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A COMPARISON OF STELLAR CLASSIFICATION POSSIBILITIES OF PHOTOMETRIC SYSTEMS. I. SOLAR METALLICITY STARS

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Abstract. Accuracy of determining effective temperatures and gravities of stars of solar metallicity in the *Vilnius, Strömvil, Walraven* and *Geneva* photometric systems is intercompared. The analysis of the systems is based on synthetic color indices and interstellar reddening-free Q-parameters calculated for the Kurucz model atmospheres.

Key words: techniques: photometric – stars: fundamental parameters, classification

1. INTRODUCTION

A number of multicolor photometric systems have been proposed for classification and quantification* of faint stars. The most recent description of these systems is given in a monograph of one of the authors (Straižys 1992). Some ideas on the future of photometric systems were recently discussed by Crawford (1988, 1993, 1994) and Sterken (1992). Although the classification properties of various systems were described many times, their direct intercomparison was not available. Jaschek & Frankel (1986) have proposed a criterion

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* The classification of stars is understood as their segregation into classes according to their temperatures, luminosities or other physical parameters; quantification is the determination of quantitative values of these parameters.

Table 1. Mean wavelengths and half-widths of passbands of the investigated systems (in nm).

Vilnius			*Strömvil*			*Strömvil-Gaia*			*Walraven*			*Geneva*		
	λ_0	$\Delta\lambda$		λ_0	$\Delta\lambda$		λ_0	$\Delta\lambda$		λ_0	$\Delta\lambda$		λ_0	$\Delta\lambda$
U	345	40	*u*	350	30	*u*	345	40	*W*	325	14	*U*	346	46
P	374	26	*P*	374	26	*P*	380	20	*U*	363	24	*B1*	402	40
X	405	22	*v*	411	19	*v*	405	20	*L*	384	22	*B*	424	81
Y	466	26	*b*	467	18	*b*	460	20	*B*	432	45	*B2*	448	42
Z	516	21	*Z*	516	21	*Z*	515	20	*V*	547	70	*V1*	540	46
V	544	26	*y*	547	23	*y*	545	20				*V*	550	72
S	656	20	*S*	656	20	*S*	656	20				*G*	580	44

for the estimation of quality of photometric systems, the purity parameter. However, this parameter was applied only to unreddened B–A–F stars in the *UBV* system.

With the necessity to choose an optimum system for the *Gaia* orbiting observatory, intercomparison of the classification properties of the existing systems is important. The system chosen for this project should be able to operate in a general galactic field where stars of different temperatures, luminosities, metallicities, peculiarities and interstellar reddenings are mixed together. At the present time, the seven-color *Strömvil* photometric system is the place-holder in the *Gaia* project. This system, combining two widely-used medium-band systems, it Strömgren and *Vilnius*, has been described by Straižys, Crawford and Philip (1996) and Straižys & Høg (1995). The latest modification of this system, proposed for the *Gaia* mission, has rectangular response functions and slightly different central wavelengths in comparison with the original *Strömvil system.* In this paper this system will be called as the *Strömvil-Gaia* system.

Other medium band systems, having numerous observations of stars, are the original four-color *uvby* system, its variety *uvbyβ*, the original *Vilnius* system, the *Geneva* system and the *Walraven* system.

In the present work we compare classification properties of five medium-band photometric systems, two of them (*Walraven* and *Geneva* systems) include some broad passbands. The mean wavelengths and half-widths of all passbands are given in Table 1. In the case of the *Strömvil-Gaia* system, instead of the widths at half-response, full widths of rectangular response functions are given.

2. THE METHOD

The method for quality estimation of a photometric system is based on color indices and interstellar reddening-free Q-parameters calculated for a grid of synthetic spectra of stellar model atmospheres of Kurucz (1995) for different values of T_e and $\log g$ of solar metallicity. The grid contains 409 models with effective temperatures ranging from 50 000 K to 3500 K and logarithms of gravities from 0.0 to 5.0. In this study we shall consider that the flux distribution functions of Kurucz models represent real stars with sufficient accuracy. As it was shown by different authors, this is close to reality, except for the models of the lowest temperatures, corresponding to M-type stars (see Straižys et al. 1997b). Some possible systematic errors are not important in the present intercomparison of photometric systems.

Color indices, color excesses and Q-parameters are calculated by the following equations:

$$m_1 - m_2 = -2.5 \ \log \frac{\int F(\lambda)\, R_1(\lambda)\, d\lambda}{\int F(\lambda)\, R_2(\lambda)\, d\lambda} + const, \tag{1}$$

$$E_{12} = -2.5 \ \log \frac{\int F(\lambda)\, R(\lambda)\, \tau^x(\lambda)\, d\lambda}{\int F(\lambda)\, R(\lambda)\, d\lambda}, \tag{2}$$

$$Q_{1234} = m_1 - m_2 - (E_{12}/E_{34})(m_3 - m_4) \tag{3}$$

where $F(\lambda)$ are the model fluxes, $R_1(\lambda)$ and $R_2(\lambda)$ are the response functions in two passbands, $\tau^x(\lambda)$ is the standard transmittance function for x mass units of interstellar dust. The integration step was the same as the binning interval of the flux functions, i.e. 2 nm. All color indices were normalized to zero for the model 35 000 K, $\log g = 4.0$ which corresponds to a main-sequence O-type star.

The first part of investigation includes quantification of solar metallicity stars only. Response functions of the photometric systems are taken from the following sources: for the *Vilnius* system and the P, Z and S passbands of the *Strömvil* system from Straižys (1992), for the u, v, b and y passbands of the *Strömgren* and *Strömvil* systems from Olson (1974) and Crawford & Barnes (1970), for the *Walraven* system from Lub & Pel (1977) and for the *Geneva* system from Rufener & Nicolet (1988). For the *Strömvil-Gaia* system the response functions are taken of rectangular shape with constant response from short to long wavelength limits. In Table 1 for this system the full widths of the response functions are given. The standard transmittance function of interstellar dust was taken from Straižys (1992).

