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# ON THE POSSIBILITIES OF SOME PHOTOMETRIC SYSTEMS FOR STAR CLASSIFICATION

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**Abstract.** The possibilities of photometric classification of solar metallicity stars of all temperatures and luminosities in the *Walraven, Vilnius, Strömvil, Geneva, uvby* (Strömgren), *UBVRI* (Johnson-Cousins) and *Sloan* (including its modification without the ultraviolet passband) photometric systems are intercompared. The analysis is based on reddening-free *Q*-parameters calculated for the Kurucz model atmospheres. The significance of the ultraviolet passbands is shown. The possibility of separation of metal-deficient and binary stars is also discussed.

**Key words:** techniques: photometric – stars: classification

## 1. INTRODUCTION

There are many photometric systems in use. Usually, they are introduced for investigation of stars in some ranges of spectral classes and luminosities. Here we compare the possibilities of photometric systems to classify stars of the solar metallicity in the whole range of traditional spectral classes (from O to M) and luminosity classes (from V to I) in the presence of unknown interstellar reddening. Similar attempt to intercompare five photometric systems has been done by Straižys et al. (1998) using a somewhat different method. In addition, the possibilities of separating metal-deficient and binary stars from the normal stars are investigated. The main characteristics of the systems investigated here are given in Table 1.

**Table 1.** Photometric systems, parameters of passbands and the used $Q$ parameters. The mean wavelengths and half-widths are given in nm. Reference sources of the response functions are given.

1. *Walraven* system: $WULBV$ (Lub & Pel 1977)

| | | | | | |
|---|---|---|---|---|---|
| $\lambda_0$ | 325 | 363 | 384 | 433 | 547 |
| $\Delta\lambda$ | 14 | 24 | 22 | 46 | 70 |

$Q$: $WUL$ $ULV$ $LBV$ $WUBV$ $WLV$

2. *Vilnius* system: $UPXYZVS$ (Straižys 1992)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\lambda_0$ | 344 | 374 | 405 | 466 | 516 | 544 | 656 |
| $\Delta\lambda$ | 40 | 26 | 22 | 26 | 22 | 26 | 18 |

$Q$: $UPY$, $PXY$, $XYZ$, $XZS$, $YZS$

3. *Strömvil* system: $uPvbZyS$ (Olson 1974, Straižys 1992)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\lambda_0$ | 347 | 374 | 411 | 467 | 516 | 546 | 656 |
| $\Delta\lambda$ | 36 | 26 | 20 | 16 | 22 | 26 | 18 |

$Q$: $uPb$, $Pvb$, $vbZ$, $vZS$, $bZS$

4. *Geneva* system: $UB_1BB_2V_1VG$ (Rufener & Nicolet 1988)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\lambda_0$ | 346 | 401 | 423 | 448 | 540 | 549 | 581 |
| $\Delta\lambda$ | 46 | 40 | 78 | 42 | 44 | 70 | 46 |

$Q$: $UB_2G_1$, $UB_1B_2$, $B_1B_2V_1G$, $B_1B_2V_1$, $UB_1B_2V_1$

5. *Strömgren* system: $uvby$ (Olson 1974, Crawford & Barnes 1970)

| | | | | |
|---|---|---|---|---|
| $\lambda_0$ | 347 | 411 | 467 | 546 |
| $\Delta\lambda$ | 36 | 20 | 16 | 26 |

$Q$: $uvb$, $vby$, $uvby$, $uby$

6. *Johnson-Cousins* system: $UBVRI$ (Ažusienis & Straižys 1969, Bessell 1983)

| | | | | | |
|---|---|---|---|---|---|
| $\lambda_0$ | 364 | 442 | 550 | 647 | 789 |
| $\Delta\lambda$ | 44 | 96 | 82 | 154 | 106 |

$Q$: $UBV$, $BVR$, $VRI$, $UBVR$, $UVR$

7. *Sloan* system: $ugriz$ (Fukugita et al. 1996)

| | | | | | |
|---|---|---|---|---|---|
| $\lambda_0$ | 357 | 483 | 627 | 767 | 920 |
| $\Delta\lambda$ | 60 | 138 | 136 | 152 | 132 |

$Q$: $gri$, $riz$, $griz$, $ugr$, $uri$

8. *Sloan* system (without $u$): $griz$

$Q$: $gri$, $riz$, $griz$

## 2. METHOD

The analysis is based on interstellar reddening-free $Q$-parameters, calculated from synthetic color indices. The color indices are calculated for synthetic spectra of stellar model atmospheres of Kurucz (1995), the response functions of the passbands are taken from the literature (as listed in Table 1) and the standard transmittance function of interstellar dust is taken from Straižys (1992). This function was used to calculate color excesses for color indices of all the investigated systems, taking the isoenergetic flux ($F(\lambda)$ = const).

The interstellar reddening-free $Q$-parameters were calculated by the following equation:

$$Q_{ijkl} = C_{ij} - \frac{E_{ij}}{E_{kl}} C_{kl}, \tag{1}$$

where the subscript $ijkl$ means different passbands of the given system. For the majority of $Q$s, indices $j$ and $k$ coincide. The ratios $E_{ij}/E_{kl}$ for all types of stars are taken the same. In this respect our definition of $Q$-parameters is different from that accepted in the Vilnius photometric system where $E_{ij}/E_{kl}$ ratios are taken variable, depending on spectral and luminosity classes (the bandwidth effect). The bandwidth and interstellar extinction effects, as depending on the amount of interstellar matter, must be taken into account during classification process. Color indices $C_{ij}$ (and $C_{kl}$) and their color excesses are calculated by the following equations:

$$C_{ij} = m_i - m_j = -2.5 \log \frac{\int F(\lambda) R_i(\lambda) d\lambda}{\int F(\lambda) R_j(\lambda) d\lambda}, \tag{2}$$

$$E_{ij} = -2.5 \log \left( \frac{\int R_i(\lambda)\tau(\lambda) d(\lambda)}{\int R_i(\lambda) d(\lambda)} - \frac{\int R_j(\lambda)\tau(\lambda) d(\lambda)}{\int R_j(\lambda) d(\lambda)} \right), \tag{3}$$

where $F(\lambda)$ are the model fluxes, $R_i(\lambda)$ and $R_j(\lambda)$ are the response functions of two passbands, $\tau(\lambda)$ is the standard transmittance function for 1 mass unit of interstellar dust. The integration step was 2 nm.

To simplify account of the errors of $Q$-parameters, the calculated $Q$ values were transformed by multiplying them by the coefficient $s = 2\,(1 + E_{ij}/E_{kl})^{-1}$. The used $Q$-parameters are listed in Table 1, in the last line of each system.

