å and 6300–10 800Å. The differences of these two sets of spectrophotometric data do not exceed 5% as mentioned above, while the mean square error of the monochoromatic fluxes for the Moscow and Alma-Ata catalogues in the range 3200–7600Å is 3–4% (the mean value for all the stars of the catalogues). The mean square error in the near-infrared is also about 3%. Comparison of the E_λ measurements of these two sets of monochoromatic fluxes, where the first one is the mean between the Alma-Ata and Moscow data in the visual range $1/2(E_A + E_M)$, and the second is the Moscow data in the near-infrared, shows that for the stars investigated the mean difference of these sets of measurements in the common range 6300–7600Å is 3.3%. This value does not exceed the mean square errors of both sets. In some cases this value is significantly less, for example for the stars BS 8634 the mean difference is about 1%.

Good agreement of data in the visual and near-infrared ranges makes it possible to average them in the range 6300–7600Å, and this was done for all the stars from Table 1. Only for two stars, BS 2540 and BS 5107, were monochoromatic fluxes at two points near the shortwave border of the infrared range excluded. Similarly, for the stars BS 269 and BS 3690 data at wavelengths 7525, 7575 and 7625Å near the red border of the range 3200–7600Å were not taken into account.

4 SYNTHETIC COLOUR INDICES

Table 2 presents observed $B-V$ and $V-R$ colour indices from the $WBVR$ catalogue and synthetic indices calculated on the basis of energy distribution data from the catalogue by Glushneva *et al.* (1992, Tables 3 and 5) and averaged monochoromatic fluxes in the range 6300–7600Å.

Table 2. Synthetic and observed $B-V$ and $V-R$ colour indices

BS	$(B-V)_{syn}$	$(V-R)_{syn}$	$(B-V)_{obs}$	$(V-R)_{obs}$
269	0.147	0.109	0.130	0.102
580	0.038	0.008	-0.003	0.013
1520	-0.138	-0.050	-0.144	0.088
2540	0.104	0.084	0.111	0.103
3690	0.071	0.112	0.072	0.066
5107	0.108	0.108	0.119	0.081
6396	-0.083	-0.094	-0.112	-0.063
7236	-0.087	-0.081	-0.081	-0.072
8335	-0.101	-0.010	-0.117	-0.068
8597	-0.080	-0.078	-0.076	-0.060
8634	-0.094	0.020	-0.087	-0.059

Response curves for the B, V and R bands from the $WBVR$ catalogue were used. The value of $C = 0.620$ for the integration constant was taken (Kharitonov *et al.*, 1994) for the calculation of the $B-V$ colour indices. This value is the mean for four sets of bright stars with reliable energy distribution data.

For $V-R$ indices the integration constant $C = 0.448$ was taken. This was calculated on the basis of energy distribution data for Vega (Hayes, 1985) and comparison with the observed $V-R$ index from the $WBVR$ catalogue.

The mean difference of the observed and synthetic $B-V$ colour indices is 0.007 mag, for $V-R$ it is 0.000 mag, and the number of negative and positive differences is 6 and 5 for both $\Delta(B-V)$ and $\Delta(V-R)$.

The mean values of $|\Delta(B-V)|$ is 0.013 mag and $|\Delta(V-R)|$ is 0.040 mag.

Three B stars, BS 1520, BS 8335 and BS 8634, have the largest discrepancies between the synthetic and observed $V-R$ indices. These differences are most probably connected with the lower accuracy of spectrophotometric data due to poor fluxes of B stars in the near infrared. If these three stars are excluded the mean value of $|\Delta(V-R)|$ for the remaining eight stars is 0.022 mag. This value does not differ significantly from the mean $|\Delta(B-V)|$ for all eleven stars. Taking into account the internal accuracy of the spectrophotometric data in the near infrared, about 4%, the agreement between the $V-R$ synthetic and observed indices is satisfactory.

Both mean values $\Delta(B-V) = 0.007$ mag and $|\Delta(B-V)| = 0.013$ mag demonstrate good agreement between the $B-V$ synthetic and observed colour indices.

5 TOTAL FLUX

Total fluxes for the investigated stars were obtained by means of monochoromatic flux integration in the ultraviolet, visual and IR ranges with addition of infrared photometry in the range $\lambda > 10\,800$Å. In the range 1150–3200Å IUE energy distribution data were used for stars BS 269, BS 3690 and BS 8335 (Heck *et al.*, 1984). For the other stars investigated, IUE low-dispersion data are absent, so TD − 1 data were taken (Jamar *et al.*, 1976) and for BS 6396 0A0-2 measurements (Code and Meade, 1979) were also used.