The following color indices and interstellar reddening-free Q-parameters were calculated.

(1) The *Vilnius* system: U–P, P–X, X–Y, Y–Z, Z–V, V–S, $Q(UPY)$, $Q(UXY)$, $Q(PYV)$, $Q(XZS)$, $Q(XYZ)$ and $Q(UPYV)$;

(2) The *Strömvil* system: u–P, P–v, v–b, b–Z, Z–y, y–S, $Q(uPb)$, $Q(uvb)$, $Q(Pby)$, $Q(vZS)$, $Q(vbZ)$ and $Q(uPby)$;

(3) The *Strömvil-Gaia* system: the same as for the *Strömvil* system;

(4) The *Walraven* system: W–U, U–L, L–B, B–V, $Q(WUBV)$, $Q(WUL)$, $Q(WLV)$, $Q(ULV)$ and $Q(LBV)$;

(5) The *Geneva* system: U–$B1$, $B1$–B, B–$B2$, $B2$–$V1$, $V1$–V, V–G, $Q(U,B1,B2)$, $Q(U,B2,G)$, $Q(B1,B2,V1)$ and $Q(B1,B2,G)$.

Let us show how the quantification process works. We will start from the case when interstellar reddening is absent. In this case the matching of color indices is sufficient.

The matching is being done by a comparison of a set of color indices $m_k - m_\ell$ of each model with the same color indices of all other models, using the mean deviation:

$$\sigma(m_k - m_\ell) = \left(\frac{\Sigma\Delta^2(m_k - m_\ell)}{n}\right)^{1/2}; \qquad (4)$$

here n is the number of color indices available for each model in a given system.

Let us quantify one of the Kurucz models, model A, with certain values of T_e and $\log g$. In the comparison process, the model itself will be always find with $\sigma = 0.0$. The next models with the smallest values of σ will be the neighbors of model A in the T_e, $\log g$ diagram. The quantification accuracy can be estimated by the size of the box in the T_e, $\log g$ diagram which contains the models giving $\sigma = 0.01$ mag or other limiting value. For a high quality system the boxes will be small with only small overlapping with the adjacent boxes. Of course, the box size will depend on the step of T_e and log g of the models used for the comparison. The number of models available can be increased by interpolation to the required amount.

However, the described situation never happens in practice since the observed color indices always contain some measurement errors as well as some "cosmic dispersion", i.e. scattering of color indices of stars having the same T_e and $\log g$. To take this into account, we have supplemented the quantification process by simulating errors of color indices. We shall name these errors as observational, however, they can be equally considered as a consequence of "cosmic dispersion".

The simulated errors were introduced in the following way. If $(m_k - m_\ell)_i$ is a color index of the model, then its "observed" value is calculated by the equation (Bevington & Robinson 1994):

$$(m_k - m_\ell)_{i,\mathrm{obs}} = (m_k - m_\ell)_i + \sigma_i r_i, \qquad (5)$$

where σ_i is the accepted uncertainty of "observations" and r_i is the random variable drawn from the standard Gaussian distribution obtained by the Box-Müller method, with the mean value equal to 0 and the standard deviation equal to 1. In this paper σ values of 0.01 mag were taken (1 % photometry). Each set of synthetic color indices of the model was generated 100 times taking statistically accidental values of r_i. Thus, instead of one fixed set of color indices, each model got 100 sets of "observed" color indices. For each of these 100 simulated "measurements" we have determined T_e and $\log g$ by fitting the "observed" color indices of the models with color indices calculated for the Kurucz models.

The total number of models used was 5673. They were obtained by splitting each interval of T_e and $\log g$ values of Kurucz models into four parts. The templates of the used model grids for different temperature intervals are shown in Figs. 1(a–d). The steps of T_e are: 250 K for early B-type models, 125 K for late B-type models and 62.5 K for A–F–G–K–M type models. Each of these simulated "observations" was plotted on the T_e, $\log g$ diagram. As a consequence, each Kurucz model in this diagram has been smeared into a cluster of 100 points of different form and orientation. We have circumscribed these point clusters by the confidence ellipses: the probability that the points are within the area marked by an ellipsis is approximately 95 %.

As a result, for each system with the "observational" error σ we have obtained T_e, $\log g$ diagrams in which, instead of standard Kurucz models, there are the confidence ellipses characterizing the quantification accuracy. If the ellipsis has great excentricity and its long axis is directed more or less horizontally, this means that