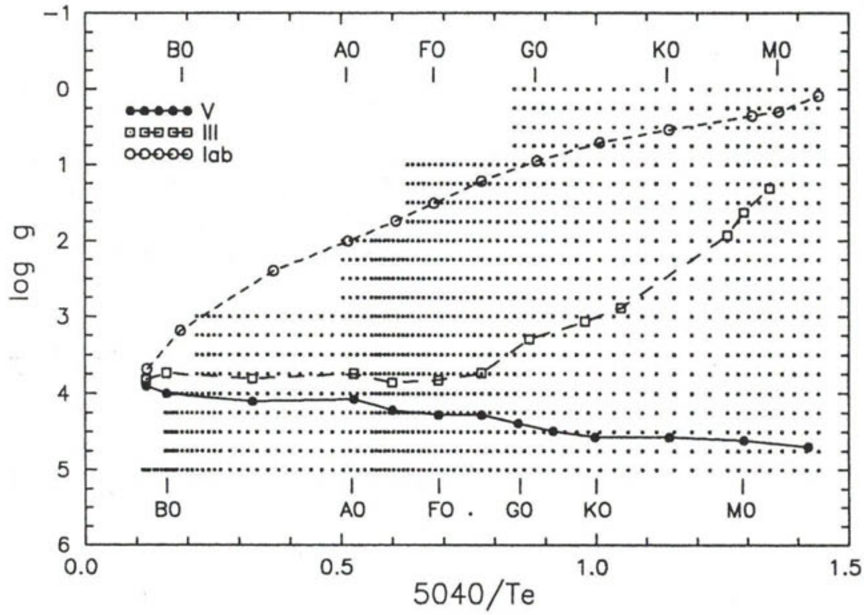


**Fig. 1.** Distribution of the used standards. The solid line represents real main-sequence stars, long-dashed line – giants and short-dashed line – supergiants. Ticks for spectral classes are given for main-sequence stars (at the bottom) and supergiants (at the top).

The calculated here $\lambda_0$ and $\Delta\lambda$ ($\pm 2$ nm) are also given in Table 1.

At first, $Q$-parameters were calculated for 92 Kurucz (1995) models with [Fe/H] = 0: 22 values of $T_e$ (listed in Table 2) and 6 values of log $g$ (0, 1, 2, 3, 4 and 5). Instead of effective temperatures, we used $\theta = 5040/T_e$ borrowed from theoretical astrophysics. Table 2 gives the $T_e$ intervals corresponding to $\Delta\theta = 0.01$ for different $\theta$ values. After that, all the temperature and gravity intervals were split into four equal parts and for them all $Q$-parameters were determined by interpolation. In this way 1145 standards were formed. Their distribution on the $\theta$ vs. log $g$ diagram is shown in Fig. 1. The standards are spaced with a constant step of 0.25 in log $g$ (21 value) and the varying step in $\theta$ (85 values). The steps of $\theta$ correspond to 62.5 K for the models with $T_e \leq 4000$ K, 125 K between 4000 and 9000 K, and for higher temperatures they increase up to 2000 K at $T_e = 40\,000$ K ($\Delta T/T$ varies from 1.6 % for the low temperature models to 5 % for the high temperature models). The number of 1145 standards is somewhat larger than the number of spectral

**Table 2.** Effective temperatures $T_e$ and $\theta = 5040/T_e$ of the primary standards.

| $\theta$ | $T_e$ | $\Delta T_e$ for $\Delta\theta = 0.01$ | $\theta$ | $T_e$ | $\Delta T_e$ for $\Delta\theta = 0.01$ |
|---|---|---|---|---|---|
| 1.440 | 3500 | 24 | 0.593 | 8500 | 144 |
| 1.344 | 3750 | 28 | 0.560 | 9000 | 161 |
| 1.260 | 4000 | 32 | 0.504 | 10000 | 198 |
| 1.120 | 4500 | 40 | 0.420 | 12000 | 286 |
| 1.008 | 5000 | 50 | 0.336 | 15000 | 347 |
| 0.916 | 5500 | 60 | 0.265 | 19000 | 719 |
| 0.840 | 6000 | 72 | 0.219 | 23000 | 1053 |
| 0.775 | 6500 | 84 | 0.180 | 28000 | 1560 |
| 0.720 | 7000 | 97 | 0.158 | 32000 | 2053 |
| 0.672 | 7500 | 112 | 0.126 | 40000 | 3195 |
| 0.630 | 8000 | 127 | 0.112 | 46000 | 4233 |

subclass and luminosity class combinations usually used in the MK system.

As a criterion of the classification possibilities of a given system, we assume a mean number of standards, which fall into the $n$-dimensional elementary space volume with a side equal to $2\Delta Q$. Here $n$ is the number of $Q$-parameters used. The maximum number of $Q$-parameters, used in this investigation is five. Such is the number of independent $Q$-parameters for a system consisting of seven passbands. The selected $Q$-parameters are most sensitive to $T_e$ or log $g$ in different temperature intervals.

The centers of the elementary volumes (in the $n$-dimensional space of $Q$s) were taken at the $Q$-values of the so-called "program" models. Two groups of the program models of [Fe/H] = 0 were used: (1) the primary 92 standards and (2) 69 models with the same temperatures $T_e$ but with log $g$ values of 0.5, 1.5, 2.5, 3.5 and 4.5. Additionally, three groups of metal-deficient models and one group of "binary" models were taken. For them the same reddening-free $Q$-parameters were calculated.

For the program models of the first group, the values of $Q$ coincide with those of the standards (the volume element is centered on the standard), while for the second group $Q$ values differ from the standard by the interpolation errors, which usually are small (the centers of the volume elements are slightly moved from the standard), but in a few cases exceed 0.01 mag.

The size of the elementary volume is limited between $Q_{i*} + \Delta Q$ and $Q_{i*} - \Delta Q$, where $Q_{i*}$ are the values of $Q$s of the program models; $i = 1,2, ..., n$, where $n$ is the number of $Q$-parameters used for a given system (Table 1). The following $\Delta Q$ values were taken: 0.01, 0.02, 0.03, 0.05, 0.07 and 0.10 mag, the sides of the elementary volumes being $2\,\Delta Q$. These values of $\Delta Q$ approximately correspond to the following errors $\sigma$ of color indices: 0.007, 0.014, 0.020, 0.035, 0.05 and 0.07 mag.

For each program model, the numbers of standard models $N$ (selected from 1145) found in the elementary volume were determined. If the photometric system is capable to separate the nearest standards, $N = 1$. When $\Delta Q$ increases, the number of standards falling in the elementary space volume grows. The mean value $\bar{N}$ for all models is a characteristic of the given photometric system to classify stars affected by interstellar reddening. The smaller the $\bar{N}$, the better classification possibilities of system. One must remember that $\bar{N}$ characterizes the average classification possibility of the system for all $T_e$ values – from the hottest to the coolest. Some systems may have low classification grade for all temperatures, but much higher grade in a limited temperature range.

