Selection of Solar analogues on the basis of various color indices

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It is possible to choose stars similar to the Sun, using various parameters as a background. However, to find a solar "twin" it is necessary first of all that the colour indices of a star obtained in different photometric systems are be similar to solar ones.

We have made a search of stars for which the colorimetric parameters are closest to those for the Sun in three catalogs: the famous catalogue of Mermilliod, containing measurements in Johnson's *UBV* system (we have chosen only stars from the Mermilliod catalogue which are included in the Henry Draper catalogue), the catalogue of measurements in the Vilnius *UPXYZVS* system [1], and in the catalogue of measurements in *WBVR* system, which recently was created at the Sternberg astronomical institute [2], [3]. One can do this as the color excesses of G-dwarfs which are brighter than the limit of the HD catalogue are practically equal to zero.

The parameter $\rho = \sqrt{\sum_{i=1}^{K}(c_{i,\odot} - c_{i,*})^2}$, where i is a counter of color indices, K is a number of independent color indices of a photometric system, $c_{i,\odot}$ are solar color indices, and $c_{i,*}$ are stellar color indices, was a closeness criterion of solar and stellar color indices.

The color indices of the Sun in some photometric system may be carried out from observations or may be calculated by integration of product of the energy distribution function of the Sun $E_\odot(\lambda)$ and the response curves of the given system $\varphi_i(\lambda)$. In Table 1 the summary of results of the main determinations is shown.

The direct measurements are now made in the *UBV* and *WBVR* systems only.

The direct measurements of the Solar color indices in the *UBV* system were made by Gallouet in 1964 [5] and by Tug and Schmidt-Kaler in 1982 [6]. However, a comparison of color indices of any two stars which were measured in the *UBV* system at different times, with different equipment and at different observatories, is not reliable because of known uncertainties of passbands and the method of determination of extra-atmospheric magnitudes.

The direct measurements of the Solar color indices in the *WBVR* system were carried out by the authors of the present report in 1996 [7]. The measurements were made with the same equipment (the four-channel photoelectric photometer [4] fixing in 48-cm reflector), with which the catalogue of WBVR-magnitudes was created.

The observations were executed on five dates in August and September 1996 in Northern Tien-Shan (altitude 2750 m above sea level).

To decrease the solar radiative flux the little screen of $BaSO_4$ (with the diameter of 27 mm) was used. It was placed 200 m from the telescope. The screen was illuminated by the Sun, but it was protected from scattered light of the sky by special construction. The screen was fixed in equatorial support and always was directed perpendicularly towards the solar rays. The observations of the Sun were executed immediately after sunrise, when the solar air mass changed from 6 down to 2. The observations of the stars were always preceded the observations of the Sun. We carried out special measures to investigate and control the apparatus sensibility and to determine atmospheric extinction.

Many investigators have calculated synthetic color indices for the Sun and a lot of versions of $E_\odot(\lambda)$ and response curves are used. We want to point, for example, to detailed article by Straižys and Valiauga [8] where solar color indices in *UBV* and Vilnius systems were calculated for several assumptions. Recently Makarova et al. [9] have obtained a new version of the solar energy distribution on a basis of five most reliable observation sets. However, as one can see from Table 1, synthetic color indices in the *UBV* system, calculated under different cases, show considerable discrepancies.

To choose the solar analogues the following color indices have been accepted:

for UBV system : we accept an average from direct measurements by Galloue [5] and Tug and Schmidt-Kaler [4]; the synthetic values did not used in view of noticeable discrepances;

for WBVR system: we accept a result of the recently direct measurements by Mironov and Kharitonov [7] which is in accordance with the result of calculation of the synthetic values [8];

for Vilnius system: we accept the results of the recent calculations by Kharitonov and Kniazeva [10] which are in good agreement with the results of Straižys and Valiauga [8].

A value of the ρ parameter was given by $r\sqrt{K}$, where K is the number of independent color indices of a photometric system; ($K = 2$ for UBV, $K = 3$ for $WBVR$ and $K = 6$ for the Vilnius system), and $r = 2\sigma = 0.04$ mag is a factor, which is approximately equal to twice the standard error of the color indices in the UBV system. Under the given values of that ρ parameter we have found 346 stars from the UBV system catalogue, 140 stars from the $WBVR$ system catalog, and 259 stars from Vilnius system catalogue.

Only 6 stars are at once in all three samples. They are listes in Table 2. They will be apparently consideres as optimal candidates chosen by closeness of color indices. Two of them are 16 Cyg A and B (HD 186408 and HD 186427), which usually are included in the number of best analogues of the Sun. But the star HD 28099 = vB 64 (Hyades), which is usually considered to be a best analogue too, is not found in this list. The latter star is a member of only one sample: the sample from the Vilnius catalogue, where it takes 180th place among 259 stars according to value of the ρ parameter.

If we rank chosen stars in increasing order of the ρ parameter and put an upper bound on the ρ parameter as a value which is in agreement with standard error $r = 0.01$ mag, thw samples from the three catalogues have no common stars. If we increase r to 0.017 mag then two common stars appear in the samples from the Vilnius and $WBVR$ catalogues: HD 4915 and HD 146233. Of course, these facts are a consequence that all color indices both for the Sun and for stars contain errors. It is known that the errors in the Vilnius and $WBVR$ catologues are less than in the Mermilliod catalogue, therefore we think that stars which are at once in the samples from Vilnius catalogue and from $WBVR$ catalogues may be considered as candidates for solar analogues too. These stars are listed in Table 3.