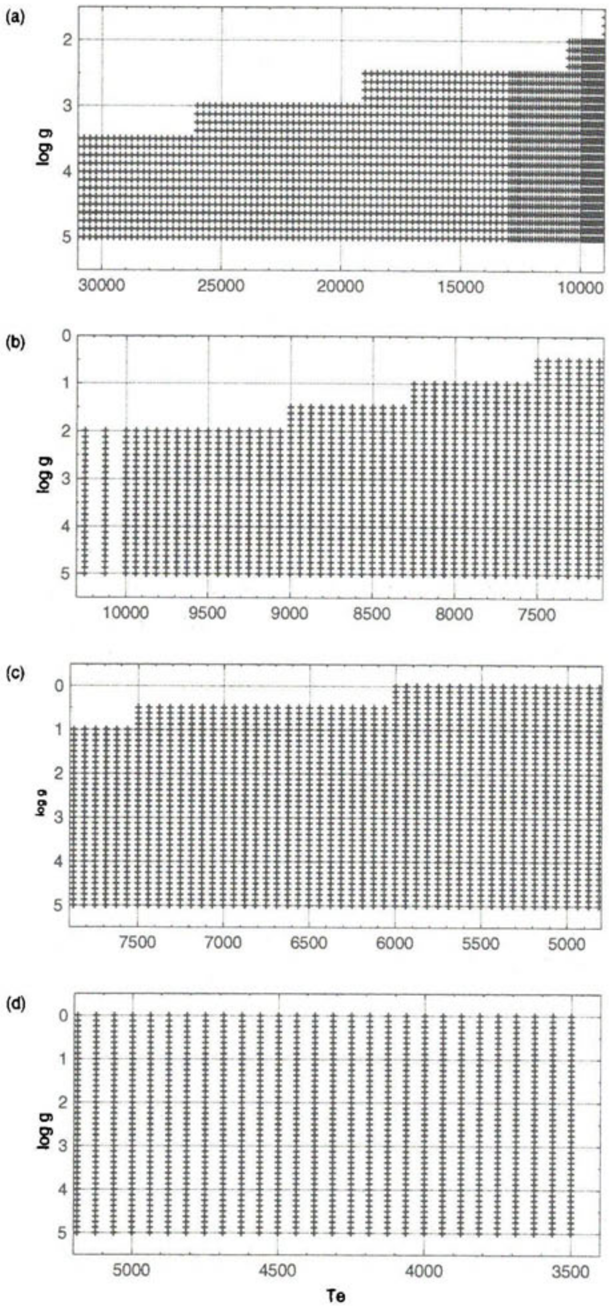

Fig. 1. The model grid used for the quantification of simulated stars. Panel (a) corresponds to B-type stars, panel (b) to A-type stars, panel (c) to F–G-type stars and panel (d) to K–M-type stars. O-type models (hotter than 31 000 K) are not shown.

temperature errors are most significant. If such ellipsis is oriented vertically, this means that gravity errors are the greatest.

When interstellar reddening is present, color indices are not suitable for quantification of stars. Instead of them, reddening-free Q-parameters defined by Eq. (3) should be used. We have made the smearing of the Kurucz models in the T_e, $\log g$ diagram by taking $\sigma(Q)$ value of 0.02 mag, which corresponds approximately to $\sigma(m_k - m_\ell) = 0.014$.

The results of quantification of the Kurucz models in each photometric system will be shown in a form of four T_e, $\log g$ diagrams, corresponding to the following temperature intervals: 30 000–10 000 K (B-type stars), 10 000–7500 K (A-type stars), 7500–5000 K (F–G-type stars) and 5000–3500 K (K–M-type stars). The correspondence of the effective temperatures to various spectral and luminosity classes of stars is given in Table 2. Trying to escape overcrowding of the diagrams, we have plotted on them the error ellipses only for 128 models, i.e. only for $\sim 1/3$ of all combinations of T_e and $\log g$. At the right and left sides of the diagrams, where the ellipses cross the y-axis, their form is somewhat distorted. This was caused by some technical difficulties, trying to show the results for all photometric systems in the same scale.

3. THE VILNIUS, STRÖMVIL AND STRÖMVIL-GAIA SYSTEMS

3.1. Unreddened models

The T_e, $\log g$ diagrams for the *Vilnius, Strömvil* and *Strömvil-Gaia* photometric systems with observational errors of color indices of $\sigma = 0.01$ mag are given in Figs. 2, 4 and 6. The diagrams for these three systems are very similar and we will discuss them together. Their general feature is very good quantification accuracy everywhere in the HR diagram.

For B-type models the temperature errors are from ±1500 K at 28 000 K to ±150 K at 10 000 K. For A-type models they are between ±100 K and ±200 K. For F–G–K–M models the temperature errors are ±(50–100) K. This temperature error everywhere is less than 1 spectral subclass in the decimal division of spectral classes. In reality, MK spectral classification system uses smaller number of

Table 2. Effective temperatures (in K) for some spectral and luminosity classes. The data are from Straižys & Kurilienė (1981).

Sp	V–III	I–II	Sp	V	III	I–II
O5	42300	41500	F2	7000	7000	7100
O6	39200	38500	F5	6500	6500	6500
O7	37000	36000	F8	6150	6050	6000
O8	35500	34300	G0	5950	5800	5700
O9	33500	32500	G2	5800	5500	5400
B0	31500	27000	G5	5500	5150	5000
B1	26500	23500	G8	5250	4950	4600
B2	23000	20300	K0	5050	4800	4400
B3	19300	17500	K1	4950	4600	4300
B5	15400	13700	K2	4850	4450	4200
B6	14200	12600	K3	4700	4250	4100
B7	12800	11700	K4	4600	4100	–
B8	11500	11000	K5	4400	4000	3850
B9	10400	10300	K7	4000	–	–
A0	9600	9800	M0	3900	3900	3700
A1	9400	9500	M1	3750	3800	3600
A2	9150	9200	M2	3550	3750	3500
A3	8900	8900	M3	3400	3650	3300
A5	8400	8300	M4	3250	3550	3100
A7	8000	7900	M5	3100	3400	2950
F0	7300	7400	M6	–	3250	–

subclasses in i.e. the quoted temperature errors lead to ≤ 0.5 of the MK subclass.

The gravity errors for B-type models change from ± 0.05 dex at 28 000 K to ± 0.01 dex at 10 000 K. For the cooler models the errors are between $\pm(0.1$–$0.2)$ dex. This means that each Kurucz model-like star can be recognized without ambiguity.

3.2. Reddened models

The T_e, $\log g$ diagrams for observational errors of Q-parameters of $\sigma = 0.02$ mag are given in Figs. 3, 5 and 7. We conclude that the quantification accuracy of the models is only a bit lower than in the case of unreddened models using their intrinsic color indices.