When $N$ is greater than 1, the classification is possible, but with lower accuracy. In this work, for the models with $N > 1$, we have accepted that the values of the parameters $\theta$ and $\log g$ obtained for a program model are the average values of all standards falling into the volume element. The differences between these mean values and the real values of model parameters are calculated and the number of program models, classified within these differences are determined. The distribution of these numbers as a function of the parameter differences is an additional criterion of the system quality.

For some models at a given $\Delta Q$ no standard models are found ($N = 0$). This occurs when the program model is abnormal or the errors of interpolation of $Q$ of standards are $>\Delta Q$. In the case of real observations such situation may take place for low accuracy photometry. The star can be considered as really abnormal if $\Delta Q > 3\sigma_Q$. In the case of metal-deficient or binary star models, $N = 0$ means a good possibility to identify their peculiarity.

## 3. RESULTS AND DISCUSSION

### *3.1. Solar metallicity stars*

As it was explained earlier, two groups of solar metallicity program models were used. For each program model, the numbers of standard models $N$ in the different $n$-dimensional space volumes were determined and their mean values $\bar{N}$ for the first and the second group of models were calculated.

The results are given in Table 3 and shown in Fig. 2. The half-sizes ($\Delta Q$) of $n$-dimensional elementary volumes are given in Column 2. Column 3 gives the mean $\bar{N}_1$ values for 92 program models of the first group, Column 4 gives $\bar{N}_2$ for 69 program models of the second group. Columns 5–8 give the numbers of the second group models for which obtained $\theta$ errors respectively are: $\Delta\theta \leq 0.01$ ($lt_1$), $0.01 < \Delta\theta \leq 0.02$ ($lt_2$), $0.02 < \Delta\theta \leq 0.05$ ($lt_3$) and $\Delta\theta > 0.05$ ($lt_4$); Columns 9–12 give the numbers of models for which log $g$ errors respectively are: $\Delta \log g < 0.2$ ($lg_1$), $0.2 \leq \Delta \log g < 0.5$ ($lg_2$), $0.5 \leq \Delta \log g < 1$ ($lg_3$) and $\Delta \log g \geq 1$ ($lg_4$). Naturally, the sum of numbers with different errors is always 69.

From examination of Table 3 the following general remarks may be made:

(1) The mean numbers $\bar{N}_1$ and $\bar{N}_2$ for the two sets of the program models are very close for all studied photometric systems. This means that the interpolation of $Q$-parameters did not introduce any noticeable errors.

(2) The ranking of the photometric systems by $\bar{N}$ does not depend on $\Delta Q$ value and is the following: *Walraven, Vilnius, Strömvil, Geneva, uvby, Sloan, UBVRI, Sloan* without $u$.

(3) There are only slight $\bar{N}$, $N_2(\Delta T)$ and $N_2(\Delta \log g)$ differences among the first three systems at $\Delta Q = 0.01$ mag. The *Geneva* system is close to the first three systems by its $\bar{N}$, while *uvby* is close to the *Geneva* system by its $N_2(\Delta T)$ and $N_2(\Delta \log g)$. When $\Delta Q$ increases up to 0.10 mag, differences between the first five systems become smaller, except of the *Walraven* system, for which $\bar{N}$ grows more slowly and at $\Delta Q = 0.10$ mag it is approximately of the same value as for the *Strömvil* system at $\Delta Q = 0.07$ mag. $\bar{N}$ for the *Sloan* and *UBVRI* systems is about three times larger and for the *Sloan* system without $u$ it is more than 15 times larger.

**Table 3.** Classification possibilities of normal stars. See the text for explanation of the limits of $\Delta\theta$ ($lt_i$) and $\Delta \log g$ ($lg_i$)

| System | $\Delta Q$ | $\bar{N}_1$ | $\bar{N}_2$ | $N_2(\Delta\theta)$ | | | | $N_2(\Delta \log g)$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $lt_1$ | $lt_2$ | $lt_3$ | $lt_4$ | $lg_1$ | $lg_2$ | $lg_3$ | $lg_4$ |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| *Walraven* | 0.01 | 1.15 | 1.17 | 65 | 3 | 1 | 0 | 65 | 4 | 0 | 0 |
| | 0.02 | 1.35 | 1.35 | 63 | 5 | 1 | 0 | 67 | 1 | 1 | 0 |
| | 0.03 | 1.93 | 1.78 | 64 | 4 | 1 | 0 | 64 | 3 | 2 | 0 |
| | 0.05 | 3.84 | 3.77 | 59 | 4 | 6 | 0 | 63 | 4 | 2 | 0 |
| | 0.07 | 6.63 | 6.87 | 55 | 6 | 8 | 0 | 64 | 3 | 2 | 0 |
| | 0.10 | 12.33 | 12.51 | 40 | 16 | 11 | 2 | 57 | 9 | 3 | 0 |
| *Vilnius* | 0.01 | 1.21 | 1.18 | 66 | 3 | 0 | 0 | 68 | 1 | 0 | 0 |
| | 0.02 | 1.73 | 1.58 | 63 | 5 | 1 | 0 | 67 | 2 | 2 | 0 |
| | 0.03 | 2.80 | 2.52 | 60 | 8 | 1 | 0 | 65 | 2 | 2 | 0 |
| | 0.05 | 6.35 | 5.65 | 49 | 11 | 9 | 0 | 65 | 2 | 2 | 0 |
| | 0.07 | 11.30 | 10.54 | 41 | 19 | 9 | 0 | 60 | 7 | 2 | 0 |
| | 0.10 | 21.48 | 21.20 | 31 | 22 | 15 | 1 | 53 | 12 | 4 | 0 |
| *Strömvil* | 0.01 | 1.27 | 1.26 | 63 | 4 | 2 | 0 | 66 | 3 | 0 | 0 |
| | 0.02 | 1.81 | 1.75 | 63 | 5 | 1 | 0 | 66 | 2 | 1 | 0 |
| | 0.03 | 2.95 | 2.71 | 59 | 7 | 3 | 0 | 65 | 2 | 2 | 0 |
| | 0.05 | 6.82 | 6.25 | 50 | 12 | 6 | 1 | 61 | 6 | 2 | 0 |
| | 0.07 | 12.41 | 11.82 | 36 | 20 | 12 | 1 | 56 | 11 | 2 | 0 |
| | 0.10 | 23.63 | 23.75 | 33 | 14 | 16 | 6 | 42 | 22 | 5 | 0 |
| *Geneva* | 0.01 | 1.45 | 1.42 | 55 | 9 | 4 | 1 | 51 | 14 | 3 | 1 |
| | 0.02 | 2.38 | 2.34 | 51 | 9 | 4 | 5 | 50 | 11 | 7 | 1 |
| | 0.03 | 3.90 | 3.45 | 49 | 10 | 4 | 6 | 50 | 10 | 7 | 2 |
| | 0.05 | 8.25 | 7.86 | 43 | 8 | 11 | 7 | 39 | 18 | 8 | 4 |
| | 0.07 | 14.50 | 14.25 | 36 | 14 | 13 | 6 | 37 | 15 | 13 | 4 |
| | 0.10 | 25.94 | 26.22 | 30 | 13 | 17 | 9 | 26 | 21 | 14 | 8 |
| *Strömgren* | 0.01 | 2.44 | 2.26 | 57 | 5 | 5 | 2 | 48 | 14 | 5 | 2 |
| | 0.02 | 3.39 | 3.31 | 52 | 8 | 6 | 3 | 44 | 16 | 5 | 4 |
| | 0.03 | 4.91 | 4.83 | 53 | 6 | 7 | 3 | 43 | 18 | 3 | 5 |
| | 0.05 | 9.85 | 10.07 | 42 | 12 | 8 | 7 | 33 | 20 | 9 | 7 |
| | 0.07 | 16.79 | 16.73 | 37 | 13 | 13 | 6 | 28 | 26 | 8 | 7 |
| | 0.10 | 29.28 | 30.48 | 34 | 9 | 19 | 7 | 18 | 30 | 12 | 9 |

