STAR CLASSIFICATION POSSIBILITIES WITH THE GAIA SPECTROPHOTOMETERS. III. THE CLASSIFICATION ACCURACY WITH DECONTAMINATED BP/RP SPECTRA

V. Stražys\textsuperscript{1} and R. Lazauskaitė\textsuperscript{2}

\textsuperscript{1} Institute of Theoretical Physics and Astronomy, Vilnius University, Goštauto 12, Vilnius, LT-01108, Lithuania
\textsuperscript{2} Department of Physics, Lithuanian University of Educational Sciences, Studenty 39, Vilnius, LT-08106, Lithuania

Received: 2011 May 25; accepted 2011 June 29

Abstract. A medium-band 12-color photometric system, based on the decontaminated Gaia BP/RP spectra, has been proposed in our Paper II. Here we analyze a possibility to apply some versions of this system for the determination of temperatures and gravities of stars both in the absence and the presence of interstellar reddening. The possibility to supplement this system with the broad BP and RP passbands is verified. We conclude that the system gives an acceptable accuracy of temperatures and luminosities if the accuracy of color indices is 0.02 mag or better and if the parallaxes of stars are known.

Key words: stars: fundamental parameters (classification, colors, spectral types, temperatures, gravities, luminosities) – space vehicles: Gaia

1. INTRODUCTION

As this was described in our earlier papers (Stražys et al. 2006, 2010; hereafter Papers I and II), due to broad wings of the image profiles of stars and other effects forming the line-spread function (LSF), the Gaia BP and RP spectra will be affected by energy redistribution. This creates serious difficulties in using of contaminated spectra for the determination of stellar physical parameters since the amount of contamination depends on the wavelength, on the star physical parameters ($T_{\text{eff}}$, \log\,$g$, [Fe/H], peculiarity) and on its interstellar reddening. In Paper II, for empirical ‘decontamination’ of color indices, a method of ‘color-equations’ was proposed. This method gives the contamination corrections which are almost independent on interstellar reddening up to $A_V \sim 3$ mag. Lower in this article we will consider that all color indices are decontaminated, i.e., are not affected by the LSF effects.

2. RESPONSE FUNCTIONS OF THE GAIA PHOTOMETRIC SYSTEMS

The passbands of the proposed photometric system were described in Paper II. They are somewhat similar to the passbands of the Vilnius seven-color system...
(Straižys 1992, 1999b) supplemented by three passbands in the far red spectrum measuring the strength and position of the Paschen jump (Straižys 1998, 1999a; Straižys & Lazauskaitė 2007). The reader must bear in mind that the passbands both of the Vilnius system and of the Vilnius + Paschen system are selected not casually, but are based on spectral energy distributions of stars and are in optimum positions for the determination of spectral classes and luminosities (or temperatures and gravities) of B-A-F-G-K-M stars in the presence of interstellar reddening. In comparison with the system described by Straižys & Lazauskaitė (2007), more passbands were added in the far red spectrum. The final set of 12 passbands (plus BP, RP and RVS) are shown in Figure 1.

![Response curves of the Gaia-based photometric systems analyzed in this paper.](image)

Fig. 1. Response curves of the Gaia-based photometric systems analyzed in this paper.

In the wavelength range covered by the BP spectra the Vilnius passbands $U$, $P$, $X$, $Y$, $Z$ and $V$ were approximated at the mean wavelengths 350, 374, 405, 465, 516 and 545 nm by averaging fluxes of BP spectra from 25 pixels in the ultraviolet to 8 pixels in the green. An additional ultraviolet passband $W$ covering the wavelengths from 338 nm to 385 nm, including 44 pixels, was formed. Its destination will be described in Section 3.

In the RP spectra we have selected also six passbands with the mean wavelengths at 657, 715, 750, 820, 875 and 940 nm simulated by 10–11 pixels in each giving the widths 20–30 nm. One of them on 657 nm, is close to the Vilnius $S$ passband centered on the H$_\alpha$ line. Other three, centered on 820, 875 and 940 nm, are close to the $p1$, $p2$ and $p3$ passbands proposed for measuring the temperature and luminosity effects at the Paschen jump (Straižys 1998, 1999a). The two remaining passbands, centered on 715 and 750 nm, were chosen to measure the depth of the TiO absorption band at 715 nm.

In the experiments, we also have applied the BP, RP and RVS passbands shown in Figure 1 according to Jordi et al. (2010).
3. CLASSIFICATION OF STARS USING COLOR INDICES AND Q-PARAMETERS

For the estimation of the classification accuracy in various parts of the \( T_{\text{eff}} \) vs. \( \log g \) diagram using a set of intrinsic color indices or reddening-free \( Q \)-parameters, we have used the confidence ellipses method described by Straizys, Liubertas & Lazauskaitė (1998). The method uses a grid of synthetic spectra to simulate observations of different accuracy. Observational errors are added to color indices (or \( Q \)-parameters) of the Kurucz (2001) models, forming 100 ‘observations’ of each model. Then for each of these simulated ‘observations’ we determine \( T_{\text{eff}} \) and \( \log g \) by fitting their color indices (or \( Q \)-parameters) to color indices (or \( Q \)-parameters) of 5673 standard models of solar chemical composition, formed from the basic 409 Kurucz models by interpolation. Then all these simulated ‘observations’ are plotted on the \( T_{\text{eff}} \) vs. \( \log g \) diagram. As a consequence, each Kurucz model in this diagram is smeared into a cluster of 100 points of different form and orientation. Each point cluster can be circumscribed by a confidence ellipse: the probability that the temperatures and gravities are within the curve is approximately 95%.