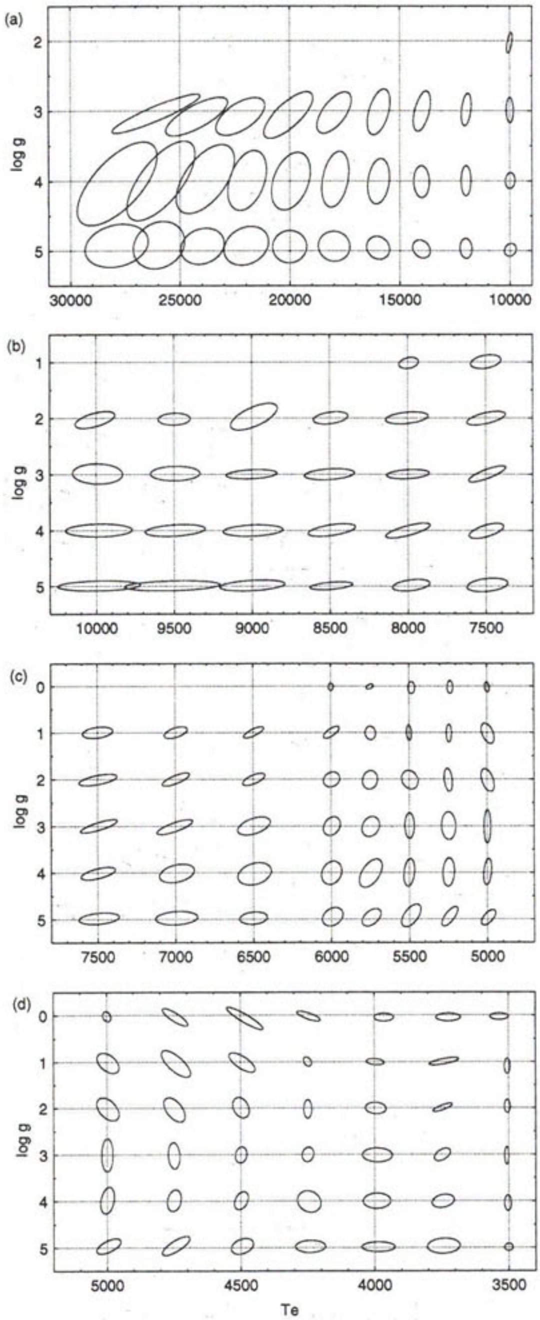

Fig. 2. The T_e vs. $\log g$ diagram for the simulated observations of unreddened stars in the *Vilnius* system. The models are quantified by their color indices.

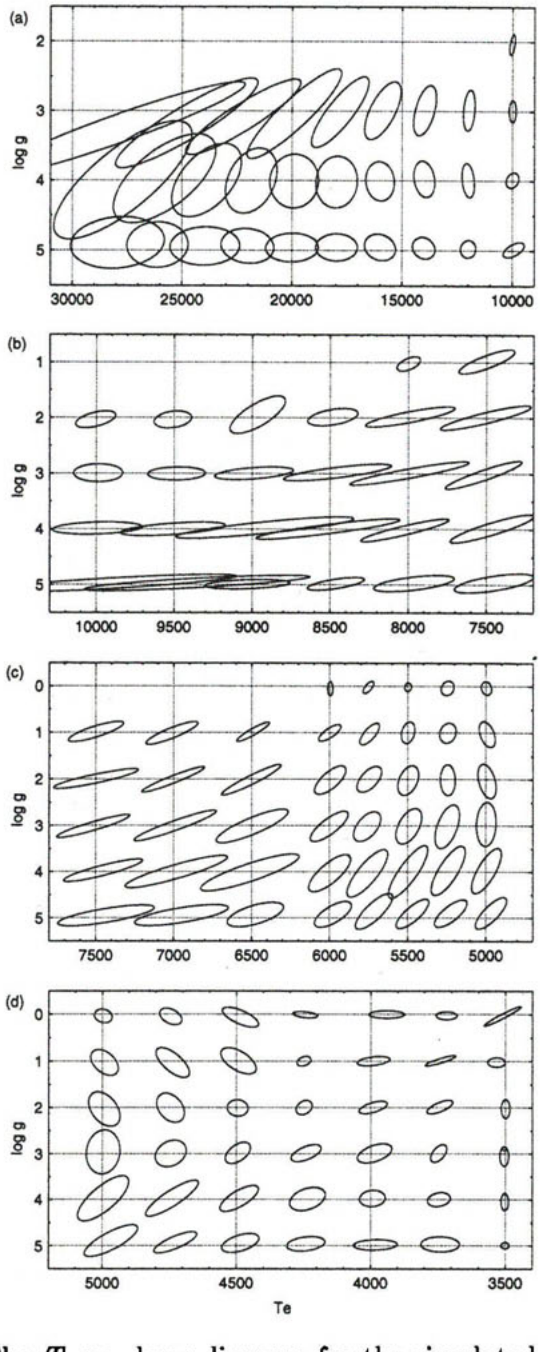

Fig. 3. The T_e vs. $\log g$ diagram for the simulated observations of reddened stars in the *Vilnius* system. The models are quantified by their Q-parameters.