Table 3 (continued)

| System | $\Delta Q$ | $\bar{N}_1$ | $\bar{N}_2$ | $N_2(\Delta\theta)$ | | | | $N_2(\Delta\log g)$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $lt_1$ | $lt_2$ | $lt_3$ | $lt_4$ | $lg_1$ | $lg_2$ | $lg_3$ | $lg_4$ |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| *Sloan* | 0.01 | 3.23 | 3.18 | 46 | 12 | 10 | 1 | 39 | 14 | 14 | 2 |
| | 0.02 | 6.66 | 6.56 | 39 | 13 | 16 | 1 | 33 | 20 | 11 | 5 |
| | 0.03 | 11.85 | 11.02 | 31 | 14 | 17 | 7 | 25 | 20 | 19 | 5 |
| | 0.05 | 25.35 | 25.77 | 22 | 12 | 15 | 20 | 19 | 18 | 19 | 13 |
| | 0.07 | 42.24 | 44.09 | 21 | 10 | 16 | 22 | 18 | 13 | 25 | 13 |
| | 0.10 | 71.47 | 75.98 | 18 | 8 | 18 | 25 | 18 | 10 | 20 | 21 |
| *UBVRI* | 0.01 | 4.01 | 3.94 | 45 | 12 | 10 | 2 | 41 | 17 | 8 | 3 |
| | 0.02 | 8.75 | 8.70 | 33 | 11 | 15 | 10 | 29 | 20 | 14 | 6 |
| | 0.03 | 16.75 | 16.06 | 26 | 16 | 18 | 9 | 25 | 18 | 18 | 8 |
| | 0.05 | 36.50 | 37.38 | 22 | 4 | 25 | 18 | 22 | 15 | 13 | 19 |
| | 0.07 | 61.18 | 62.15 | 16 | 8 | 14 | 31 | 25 | 11 | 15 | 18 |
| | 0.10 | 104.06 | 105.36 | 13 | 9 | 10 | 37 | 21 | 14 | 17 | 17 |
| *Sloan–u* | 0.01 | 20.01 | 17.45 | 29 | 13 | 16 | 11 | 24 | 21 | 14 | 10 |
| | 0.02 | 48.73 | 44.00 | 16 | 11 | 24 | 18 | 16 | 21 | 21 | 11 |
| | 0.03 | 82.77 | 77.48 | 10 | 14 | 19 | 26 | 13 | 18 | 21 | 17 |
| | 0.05 | 153.99 | 151.60 | 12 | 7 | 17 | 33 | 8 | 13 | 24 | 24 |
| | 0.07 | 223.24 | 224.70 | 6 | 12 | 13 | 38 | 6 | 12 | 24 | 27 |
| | 0.10 | 328.87 | 331.40 | 10 | 7 | 11 | 41 | 9 | 11 | 22 | 27 |
| *Sloan** | 0.01 | 3.23 | 3.18 | 46 | 12 | 10 | 1 | 39 | 14 | 14 | 2 |
| | 0.05 | 7.97 | 7.40 | 44 | 12 | 12 | 2 | 41 | 18 | 10 | 0 |
| | 0.10 | 12.46 | 11.35 | 47 | 13 | 6 | 3 | 38 | 19 | 10 | 2 |
| | 0.20 | 16.63 | 14.44 | 38 | 14 | 13 | 4 | 31 | 20 | 11 | 7 |
| | 0.30 | 18.20 | 15.96 | 35 | 13 | 16 | 5 | 29 | 20 | 13 | 7 |
| | | 20.01 | 17.45 | 29 | 13 | 16 | 11 | 24 | 21 | 14 | 10 |

Note:
* $\Delta Q$ values given in Column 2 are only for the $Q$s containing the $u$ passband. For all other $Q$s, $\Delta Q = 0.01$ mag is taken.

(4) For the first three systems the number of models with classification errors $\Delta\log g \geq 1$ is 0 (zero) even at $\Delta Q = 0.10$ mag (Column 12), i.e. at very low accuracy of observations (when rms errors of color indices are of the order of $\pm 0.07$ mag).