It is impossible not to note the fact that there are stars in a wide interval of spectral subclasses (from G0 to G5) in the Tables 2 and 3. It is obvious that the fact is a consequence of errors of spectral classification on the one hand, and of natural differences of spectral line parameters of stars having identical color indices (i.e. having similar energy distribution) on the other hand.

Pay attention that there are two stars, 16 B Cyg and 47 UMa, in tables 2 and 3, which, as found recently, have planetary systems. The whole sample from the Vilnius catalogue (259 stars) contain stars with planetary system 51 Peg and ρ CrB too.

Table 1. Summary of observed and synthetic color indices of the Sun

1. *UBV* system

author	method	*U-B*	*B-V*	Source: energy distrib.	Source: response curves
Gallouet	observ.	0.15	0.68	-	-
Tug, Schmidt-Kaler	observ.	0.183	0.686	-	-
Kharitonov, Kniazeva	calcul.	0.033	0.648	[9]	[12]
-"-	calcul.	0.067	0.652	[9]	[13]
Straižys, Valiauga	calcul.	0.14	0.64	[11]	[12]
-"-	calcul.	0.13	0.60	[14]	[12]
-"-	calcul.	0.15	0.62	[15]	[12]

2. *WBVR* system

author	method	*W-B*	*B-V*	*V-R*	Source: energy distrib.	Source: response curves
Mironov,Kharitonov	observ.	-0.050	0.667	0.531	-	-
Kharitonov,Kniazeva	calcul.	-0.072	0.674	0.505	[9]	[3]

3. Vilnius system

author	method	*U-V*	*P-V*	*X-V*	*Y-V*	*Z-V*	*V-S*	Source: energy distrib.	Source: response curves
Straižys,Valiauga	calcul.	2.51	2.06	1.41	0.55	0.21	0.59	[11]	[12]
-"-	calcul.	2.48	2.01	1.35	0.54	0.22	0.51	[14]	[12]
-"-	calcul.	2.48	2.06	1.39	0.54	0.21	0.59	[15]	[12]
Kharitonov,Kniazeva	calcul.	2.46	2.02	1.37	0.54	0.21	0.55	[9]	[12]

Table 2. List of stars whose color indices are close to solar ones in all three catalogues in the three photometric systems.

BS	HD	α_{2000}	δ_{2000}	Sp	V	W-B	B-V	V-R
6060	146233A	$16^h15^m.6$	−08 22	G2Va	5.499	-0.028	0.650	0.524
6538	159222	17 32.0	+34 16	G5V	6.537	-0.006	0.646	0.510
7503	186408	19 41.8	+50 32	G1.5V	5.986	-0.004	0.659	0.521
7504	186427	19 41.9	+50 31	G2.5V	6.244	+0.008	0.671	0.531
	187237	19 48.0	+27 52	G2III	6.896	-0.013	0.654	0.512
7569	187923A	19 52.1	+11 38	G0V	6.164	-0.032	0.664	0.520

Table 3. List of stars whose color indices are close to solar ones in two catalogues: in the Vilnius and *WBVR* photometric systems

BS	HD	α_{2000}	δ_{2000}	Sp	V	W-B	B-V	V-R
203	4307A	$00^h45^m.5$	−12 53	G2V	6.158	-0.086	0.612	0.512
	4915	00 51.2	−05 02	G0V	6.982	-0.027	0.666	0.543
	8262	01 22.3	+18 41	G3V	6.973	-0.079	0.630	0.513
483	10307	01 41.8	+42 37	G1.5V	4.965	-0.049	0.623	0.499
	29310*	04 37.5	+15 09	G1V	7.547	-0.045	0.608	0.516
1729	34411A	05 19.1	+40 06	G2IV/V	4.705	-0.033	0.622	0.499
4277	95128	10 59.5	+40 26	G0V	5.037	-0.056	0.622	0.505
5384	126053	14 23.3	+01 14	G1V	6.266	-0.110	0.644	0.527
5596	133002	14 50.3	+82 31	F9V	5.643	0.003	0.682	0.555
5868	141004	15 46.4	+07 21	G0V	4.419	-0.064	0.611	0.494
	152792	16 53.5	+42 49	G0V	6.827	-0.093	0.645	0.535
6573	160269AB	17 35.0	+61 52	G0Va+K3V	5.233	-0.082	0.608	0.525
	168874AB	18 20.8	+27 32	G2IV	7.014	-0.046	0.637	0.512
	177082	19 02.6	+14 34	G2V	6.895	-0.076	0.641	0.518
7683	190771AB	20 05.2	+38 29	G5IV	6.185	+0.000	0.668	0.523
7914	197076A	20 40.8	+19 56	G5V	6.444	-0.082	0.628	0.505
8964	222143	23 38.0	+46 12	G5	6.591	-0.018	0.652	0.522
9107	225239	00 04.9	+34 40	G2V	6.111	-0.098	0.640	0.541

* var. V998 Tau

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