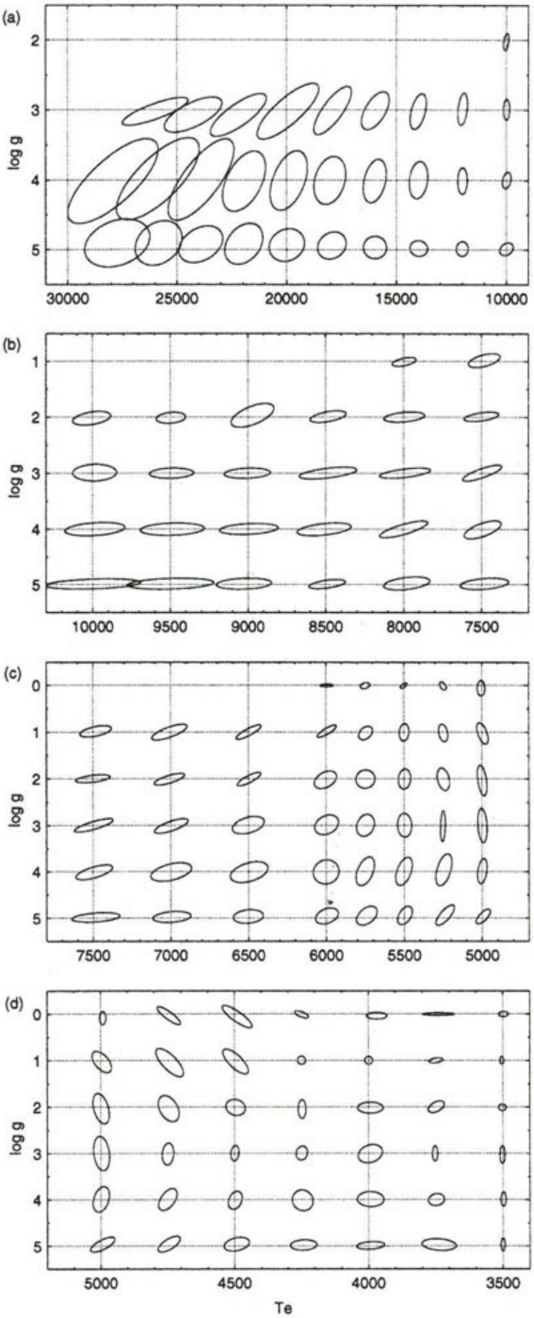

Fig. 4. The T_e vs. $\log g$ diagram for the simulated observations of unreddened stars in the *Strömvil* system. The models are quantified by their color indices.

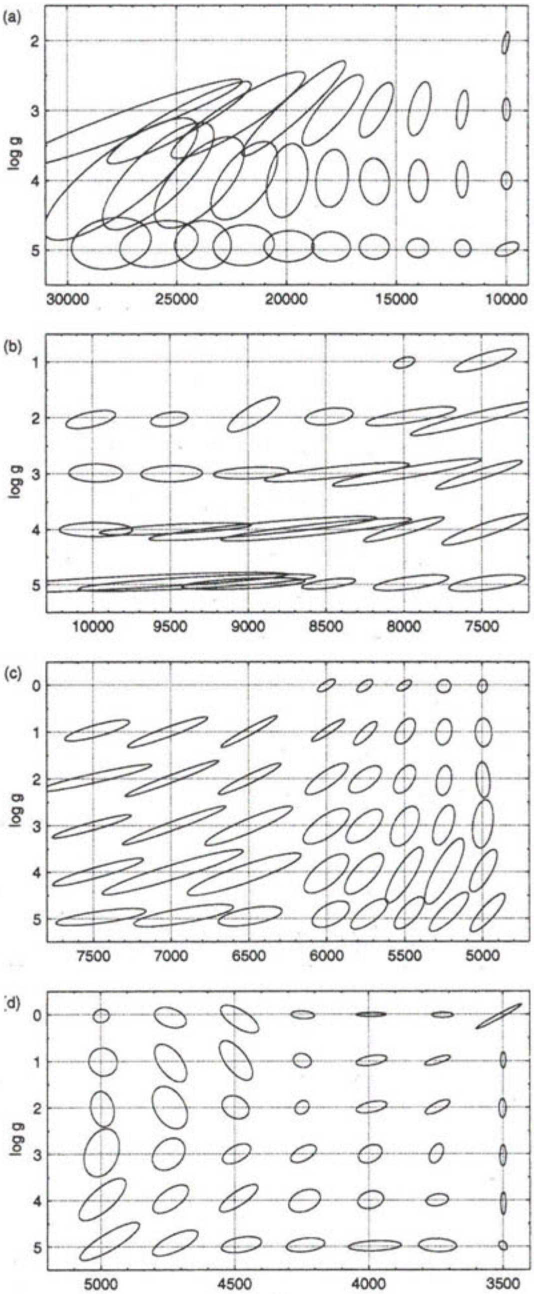

Fig. 5. The T_e vs. $\log g$ diagram for the simulated observations of reddened stars in the *Strömvil* system. The models are quantified by their Q-parameters.

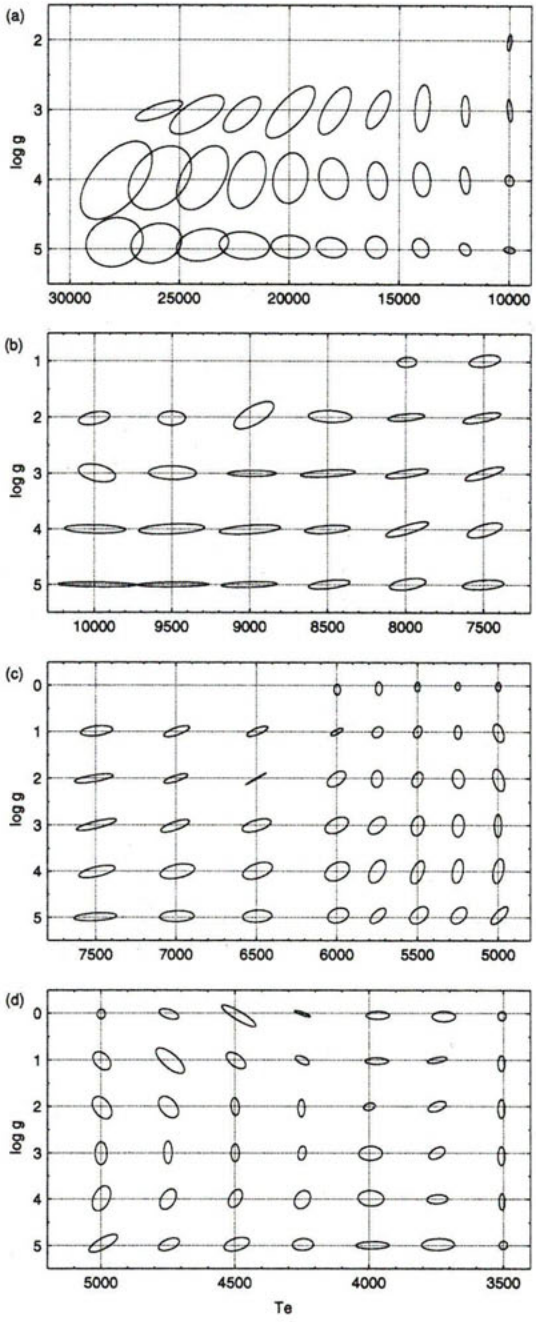

Fig. 6. The T_e vs. $\log g$ diagram for the simulated observations of unreddened stars in the *Strömvil-Gaia* system. The models are quantified by their color indices.