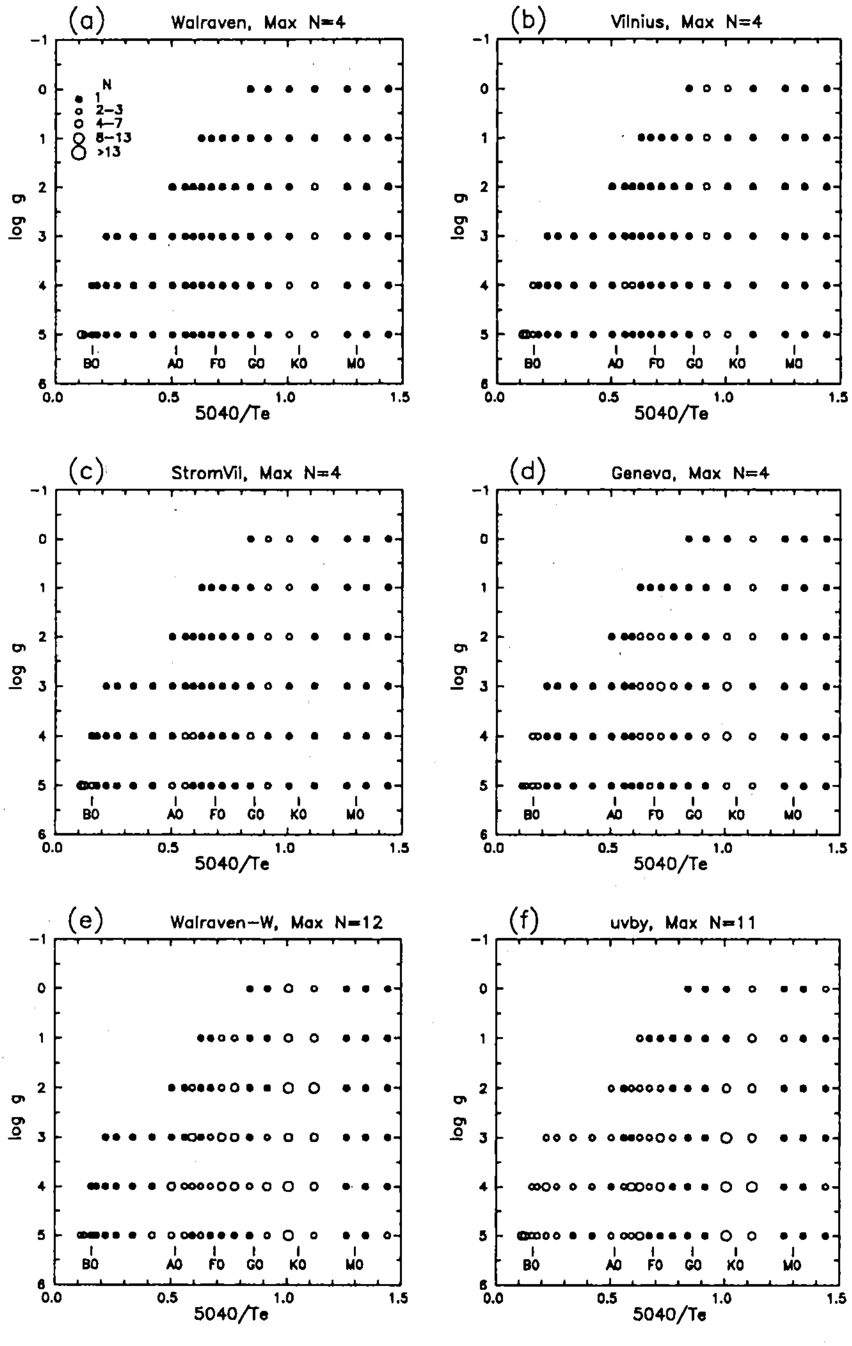


**Fig. 2.** (a–f). Distribution of $N_1$ on the $\theta$, log $g$ plot for different photometric systems. Explanation of symbols is given in the insert of panel (a).

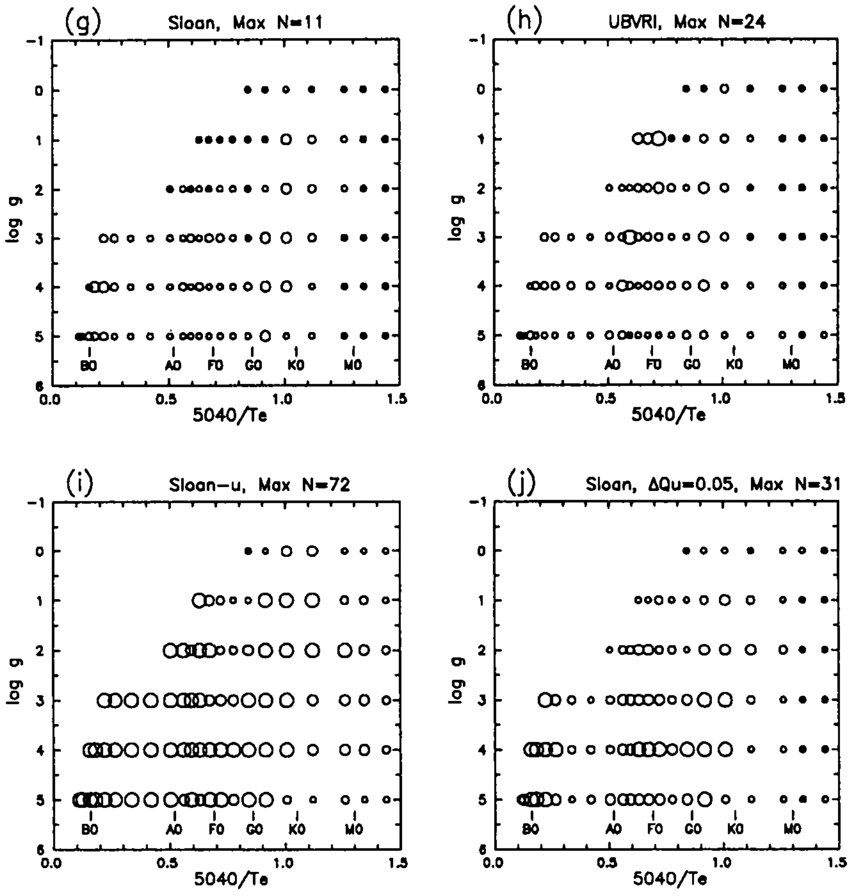


**Fig. 2.** (g–j). Explanation of symbols is given in the insert of panel (a).

(5) The lowest classification accuracy is seen for the *Sloan* system without $u$ passband. Addition of the ultraviolet magnitude $u$, even of lower accuracy, increases the classification possibilities of the system considerably.

The highest sensitivity of the *Walraven* system is due to the presence of two ultraviolet passbands shortward of the Balmer jump. Additional calculation show, that without the narrowest passband $W$ the mean number $\bar{N} = 2.24$ (for $\Delta Q = 0.01$). This places the system between the *Geneva* and *Strömgren* systems. After rejecting $U$ (but leaving $W$), $\bar{N}$ becomes smaller (1.67), but the system remains at the same rank.

Different panels of Fig. 2 show the distribution of $N_1$ when $\Delta Q =$ 0.01 (for the first (92) program models group) in the $\theta$ vs. log $g$, diagram for various photometric systems. The circle sizes mark the classification accuracy everywhere: the filled circles are for $N = 1$ and the other symbols are explained in the insert to Fig. 2, (a) panel. Also, the maximum $N$ in each panel is indicated. As it is seen from Fig. 2, the most difficult region for all systems is at high temperature end (> 32 000 K). Each of the systems has other regions of lower accuracy. For the *Walraven* system such a region corresponds to early K subclasses, for the *Vilnius* and *Strömvil* systems – G-type stars, for the *Geneva* system – late A, early F, late G and K-type stars, for the *Strömgren* system – B, A, early F, late G and K-type stars. The *UBVRI* and *Sloan* systems recognize photometrically only the late K and M models and some small islands in other places of the $\theta$, log $g$ diagram. The Sloan system without $u$ has only one model with $N = 1$.

A comparison of our results with those of Straižys, Liubertas & Lazauskaitė (1998) shows an agreement in principle. It is problematic to compare the results in detail since both investigations use different criterions, set of standards, temperature steps and error values.