For all the stars the flux contribution for $\lambda < 1150$Å was calculated in the case of IUE measurements and $\lambda < 1360$Å when TD − 1 data were available. Model atmospheres by Kurucz (1979) were used for the construction of spectra in these far ultraviolet ranges. Models were chosen for effective temperature values nearest to these taken from the $T_{\rm eff}$ scale for the corresponding spectral subtype. The effective temperature scales from the papers by Glushneva (1985) and Straizys and Kuriliene (1981) were used.

On the longwave boundary of the far ultraviolet range, monochoromatic flux values were taken for the wavelength 1162Å where IUE measurements are available and for 1360Å in the cases of TD − 1 observations.

In the range with $\lambda < 1360$Å, the maximal contributions to the total flux are 15.6% for BS 1520 and 11.2% for BS 6396. For BS 5107 A3V the contribution is only 0.07%.

In the range 3200–10 800Å spectrophotometric data obtained at the Crimean Station of the Sternberg Institute and the Alma-Ata Astrophysical Institute from the catalogue of 238 secondary spectrophotometric standards were used. These data are based on the calibration of α Lyr by Hayes (1985) for the range 3200–8000Å and by Hayes and Latham (1975) for $\lambda > 8000$Å.

In the range with $\lambda > 10\,800$Å, infrared photometry by Johnson *et al.* (1996) in the J, K and L bands was used and for BS 269, BS 2540 and BS 5107 the measurements by Blackwell *et al.* (1990) were also taken into account.

In the absence of infrared photometry data in the range with $\lambda > 10\,800$Å, the models of Kuricz were used and the "construction" of the spectra was done from the shortwave boundary at 10 775Å. Monochromatic fluxes for this wavelength were taken from Table 5 of the catalogue by Glushneva *et al.* (1992). For BS 8335 with colour excess $E_{B-V} = 0.06$ mag, energy distribution data were corrected for interstellar reddening.

The values of the total flux obtained are presented in Table 3.

6 EFFECTIVE TEMPERATURE, ANGULAR DIAMETER, RADIUS AND LUMINOSITY

The effective temperature was obtained using the infrared flux method modified by Blackwell *et al.* (1980), for eight bright spectrophotometric standards of the Moscow and Alma-Ata catalogues (Glushneva, 1993).

$R = F_{tot}/F_\lambda$ were calculated, where F_{tot} is the total flux and F_λ are the monochoromatic fluxes in the I, J, K and L Johnson photometric bands, using infrared photometry by Johnson *et al.* (1966). Monochromatic fluxes were taken also for 10 775Å near the longwave border of the near-infrared range of the Moscow spectrophotometric catalogue and for 9000Å. The last one is the mean of the monochromatic fluxes for 8975 and 9025Å, because energy distribution data are presented in our catalogue for wavelengths from 3225 up to 10 825Å in 50Å steps. In order to obtain the effective temperature we plotted R versus $T_{\rm eff}$ for log g = 3.5, 4.0 and 4.5 using the atmosphere model of Kurucz (1979).

As mentioned repeatedly (for example, in the papers by Glushneva, 1989, 1993) systematic differences between the temperatures obtained using photometric measurements in different infrared bands were found. These differences are connected with calibration, so it is interesting to compare the effective temperature estimations T_I, T_J (effective wavelengths 0.9 μm and 1.25 μm, respectively) with T_{9000} and $T_{10\,775}$ obtained on the basis of the monochoromatic fluxes at 9000Å and 10 775Å.

For the majority of stars investigated $T_{10\,775}$ and T_{9000} are less then T_I and these differences may also be connected with calibration.

T_I are nearer to T_{9000}, and $T_{10\,775}$ to T_J; that seems to be natural.

Effective temperatures T_I, T_{9000}, $T_{10\,775}$, T_J

BS	T_I	T_{9000}	$T_{10\,775}$	T_J
2540	8360	8190	7700	7720
5107	8460	8320	7910	8070
7236	11390	11960	11100	10830

The effective temperatures presented in Table 3 were obtained as the mean of T_I, T_{9000}, $T_{10\,775}$ and T_J, T_K, T_L if longwave measurements were available. The angular diameter was calculated from the total flux and mean effective temperature

Table 3. The physical parameters of the stars: total flux ($w\ m^{-2}$), bolometric correction B.C., effective temperature, angular diameter Θ'' (milliarcsec), Radius $R/R_\odot$, Luminosity log $L/L_\odot$, log $M/M_\odot$, log g.

