ENERGY DISTRIBUTION, PHOTOMETRY AND PHYSICAL CHARACTERISTICS OF THE SUN AND SOLAR ANALOGS

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ABSTRACT: Color indices of solar analogs in the Vilnius seven-color photometric system are discussed. The physical parameters (effective temperatures, radii and luminosities) for solar analogs with reliable spectrophotometric and photometric data were obtained by means of infrared fluxes. The effective temperatures of 16 Cyg A and B, which are considered to be the closest solar analogs are 5854 and 5664 K, respectively. The radii of both stars are in the range of 1 $R_0 < R < 1.4\ R_0$ and luminosities $1.2\ L_0 < L < 2.1\ L_0$ for 16 Cyg A and $L_0 < L < 1.7 L_0$ for 16 Cyg B depending on different evaluations of the distances. We find that the relative solar energy distribution in the 0.33 - 1.25 μm range determined by Neckel and Labs (1984) is reliable enough, however the absolute fluxes are slightly too low at the maximum of energy distribution.

1. INTRODUCTION

The comparison of the physical parameters of stars and the Sun is of great importance since the Sun serves as a standard in many astrophysical investigations. In the present paper we are checking the reliability of the solar energy distribution data using multicolor photometry of stars. We then compare solar and stellar physical parameters.

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2. SOLAR ANALOGS

The list of stars which are similar to the Sun in spectral type (Table I) was compiled from the paper by Taylor (1984) and from the spectrophotometric catalog of the Sternberg Astronomical Institute (Glusneva et al. 1982). As a rule the stars with infrared photometric data up to the K band were included. Their effective temperatures T_{eff} and angular diameters Θ were obtained by means of the method of infrared fluxes (Blackwell and Shallis 1977). In this case the basic data are the total flux of the radiation and the monochromatic infrared flux emitted from the stellar surface and determined from model atmospheres. The strength of this method lies in the weak dependence of the emitted flux on the temperature, so even a first approximation of the effective temperature gives an angular diameter value which differs by only a few percent from the final one. The influence of the interstellar absorption and blanketing is small in the infrared. The accuracy of the effective temperature determination by means of this method probably is of the order of ~ 1 % if the basic data are reliable enough (Glushneva 1983).

TABLE I

Total Fluxes, Effective Temperatures, Angular Diameters Radii and Luminosities of the Solar Analogs

HR	Name	Sp	Π''	F erg/cm^2 s	T_{eff} K	Θ 10^{-3}	$R/R_\odot$	$L/L_\odot$
483		G1.5 V	0.081	2.81 10-7	6097	0.78	1.04	1.24
937	i Per	G0 V	0.092	6.24 10-7	6109	1.16	1.36	2.31
4496	61 UMa	G8 V	0.119	2.03 10-7	5514	0.810	0.73	0.44
4785	B CVn	G0 V	0.117	4.87 10-7	5846	1.12	1.03	1.11
5868	1 Ser	G0 V	0.094	4.27 10-7	5951	1.01	1.16	1.51
6623	m Her	G5 IV	0.133	1.36 10-6	5935	1.81	1.46	2.37
7503	16 Cyg A	G1.5 V	0.039	1.04 10-7	5854	0.514	1.42	2.12
7504	16 Cyg B	G3 V	0.039	8.36 10-8	5664	0.493	1.36	1.71
996	K Cet	G5 V	0.108	3.16 10-7	5445	1.04	1.04	0.85
1729	1 Aur	G2IV-V	0.070	3.36 10-7	6099	0.858	1.32	2.16
4375	z UMa	G0 V	0.137	8.50 10-7	5891	-	-	-
5072	70 Vir	G2.5Va	0.043	2.64 10-7	5811	0.832	2.08	4.42
	Sun			1.37 10+6	5780		1.00	1.00

The values of the integrated total radiation flux are presented in Table I. The energy distributions for the first eight stars of the table were taken from Taylor (1984) and for the remaining stars were obtained from spectrophotometric data obtained at the Sternberg Institute and transformed to the calibration of Vega by Kharitonov et al., (1980). Our energy distribution data in the 3200 - 7600 Å range were extended into the infrared using 13-color photometry (Johnson and Mitchell 1975).