### *3.2. Separation of metal-deficient stars*

As was mentioned earlier, three groups of metal-deficient models with [Fe/H] of –0.5, –1.0 and –2.0, consisting of 71, 76 and 76 models respectively, were used to check the possibility of separating them from models of solar metallicity. For this, the numbers of solar metallicity standards falling into the volume element with the side $2\Delta Q$ centered on each metal-deficient model were determined. Four values of $\Delta Q$ were taken: 0.01, 0.02, 0.03 and 0.04 mag. In each case we counted the numbers $n_1$, $n_2$, $n_3$ and $n_4$ of metal-deficient models, for which no solar metallicity standards in the elementary volume were found (Table 4). For example, $n_4$ gives the number of metal-deficient models for which no standards of solar metallicity in the elementary volume with a half-side of 0.04 mag were found ($N = 0$). In the case of observations of real stars with the rms error of color indices $\sigma = 0.01$ mag (corresponding to $\sigma(Q) = 0.014$ mag), the absence of any standard in $3\,\sigma$ volume means that this program star is really peculiar. If $\Delta Q$ is taken smaller, the probability to

**Table 4.** Separation of the metal-deficient models. Numerals $n_i$ are the numbers of metal-deficient models for which no solar composition models were found inside the $n$-dimensional volume with the $2\Delta Q$ side, $\Delta Q$ being 0.04, 0.03, 0.02 and 0.01 mag.

| System | [Fe/H] | $n_4$ | $n_3$ | $n_2$ | $n_1$ | Unrecognized all | Unrecognized F–M |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| *Walraven* | –0.5 | 46 | 52 | 57 | 58 | 13 | 2 |
| | –1.0 | 50 | 58 | 62 | 65 | 11 | 2 |
| | –2.0 | 56 | 58 | 63 | 70 | 06 | 0 |
| *Vilnius* | –0.5 | 41 | 44 | 51 | 53 | 18 | 4 |
| | –1.0 | 50 | 53 | 58 | 62 | 14 | 1 |
| | –2.0 | 53 | 54 | 56 | 59 | 17 | 0 |
| *Strömvil* | –0.5 | 37 | 45 | 54 | 57 | 14 | 0 |
| | –1.0 | 52 | 55 | 56 | 60 | 16 | 1 |
| | –2.0 | 52 | 54 | 55 | 58 | 18 | 0 |
| *Geneva* | –0.5 | 7 | 17 | 26 | 42 | 29 | 13 |
| | –1.0 | 22 | 32 | 49 | 53 | 23 | 4 |
| | –2.0 | 29 | 36 | 42 | 53 | 23 | 7 |
| *uvby* | –0.5 | 1 | 9 | 13 | 18 | 53 | 35 |
| | –1.0 | 7 | 11 | 13 | 21 | 55 | 33 |
| | –2.0 | 22 | 24 | 28 | 36 | 40 | 18 |
| *Sloan* | –0.5 | 6 | 14 | 25 | 37 | 34 | 17 |
| | –1.0 | 12 | 20 | 31 | 43 | 33 | 12 |
| | –2.0 | 36 | 45 | 49 | 56 | 20 | 1 |
| *UBVRI* | –0.5 | 2 | 5 | 11 | 28 | 43 | 25 |
| | –1.0 | 4 | 7 | 18 | 41 | 35 | 13 |
| | –2.0 | 15 | 18 | 25 | 35 | 41 | 20 |
| *Walraven–W* | –0.5 | 8 | 18 | 33 | 39 | 32 | 20 |
| | –1.0 | 22 | 24 | 30 | 36 | 40 | 23 |
| | –2.0 | 15 | 19 | 25 | 33 | 43 | 26 |
| *Sloan–u* | –0.5 | 1 | 3 | 4 | 13 | 58 | 50 |
| | –1.0 | 3 | 7 | 11 | 27 | 49 | 28 |
| | –2.0 | 18 | 21 | 30 | 48 | 28 | 24 |

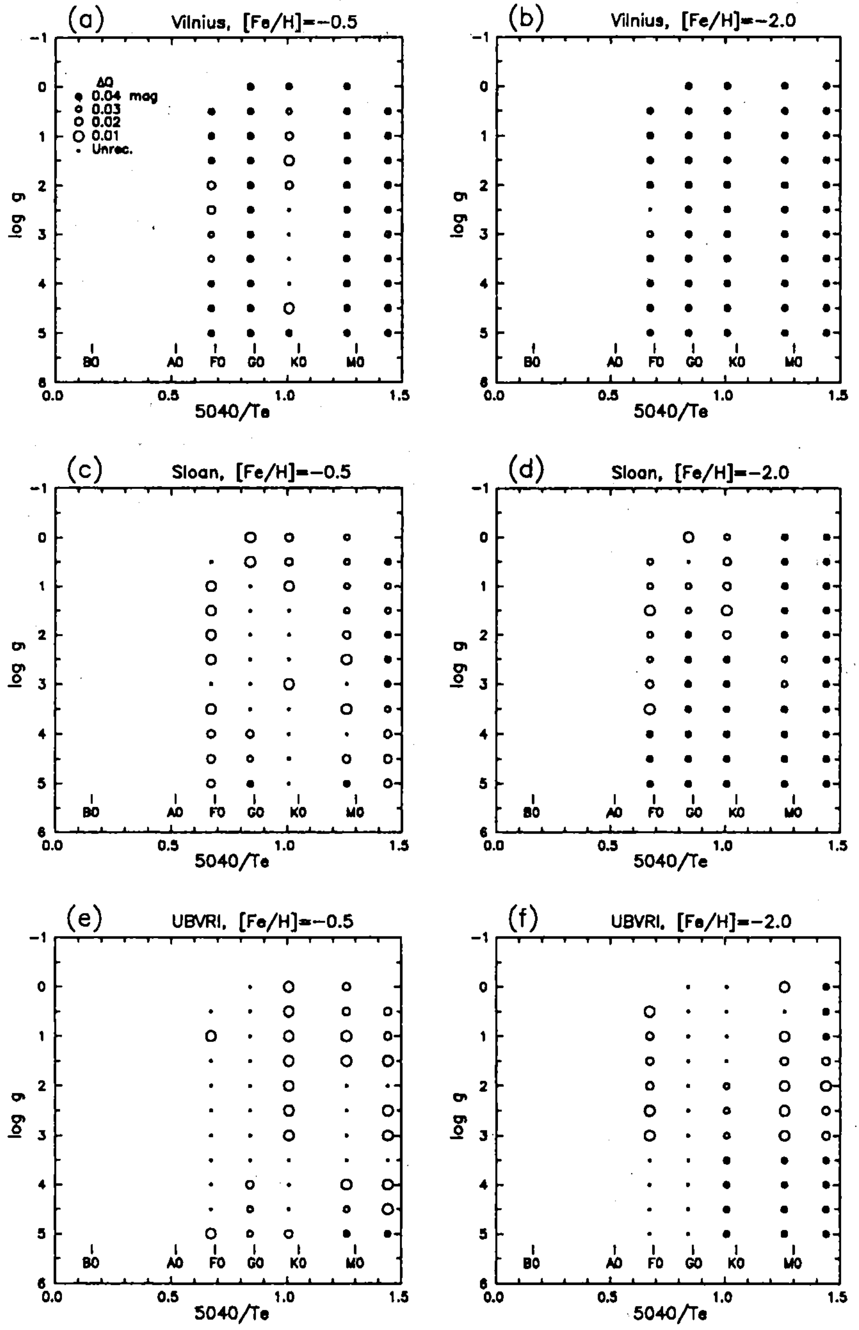


**Fig. 3.** Distribution of F–G–K–M metal-deficient models on the $\theta$, log $g$ plot. Filled circles – best separable, small dots – inseparable from solar metallicity models. All symbols are explained on the (a) panel.

recognize peculiarity of the star becomes lower since $\Delta Q < 3\,\sigma$ (at the same $\sigma$ of observations). At smaller $\Delta Q$ for the recognition of peculiarity more precise observations are needed.