BS	F_{tot}	*B.C.*	T_{eff}	Θ	$R/R_\odot$	$log\, L/L_\odot$	$log\, M/M_\odot$	$log\, g$
269	6.96×10^{-10}	0.01	8060	0.704	1.94	1.152	0.26	4.13
580	7.23×10^{-10}	−0.14	9030	0.571	2.19	1.456	0.32	4.09
1520	1.80×10^{-9}	−1.17	14367	0.356	4.78	2.940	0.72	3.81
2540	9.12×10^{-10}	−0.10	8072	0.803	4.11	1.844	0.36	3.64
3690	8.23×10^{-10}	−0.12	8573	0.676	1.73	1.160	0.30	4.27
5107	1.12×10^{-9}	0.00	8290	0.844	2.06	1.296	0.30	4.08
6396	2.85×10^{-9}	−0.82	12330	0.608	2.84	2.224	0.68	4.22
7236	1.70×10^{-9}	−0.53	11350	0.554	1.86	1.712	0.41	4.32
8335	2.52×10^{-9}	−1.74	16980	0.302	8.12	3.688	0.94	3.57
8597	9.76×10^{-10}	−0.50	11130	0.437	1.88	1.684	0.41	4.31
8634	1.71×10^{-9}	−0.49	10997	0.592	2.77	2.000	0.48	4.04

These values are presented in Table 3 also with $R/R_\odot$ calculated using the angular diameter and parallax. Table 3 also contains the bolometric correction, luminosity and log g, obtained for log $M/M_\odot$ taken from Straizys and Kuriliene (1981).

7 DISCUSSION

The comparison of the total flux obtained in this paper with the data by Blackwell *et al.* (1990) for three common stars BS 269, BS 5107 and BS 2540 shows that they are in good agreement. The mean differences of F values are 2.3% and for BS 5107 the fluxes are equal. The differences of the mean effective temperatures are less than 1% and for BS 2540 $T_{\rm eff}$ are also equal.

In the paper by Blackwell *et al.* (1990) the infrared flux method modified by Blackwell *et al.* (1980) was also used. The differences of effective temperatures from Table 3 and from the paper by Blackwell *et al.* (1990) are within the limits of accuracy of the infrared flux method, which is about 1%.

For the majority of the stars considered here, one can compare the values of the physical parameters from Table 3 with the results obtained earlier (Glushneva 1985, 1989, 1993). Some differences in total flux (about $\sim 3\%$) are connected with initial data: in earlier papers only data from the spectrophotometric catalogue of the Sternberg Institute were used, but in this paper data from the catalogue of 238 spectrophotometric standards were used. The α Lyr calibration used in earlier papers (Glushneva 1985, 1989) differs also from the calibration by Hayes (1985).

Effective temperatures differ systematically by about 3.7% and that is connected with the method of determination of $T_{\rm eff}$. In the papers by Glushneva (1985, 1989) the basic photometric band was the K band with effective wavelength 2.2 μm and $T_{\rm eff}$ obtained in the other bands was transformed to the "K system" and then averaged. The $T_{\rm eff}$ values presented in Table 3 for the majority of stars are based on measurement in the I band and spectrophotometry at wavelength 9000Å and 10 775 Å.

As was shown by Glushneva (1985) and Glushneva *et al.* (1993) effective temperatures obtained on the basis of measurements in the I and K bands differ systematically and T_I are less than T_K. So the choice of photometric system is important and the simple procedure of averaging the data using measurements in different photometric bands is not a guarantee of the absence of systematic errors.

8 CONCLUSIONS

For the 11 stars of 3–4 mag belonging to the B and A spectral types chosen from the catalogue of 238 spectrophotometric standards reliable energy distribution data are available in a wide spectral range 3200–10 800Å.

These stars are not variable or suspected variable and the absence of brightness variations, excluding the internal accuracy of $WBVR$ photometry, makes it possible to use them as spectrophotometric standards.

Comparison of $B - V$ synthetic colour indices calculated on the basis of energy distribution data shows good agreement with observed indices obtained at a place with good seeing and altitude about 3000 m above sea level. This comparison is additional evidence for the reliability of the energy distribution data.

Spectrophotometric data in the near-infrared may be used for the determination of effective temperature by means of the infrared flux method. $T_{\rm eff}$, based on spectrophotometric measurements in the range T_{9000} and $T_{10\,775}$, are in good enough agreement with the results based on photometry in the I and J bands respectively in spite of possible differences in photometric and spectrophotometric calibrations.

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