The contribution of the radiation with $\lambda < 3200$ Å to the total flux for HR 483 obtained from IUE measurements (Heck et al. 1984) is 1.63 %. For other stars this contribution was calculated according to the data for G0 - G8 stars (Glushneva 1984). It changes from 2 % for G0 stars to 0.5 % for G 8 stars. The energy distribution of HR 6623 was corrected for interstellar extinction according the a color excess $E_{(B-V)} = 0.09$ mag. Spectral types were taken from Keenan and Yorka (1985).

Effective temperatures and angular diameters of the stars, together with the solar data, are also listed in Table I. The errors in T_{eff} do not exceed 2 % as a rule (Glushneva 1983, 84). The effective temperature of the Sun (5780 K) is in between that of 16 Cyg A and 16 Cyg B. These two stars are usually considered to be the best analogs of the Sun. the difference in the effective temperatures of 16 Cyg B and the Sun is about 100 K and this does not exceed the errors of the T_{eff} determinations, which mainly depend on the accuracy of the monochromatic flux measurements and the calibration in the infrared.

The effective temperature of HR 1729 in the table is too high, however some authors (Johnson et al. 1966, Hirshfeld and Sinnott 1982) consider that this star is of spectral type G0 V.

It was shown (Glushneva 1983) that T_{eff} values obtained using photometry at the K band at 2.2 μm are the most reliable because they are in the best agreement with T_{eff} values obtained from interferometric measurements of angular diameters. The results presented in Table I were obtained at the K band for all the stars except HR 996 and HR 5072. For these two stars photometry at the K band was not available and the effective temperatures were determined from photometric measurements at 11084 Å.

Table I also includes radii of the stars which were obtained using parallaxes from Hoffleit (1982). The radii of two of the closest solar analogs, 16 Cyg A and B are about $\sim 1.4\ R_\odot$. For HR 5072 the value of the radius is too large if it is compared with stars of this

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spectral type. It may be connected with the low accuracy of the parallax determination. On the basis of the distances for 16 Cyg A, 16 Cyg B (19 pc) and HR 5072 (10 pc) from Sky Catalog 2000.0 (Hirshfeld and Sinnott 1982) we obtained radii of 1.05 $R_\odot$ for 16 Cyg A, 1.01 $R_\odot$ for 16 Cyg B and 0.89 $R_\odot$ for HR 5072. Likewise the luminosities of 16 Cyg A and 16 Cyg B are about $2L_\odot$ if parallaxes from Hoffleit (1082) are taken. In the case of the parallaxes from Sky Catalog, 2000.0 the luminosities for 16 Cyg A, 16 Cyg B and HR 5072 are 1.16 $L_\odot$, 0.94 $L_\odot$ and 0.81 $L_\odot$ respectively. For 16 Cyg A and B they do not differ significantly from the solar luminosity. On the other hand it is necessary to stress that nine stars out of eleven from Table I have luminosities which are greater than the solar luminosity. It is difficult to suppose that all the parallaxes of these nine stars are underestimated.

3. ENERGY FLUXES OF THE SUN AND SEVEN COLOR PHOTOMETRY

The success of the search for solar analogs depends on the reliability of our knowledge of the energy distribution in the solar spectrum. It is interesting to note that the energy fluxes of the Sun as a star in the visible spectral range are known with less accuracy than for main sequence stars of similar spectral types. The discrepancies between separate series of observations near the maximum of the energy distribution at 4600 - 4800 Å reach 10 - 15 %. In the paper by Pierce and Allen (1977) a recent series of observations in the range 0.3 - 3 μm are quoted as the best. Disagreements in these series are within the limits of 5 - 15 %; sometimes 20 %.

The problem of the selection of "the best" solar energy distribution is complicated by the fact that the integral of the energy distribution, i.e. "solar constant" is the same for different distributions within the limits of 1 - 2 %. However energy distributions in different series show considerable disagreements in different wavelengths.

On the contrary the energy distributions of many stars are known with better precision. For the standard star Vega, the errors are estimated as 1 % (Hayes 1985); these errors are ten times smaller than for the Sun. It is important to determine the energy distribution of the Sun with better precision.