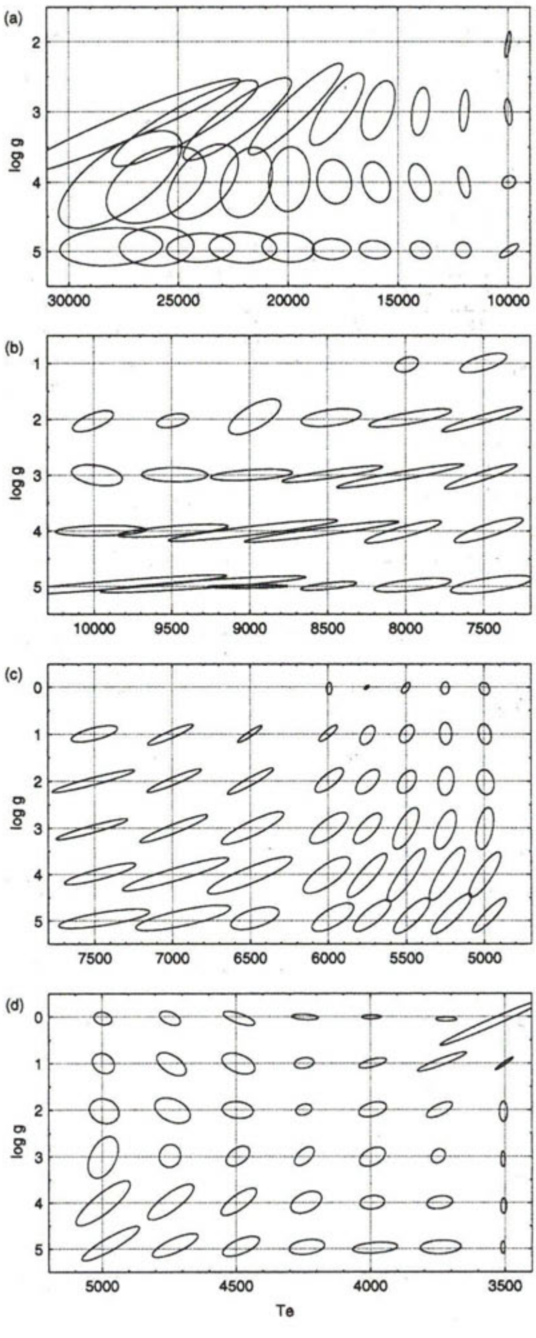

Fig. 7. The $T_{\rm e}$ vs. $\log g$ diagram for the simulated observations of reddened stars in the *Strömvil-Gaia* system. The models are quantified by their Q-parameters.

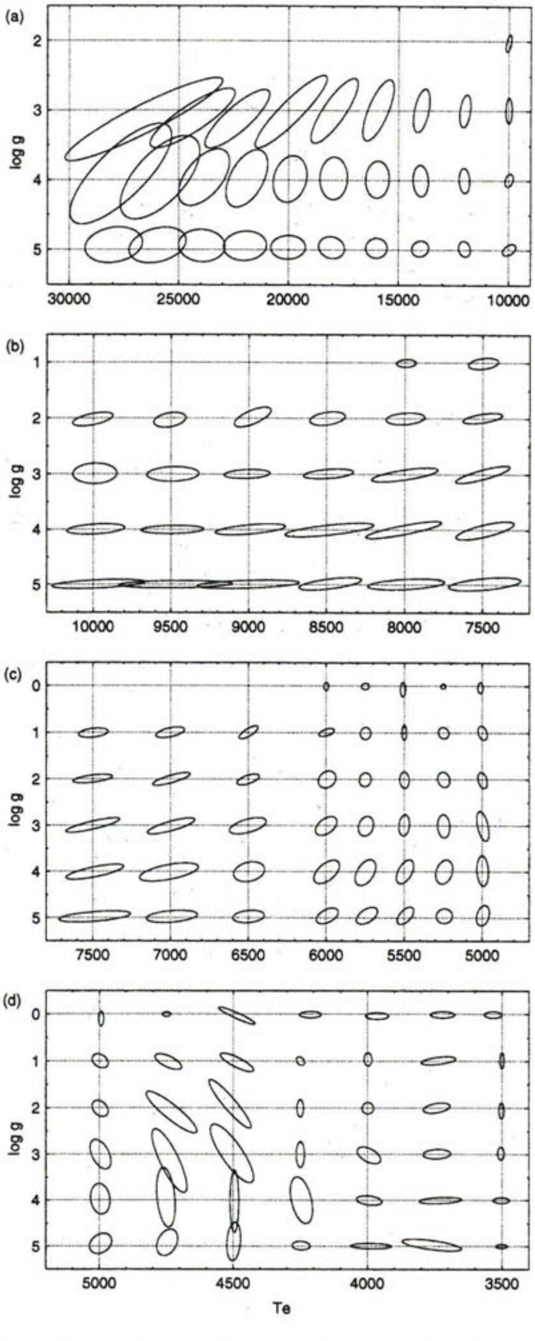

Fig. 8. The T_e vs. $\log g$ diagram for the simulated observations of unreddened stars in the *Walraven* system. The models are quantified by their color indices.