Columns 4–6 give the same for other (0.03–0.01 mag) $\Delta Q$ values. The metal-deficient models, for which solar metallicity standards are found in the elementary volume with a half-side of 0.01 mag, we call as unrecognizable. This means, these models cannot be recognized as metal-deficient, when $Q$ errors are 0.01 mag or larger. The numbers of unrecognized models are given in Column 7 for all used models, and in Column 8 only for the models with $T_e < 8000$ K (F, G, K and early M stars).

It is natural to see that the majority of unrecognizable metal-deficient models occur at the temperatures of B–A stars – such stars do not show a sufficient blanketing effect. Table 4 shows that the separation of metal-deficient models with [Fe/H] = –0.5 in the first three systems i.e. *Walraven, Vilnius* and *Strömvil* is even better, than the models with [Fe/H] = – 2.0 in other systems. Among other systems, the satisfactory separation of models with large metal-deficiency ([Fe/H] = –2) is seen in the *Sloan* system, a little worse in the *Geneva* system.

More information on the identification possibility of metal-deficient models as a function of $\theta$ and log $g$ for the *Vilnius, Walraven* and *UBVRI* systems is shown in Fig. 3 (a–f). The separation is better in the areas where the classification of solar composition models is more accurate.

### *3.3. Separation of binary stars*

Nine Kurucz models with log $g = 5$ and $T_e$ values: 3500, 4000, 5000, 6000, 7500, 10 000, 15 000, 23 000 and 32 000 K have been used for synthesizing a set of "binary stars". 72 binary models with magnitude differences between the components of 0, 1.0, 2.5 and 4.25 mag were constructed. The information characterizing the recognition possibilities of binary models at different $\Delta Q$ values is given in Table 5. Column 2 gives the differences of magnitudes $V$ between the components. Column 3 gives the numbers of models for which $N = 0$, i.e. they are recognized as peculiar, when $\Delta Q$ is 0.04 mag. Other columns, as in the case of metal-deficient models, give similar numbers for $\Delta Q = 0.03$, 0.02 and 0.01 mag. Column 7 gives the number of models which are classified as normal at $\Delta Q = 0.01$ mag, i.e. their peculiarity is not recognized.

**Table 5.** Separation of binary models. Numerals $n_4, n_3, n_2$ and $n_1$ are the numbers of binary models for which no single models were found inside the $n$-dimensional volume with the $2\,\Delta Q$ side, $\Delta Q$ being 0.04, 0.03, 0.02 and 0.01 mag

| System | $\Delta V$ | $n_4$ | $n_3$ | $n_2$ | $n_1$ | Unrecognized |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| *Walraven* | 0.0 | 60 | 66 | 66 | 68 | 4 |
| | 1.0 | 52 | 59 | 63 | 67 | 5 |
| | 2.5 | 32 | 41 | 53 | 62 | 10 |
| | 4.25 | 22 | 25 | 27 | 29 | 43 |
| *Vilnius* | 0.0 | 64 | 66 | 66 | 66 | 6 |
| | 1.0 | 55 | 63 | 66 | 66 | 6 |
| | 2.5 | 44 | 46 | 54 | 61 | 11 |
| | 4.25 | 15 | 18 | 33 | 42 | 30 |
| *Strömvil* | 0.0 | 62 | 66 | 66 | 66 | 6 |
| | 1.0 | 54 | 62 | 65 | 66 | 6 |
| | 2.5 | 43 | 45 | 54 | 59 | 13 |
| | 4.25 | 15 | 20 | 30 | 42 | 30 |
| *Geneva* | 0.0 | 52 | 56 | 56 | 60 | 12 |
| | 1.0 | 44 | 47 | 56 | 60 | 12 |
| | 2.5 | 23 | 29 | 35 | 53 | 19 |
| | 4.25 | 16 | 18 | 21 | 28 | 44 |
| *uvby* | 0.0 | 26 | 38 | 40 | 50 | 22 |
| | 1.0 | 24 | 31 | 37 | 50 | 22 |
| | 2.5 | 14 | 17 | 21 | 32 | 40 |
| | 4.25 | 8 | 10 | 12 | 19 | 53 |
| *Sloan* | 0.0 | 30 | 36 | 50 | 58 | 14 |
| | 1.0 | 33 | 36 | 42 | 54 | 18 |
| | 2.5 | 32 | 35 | 41 | 47 | 25 |
| | 4.25 | 17 | 19 | 25 | 34 | 38 |
| *UBVRI* | 0.0 | 32 | 36 | 44 | 56 | 16 |
| | 1.0 | 32 | 38 | 45 | 51 | 21 |
| | 2.5 | 25 | 30 | 36 | 46 | 26 |
| | 4.25 | 11 | 17 | 24 | 27 | 45 |
| *Walraven–W* | 0.0 | 22 | 30 | 36 | 38 | 34 |
| | 1.0 | 16 | 26 | 34 | 41 | 31 |
| | 2.5 | 12 | 14 | 18 | 25 | 47 |
| | 4.25 | 5 | 7 | 8 | 9 | 63 |
| *Sloan–u* | 0.0 | 20 | 26 | 32 | 40 | 32 |
| | 1.0 | 16 | 19 | 24 | 33 | 39 |
| | 2.5 | 5 | 7 | 12 | 21 | 51 |
| | 4.25 | 2 | 3 | 7 | 7 | 65 |