Recently it has been proposed to consider the energy fluxes of the Sun published by Neckel and Labs (1984) as the most exact. Undoubtedly their data are the best ones among those existing now. As a matter of fact the authors have replaced some of their earlier observations by unpublished observations by Brault. Brault's high resolution Fourier transform spectra (FTS) observations were carried out at Kitt Peak National Observatory and are in relative units. Their accidental errors are considered to be about 0.1 %. However the losses of light in the Earth's atmosphere and the influence of the celostat has not been taken into account. The absolute calibration of the FTS spectra was done by shifting them to the Neckel and Labs (1981) absolute integral values in 20 Å bands. This is the weakest point in the proposed distribution. There is no guarantee against that this one distribution has no systematic errors. It is necessary to take into account that the initial absolute data in the range $\lambda < 6000$ Å are based on two days of observations only, seldom on three but sometimes on one day (Labs and Neckel (1967, Fig. 7.).

It seems reasonable to use multicolor photometry for checking the reality of different series of solar fluxes in the visible range of the spectrum. for this we decided to use the Vilnius seven color photometric system (Straizys and Zdanavicius 1970) having mean wavelengths 3450, 3740, 4050, 4660, 5160 and 6550 Å respectively and half-widths of the order of 200 Å.

The dependence of the Vilnius color system on spectral type is shown in Fig. 1. The spectral types of the stars are taken from keenan and Yorka (1985). The data for 16 Cyg B are plotted as crosses. Colors and color indices of the Sun for different series of energy distributions were calculated by integrating them with the response curves of the system (Tables II and III). The zero-point of the color indices was determined by comparing the synthetic color indices of Vega (Knyazeva et al. 1985) with the observed ones by Zdanavicius et al. (1969). The initial data for the calculations of different energy distributions were contained in Tables 2 of Marakova (1970) and 19 of Kharitonov (1972). Neckel and Labs (1984) data were taken from Table X of their paper and these color indices are shown by open circles at spectral class G2 in Fig. 1. These points are within the scattering of points for stars of similar spectral types. It means that the relative energy distribution is more or less correct.

On the other hand the colors of Table II give us values proportional to the absolute integral fluxes for the Sun in every bandpass of the Vilnius photometric system for the energy curves of different authors. These results allow us to try to check the reality of the different results. For example, Neckel and Labs (1984) energy fluxes near the maximum energy distribution in color Y and Z (λ_{eff} 4660 and 5160 Å) are too small comparatively to all other series. This point must be checked.

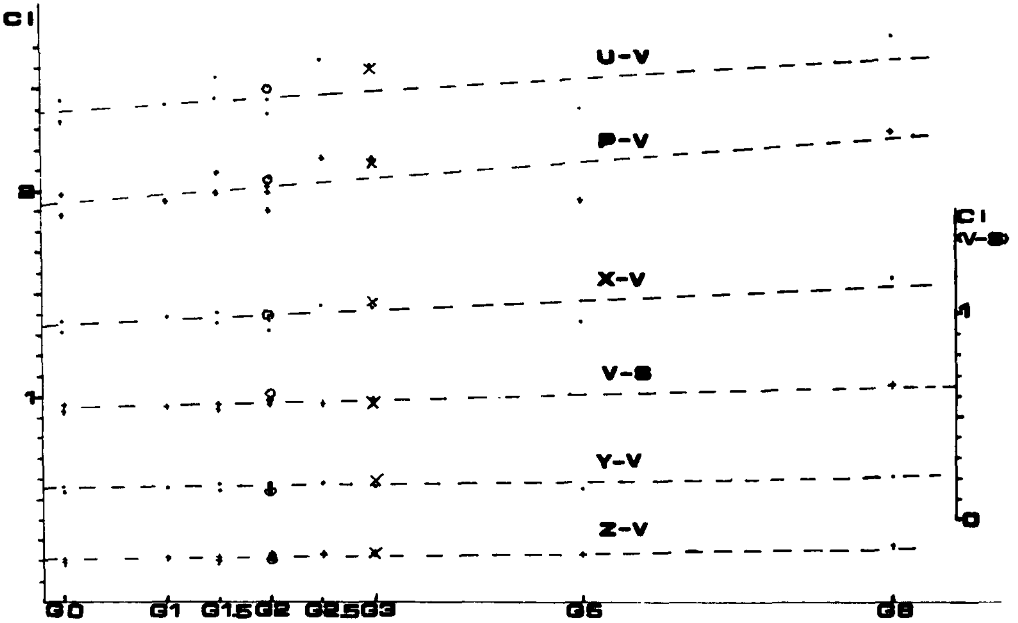

Fig. 1. The color indices for G main-sequence stars of different subtypes in the Vilnius photometric system. The data for 16 Cyg B are marked by crosses and Neckel and Labs (1984) solar data are marked by open circles. The scale for the (V-S) color index is on the right.