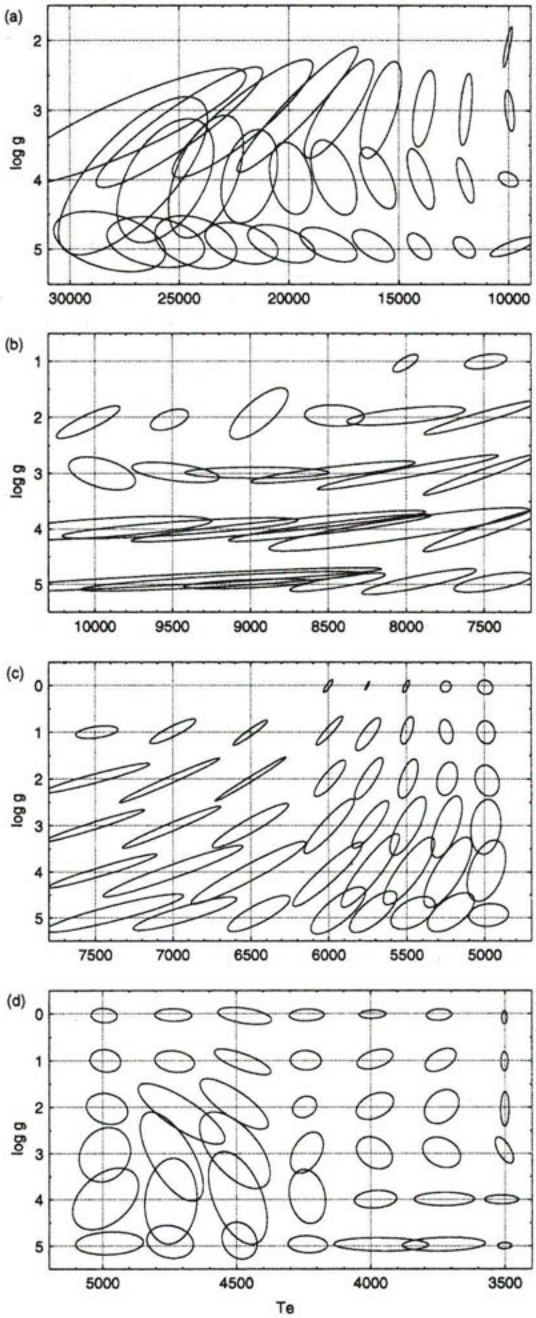

Fig. 9. The T_e vs. $\log g$ diagram for the simulated observations of reddened stars in the *Walraven* system. The models are quantified by their Q-parameters.

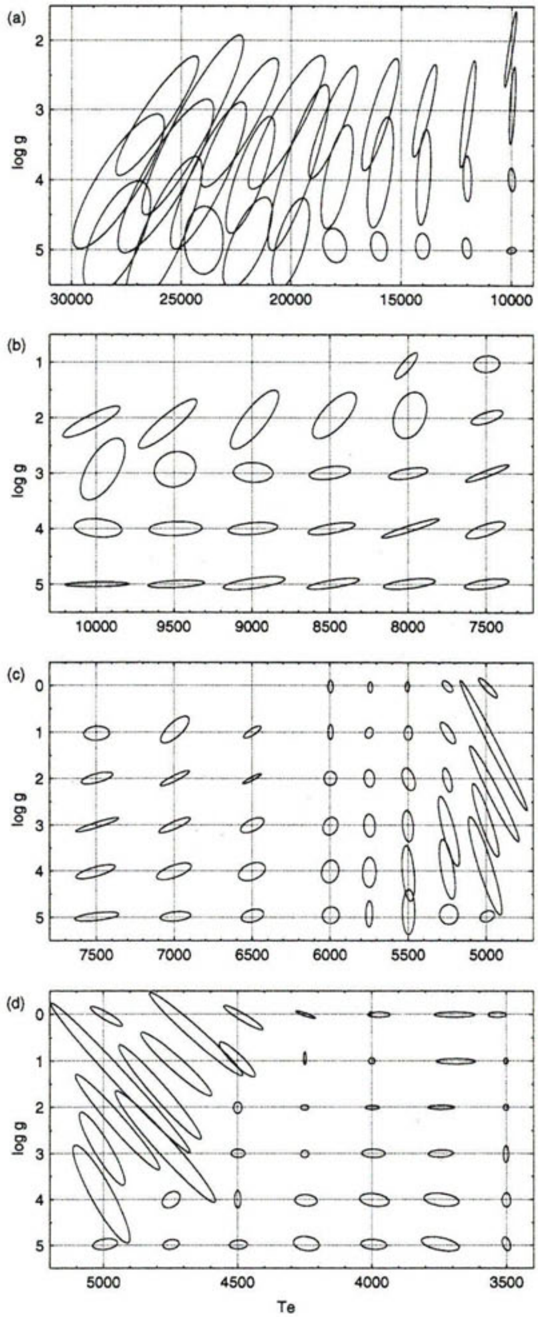

Fig. 10. The T_e vs. $\log g$ diagram for the simulated observations of unreddened stars in the *Geneva* system. The models are quantified by their color indices.