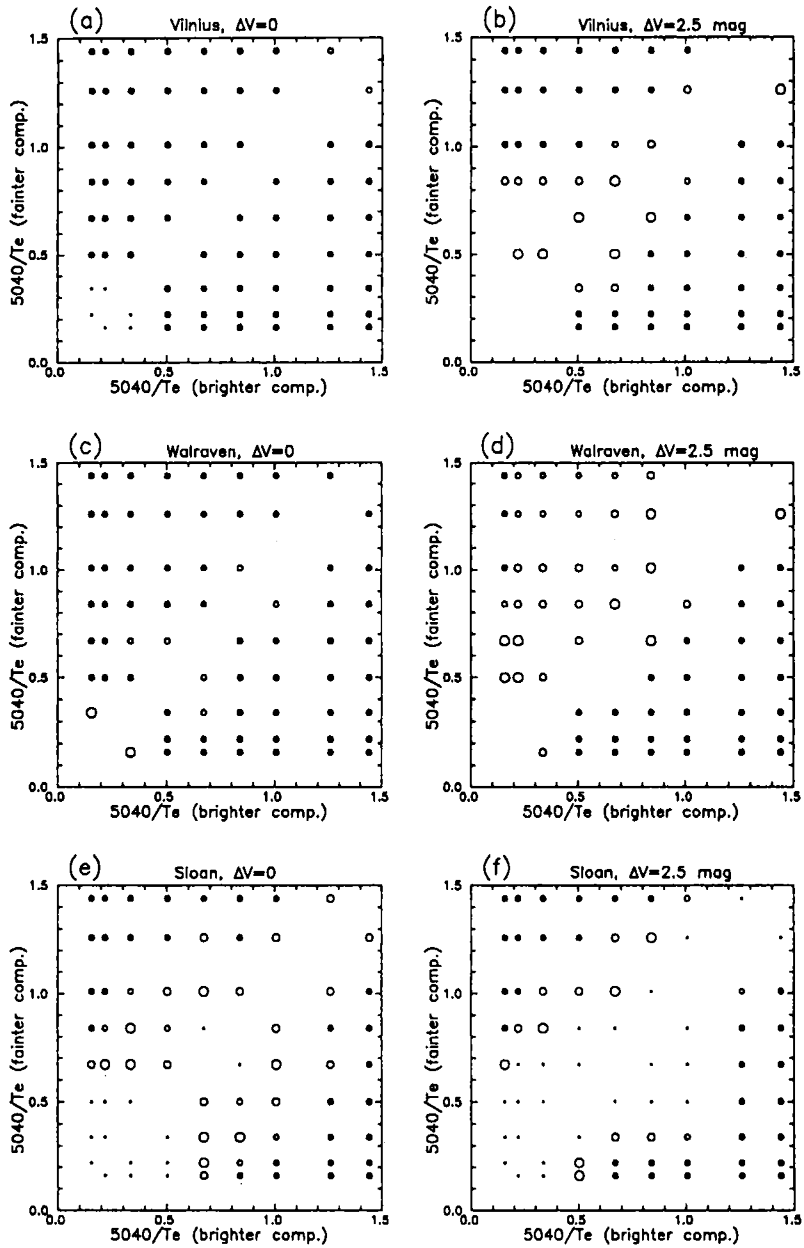


**Fig. 4.** Distribution of the recognized binary models as a function of temperature of the components for $\Delta V = 0$ and 2.5. Filled circles are for binary models which are identified at $\Delta Q = 0.04$ mag, small dots are for binary models, which are inseparable from single models. Explanation of other symbols is in panel (a) of Fig. 3.

The numbers of recognized binary models as a function of temperature of the components for $\Delta V = 0$ and 2.5 mag is shown in Fig. 4. The symbols are the same as in Fig. 3(a).

One can see that the best identification of binaries with components of equal $V$ (but different temperatures) is in the *Vilnius, Strömvil* and *Walraven* systems, a little worse in the *Geneva* system. In the *Vilnius* and *Strömvil* systems binaries are recognized better than in other systems up to $\Delta V = 2.5$ mag. The numbers of recognized binaries with $\Delta V = 4.25$ mag are approximately the same in the *Walraven, Sloan, Geneva, Vilnius* and *Strömvil* systems. The lowest identification takes place in the systems without ultraviolet passbands.

As it is seen in Fig. 4, in the case of binaries with equal components ($\Delta V = 0$) the plots are symmetrical with respect to the bisector. The plots of binaries with components of different brightness in $V$ are more or less asymmetric; for instance, in the *Walraven* system (panel (d)) the recognition is better for binaries with high temperature faint component. The plots for the *Vilnius* and *Sloan* systems are more or less symmetrical, and the identification of binaries mainly depends on temperature difference of the components.

## 4. CONCLUSIONS

The analysis shows, that all the investigated photometric systems may be ranked in the following sequence in regards of their classification possibilities of solar metallicity models: *Walraven, Vilnius, Strömvil, Geneva, uvby, Sloan, UBVRI, Sloan* without $u$. The first three systems (*Walraven, Vilnius* and *Strömvil*) are most sensitive to log $g$.

A high overall accuracy of classification in the *Walraven* system is due to the presence of two ultraviolet passbands shortward of the Balmer jump, where color indices (and $Q$-parameters) are most sensitive to $T_e$ and log $g$. But the efficiency of the system is low in classifying K-type stars, especially in gravities. Also, the system contains too many ultraviolet passbands to be used for faint late-type and considerably reddened stars.

The broad-band *UBVRI* and *Sloan* systems give very low classification accuracy of stars affected by interstellar reddening. If the $u$ passband is abandoned (as it is suggested to do with the *Sloan* system of the Gaia orbiting observatory), the system becomes useless for stellar classification. Its classification possibilities even at the high accuracy of observations ($\Delta Q = 0.01$ mag) are lower than for the *Vilnius* or *Walraven* systems even with $\Delta Q = 0.10$ mag! The addition of $u$, even of low accuracy (0.1 mag) increases the classification accuracy by a factor of two. This emphasizes the importance of the ultraviolet passband.

The capability to recognize and separate metal-deficient models in the *Walraven, Vilnius* and *Strõmvil* systems is the best. There is very large difference between these and other systems.

According to the capability of separating binary stars, the ranking of all systems is approximately the same, but the *Vilnius* and *Strõmvil* are slightly better than the *Walraven* system.

In comparison to other investigated systems, the *Vilnius* and *Strõmvil* systems give sufficiently high classification accuracy for all spectral classes and gravities, especially for K–M type stars. These systems are also most effective in recognition of metal-deficient stars and unresolved binary systems.

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## REFERENCES

Ažusienis A., Straižys V. 1969, AZh, 46, 402 = Soviet Astron., 13, 316

Bessell M. S. 1983, PASP, 95, 480

Crawford D. L., Barnes J. V. 1970, AJ, 75, 978

Fukugita M., Ichikawa T., Gunn J. E., Doi M., Shimasaku K., Schneider D. P. 1996, AJ, 111, 1748

Kurucz R. L. 1995, personal communication to V. Straižys

Lub J., Pel J. W. 1977, A&A, 54, 137

Olson E. C. 1974, PASP, 86, 80

Rufener F., Nicolet B. 1988, A&A, 206, 357

Straižys V. 1992, Multicolor Stellar Photometry, Pachart Publishing House, Tucson, Arizona

Straižys V., Liubertas R., Lazauskaitė R. 1998, Baltic Astronomy, 7, 529