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TABLE II

"Colors" of Different Solar Energy Distributions in UPXYZVS Photometry

Authors	CU	CP	CX	CY	CZ	CV	CS
Abbot et al. 1902 - 1910	13.3	17.7	19.5	40.4	39.5	27.8	11.2
Abbot et al. 1920 - 1923		15.7	17.8	35.2	33.8	23.7	10.9
Sitnik	10.6	11.2	17.9	39.0	35.8	25.4	11.3
Makarova			16.5	35.0	36.4	25.7	10.5
Stair and Ellis	13.9	14.6	17.9	31.1			
Peyturaux				37.1	33.9	23.4	11.5
Houtgast	12.7	12.7					
Thekaekara et al.	15.8	15.1	17.8	33.8	31.6	21.8	9.9
Arvesen	14.5	14.6	18.6	34.3	32.2	23.1	10.6
Labs and Neckel 1968	13.1	13.3	16.9	32.4	31.1	22.6	10.2
Neckel and Labs 1984	13.5	14.1	17.4	32.6	31.2	22.7	10.3
Makarova and Kharitonov 1972 (mean)	13.9	13.9	17.4	33.5	32.4	22.8	10.3

TABLE III

Synthetic Seven-Color Photometry of Different Energy Distributions of the Sun and Observed Color Indices For Some Stars

Authors/Stars	U-V	P-V	X-V	Y-V	Z-V	V-S
Abbot 1902 - 1910	2.73	2.01	1.49	0.53	0.16	0.48
Abbot 1920 - 1923	-	1.97	1.42	0.51	0.16	0.63
Sitnik	2.78	2.42	1.49	0.47	0.18	0.59
Makarova	-	-	1.59	0.61	0.17	0.50
Thekaekara et al.	2.31	1.93	1.33	0.46	0.15	0.62
Arvesen	2.45	2.03	1.35	0.51	0.19	0.62
Labs and Neckel 1968	2.53	2.10	1.43	0.55	0.20	0.61
Neckel and Labs 1984	2.50	2.04	1.40	0.54	0.20	0.61
Makarova and Kharitonov 1972 (mean)	2.47	2.07	1.40	0.52	0.17	0.61
16 Cyg A	2.55	2.09	1.41	0.57	0.22	0.56
16 Cyg B	2.59	2.13	1.45	0.58	0.23	0.57
Mean for G2 Stars (Fig. 1)	2.46	2.02	1.39	0.56	0.22	0.57

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So far it seems that the best way to construct the best solar energy distribution may well be to take weighted mean data. As a first approximation a reasonable weight of each distribution may be found from the comparison of the synthetic color indices of the Sun with the observed ones of the solar analog. The data from Fig. 1 and Table III confirm the unreliability of the relative energy distribution in the solar spectrum comparatively to the stellar ones. The color indices (U-V) are within the limits 2.31 - 2.87 for the different solar energy distributions (Table III). This scatter is more than the differences for the stars in the spectral range from G0 to G8 (2.33 - 2.74), for G2 V stars (U-V) indices are within the limits of 2.37 - 2.49.

Synthetic colors give us the possibility of proposing some weights which cover only a narrow region of the spectrum. The complete computation of the proposed mean data needs considerable time as it is necessary to take into account new data concerning limb darkening of the Sun, the change of the Pyrheliometric scale and so on. However, all these alterations hardly can change the fact that the excellent data of Neckel and Labs (1984) possibly are too small near the maximum of the solar energy distribution. It seems not quite correct to take only one distribution as a standard.

4. CONCLUSION

Multicolor photometry is used for the comparison with the solar analogs to define more precisely the mean data on the solar energy distribution. However, it is necessary to be careful with the conception of the solar analog. The physical characteristics of the Sun are rather anomalous for G-type stars (Table I), the radii and luminosities of the majority of the stars are more than the solar values if the parallaxes of some of the stars are underestimated. For 16 Cyg B, which is considered to be the best solar analog, five color indices in the Vilnius photometric system are more than the mean values for G2 V stars (Table III) and the position of this star in Fig. 1 is nearer to the stars of spectral type later than G3.

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