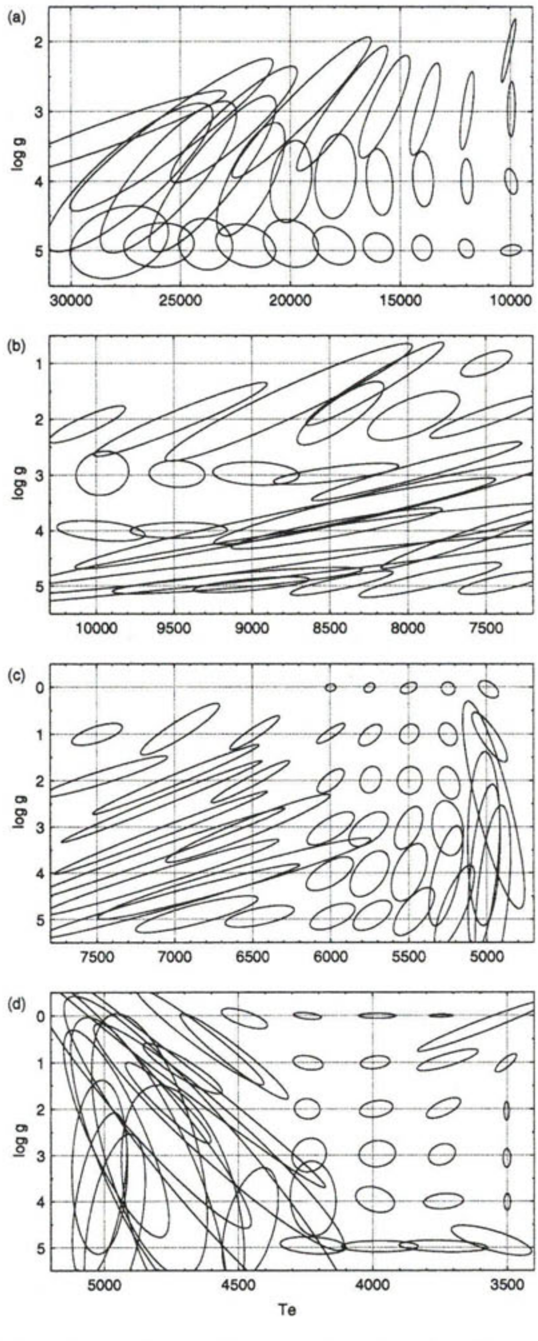

Fig. 11. The $T_{\rm e}$ vs. $\log g$ diagram for the simulated observations of reddened stars in the *Geneva* system. The models are quantified by their Q-parameters.

For B-type models sizes of ellipses increase with increasing temperature: the T_e error is about ±500 K at B9 V, ± 1000 K at B3 V and ±2000 K at B0 V. However, the relative error variations are small: from $\Delta T/T = 0.05$ for B9 to 0.07 for B0. These temperature errors correspond to approximately ±0.5 of spectral subclass. For early B supergiants the temperature errors are somewhat larger, ±(3000–6000) K.

For A-type models the temperature errors are ±(200–500) K, for F-type models they are ±(150–400) K and for G–K–M models they are ±(50–150) K. In all cases these temperature errors do not exceed the errors of 1–2 spectral subclasses in the decimal division of spectral classes or 0.5 subclasses in the MK division.

Gravity errors in quantification by Q-parameters are also slightly larger than in the case of quantification by color indices. For B-type models the gravity errors increase with increasing temperature and luminosity: the $\log g$ error is ±(0.1–0.3) dex at B9, ±(0.2–0.3) dex at B5 and ±(0.4–0.7) dex at B0.

For A-type models the quantification errors in gravity are relatively small: they are between 0.1 and 0.4 dex. For F-type models the gravity errors are between ±0.2 and ±0.4 dex. In this range of temperatures, the error in $\log g$ is related with the temperature error: if T_e error is positive, gravity error is also positive. For G-type models the gravity errors are between ±(0.2–0.5) dex. For them the quantification errors decrease with increasing decreasing gravity (increasing luminosity). For K-type models the gravity errors are ±(0.2–0.4) dex.

The Kurucz models of M-type star temperatures are not sufficiently exact to represent real stars of different luminosities (see Straižys et al. 1997b). However, if the models were accurate, their quantification in the *Vilnius* system would be fine.

There are some small differences between the *Vilnius*, *Strömvil* and *Strömvil-Gaia* quantification accuracy of B and A models: the length and form of the error ellipses are somewhat different.

4. THE WALRAVEN SYSTEM

For unreddened B–A–F–G–K0 and M-type models (Figs. 8a–d) the *Walraven* system is as good as the *Vilnius* system. For early K-models, especially for K-giants the quantification accuracy in the *Walraven* system is lower than that in the *Vilnius* system. However, for reddened models of types B–A–F–G (Fig. 9) the quantification accuracy is much lower: the axes of ellipses are by 1.5–2.0 times longer than in the *Vilnius* system.

5. THE GENEVA SYSTEM

For unreddened B-type models (Fig. 10a) the quantification accuracy is lower than in the *Vilnius* system, especially in gravities. For unreddened A-type models (Fig. 10b) of lower luminosities the accuracy is almost as good as the accuracy in the *Vilnius* system, but for higher luminosities the sizes of ellipses are larger by a factor of 2. For F-type and early G-type models (Fig. 10c) the accuracy of quantification is comparable to the accuracy in the Vilnius system. However, for G5–G8 and K-type models (Figs. 10c,d) the *Geneva* system gives a considerably lower accuracy of quantification: by a factor of 2 in temperatures and by a factor of 3–5 in $\log g$.

For reddened models the situation is much more complicated. Among B-type models (Fig. 11a) the system gives satisfactory quantification only for B5–A0 classes. For A- and F-type models the quantification is impossible (Fig. 11b and the left side of Fig. 11c). G0–G8 models can be quantified satisfactory (right side of Fig. 11c) but there is some interference of ellipses of F-type models which overlap the G-type domain. For the reddened K-type models the *Geneva* system is again inapplicable for quantification (left side of Fig. 11d).

6. DISCUSSION AND CONCLUSIONS

We have compared quantification properties of the *Vilnius, Strömvil, Strömvil-Gaia, Walraven* and *Geneva* systems for solar metallicity stars in a wide range of temperatures and gravities. Among these systems, only the *Vilnius*, *Strömvil* and *Strömvil-Gaia* systems give a single-valued classification and quantification of star models of all temperatures and gravities. The *Strömvil-Gaia* system with rectangular response functions shows somewhat better accuracy than the original system set up with interference filters.

Other two investigated photometric systems have larger quantification errors and are applicable in narrower spectral and luminosity ranges than the *Vilnius* and *Strömvil* systems.

Future steps in this direction should be intercomparison of photometric systems in possibility to identify stars with various peculiarities in their chemical composition (Am- and Ap-stars, F–G–K subdwarfs, metal-deficient giants, carbon-rich stars, barium stars, white dwarfs, etc.), stars with the peculiar structure of atmospheres and envelopes (Of, Be, WR, Herbig Ae/Be stars, G–K–M dwarfs with active chromospheres, etc.) and the unresolved binary stars.

For this we need either sufficiently exact synthetic flux distributions of models or the observed flux distributions of stars with all the possible peculiarities observed among the real stars. Unfortunately, such a database is still far from being complete.

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