We emphasize that only the models of solar metallicity are analyzed.

We have simulated the observations in the Gaia system by taking the rms errors of \( \sigma = \pm 0.01 \) mag for color indices 350–545, 374–545, 405–545, 465–545, 516–545, 657–820, 715–820, 750–820, 820–875, 820–940, BP–RP, RP–RVS, and the rms errors of \( \sigma = \pm 0.02 \) for a set of reddening-free \( Q \)-parameters. These errors of \( Q \)-parameters approximately correspond to the \( \pm 0.01 \) mag errors of color indices.

The confidence ellipses on the \( T_{\text{eff}} \) vs. \( \log g \) diagrams are plotted for different combinations of the intrinsic color indices and \( Q \)-parameters. Here we demonstrate a few typical diagrams which allow to estimate the usefulness of the method. Left-hand panels of Figures 2–4 exhibit diagrams where the confidence ellipses are obtained by comparing the intrinsic color indices, i.e., they correspond to unreddened or dereddened stars. Right-hand panels of Figures 2–4 are obtained by comparing \( Q \)-parameters, i.e., they are applicable for reddened stars.

In Figure 2 (left) the \( T_{\text{eff}} \) vs. \( \log g \) diagrams for the 12-color medium-band system, using the first ten color indices listed above, are plotted. The first of the four panels corresponds to the temperatures of B-type stars, the second one – to A-type stars, the third one – to F- and G-type stars and the fourth one – to K- and M-type stars. The next Figures are constructed in a similar way but for the determination of the \( T_{\text{eff}} \) and \( \log g \) values they use other sets of color indices: Figure 3 uses the same set of 10 color indices as Figure 2, but with the additional broad-band BP–RP and RP–RVS colors. Figure 4 uses a set of color indices in which two of them, 350–545 and 374–545, are replaced by one broad passband \( W \). Figure 5 uses only eight color indices without ultraviolet magnitudes.

The first glance at Figure 2 (left) gives an impression that the quality of the determination of temperatures and gravities for unreddened stars in the Gaia 12-color system is of similar accuracy as in the standard Vilnius seven-color system, investigated by the same method by Straizys et al. (1998a). For B-type stars the \( T_{\text{eff}} \) errors are from \( \pm 1500 \) K at \( 28000 \) K to \( \pm 100 \) K at \( 10000 \) K, for A–F stars they are \( 100–150 \) K, for G–K–M stars they are less than \( 100 \) K. These \( T_{\text{eff}} \) errors lead to \( \pm 1 \) spectral subclass errors. Consequently, the classification accuracy is of the same order as (or even better than) in the MK classification system. The accuracy of \( \log g \) determination is also quite good: from \( \pm 0.5 \) dex for early B subclasses to \( \pm (0.1–0.3) \) dex for cooler models.
Fig. 2. The $T_{\text{eff}}$ vs. $\log g$ diagram for simulated observations of unreddened (left-hand panels) and reddened (right-hand panels) stars in the 350, 374, 405, 465, 516, 545, 657, 715, 750, 820, 875 and 940 nm system: (a) B-type stars, (b) A-type stars, (c) F- and G-type stars, (d) K- and M-type stars. The models are quantified by their color indices with $\sigma = 0.01$ mag or $Q$-parameters with $\sigma = 0.02$ mag.
Fig. 3. The $T_{\text{eff}}$ vs. $\log g$ diagram for simulated observations of unreddened (left-hand panels) and reddened (right-hand panels) stars in the 350, 374, 405, 465, 516, 545, 657, 715, 750, 820, 875, 940 nm, BP, RP and RVS system: (a) B-type stars, (b) A-type stars, (c) F- and G-type stars, (d) K- and M-type stars. The models are quantified by their color indices with $\sigma = 0.01$ mag or $Q$-parameters with $\sigma = 0.02$ mag.
Fig. 4. The $T_{\text{eff}}$ vs. log $g$ diagram for simulated observations of unreddened (left-hand panels) and reddened (right-hand panels) stars in the W, 405, 465, 516, 545, 657, 715, 750, 820, 875 and 940 nm system: (a) B-type stars, (b) A-type stars, (c) F- and G-type stars, (d) K- and M-type stars. The models are quantified by their color indices with $\sigma = 0.01$ mag or $Q$-parameters with $\sigma = 0.02$ mag.
Fig. 5. The $T_{\text{eff}}$ vs. log $g$ diagram for simulated observations of unreddened (left-hand panels) and reddened (right-hand panels) stars in the 405, 465, 516, 545, 657, 715, 750, 820, 875 and 940 nm system: (a) B-type stars, (b) A-type stars, (c) F- and G-type stars, (d) K- and M-type stars. The models are quantified by their color indices with $\sigma=0.01$ mag or Q-parameters with $\sigma=0.02$ mag.
Figure 3 shows that the addition of two broad-band colors, BP–RP and RP–RVS, decreases the size of the error ellipses in some temperature and gravity ranges, but not significantly.

However, Figures 2 and 3 give more or less ideal case which would be reality if the Gaia mirrors were coated by aluminum. The silver-coated mirrors reduce the ultraviolet sensitivity of the Gaia system drastically: the sensitivity at 350 nm is about 10 times lower than in the green. As it was shown in Paper II, the spectrum contamination in ultraviolet by the alien photons is also very high, and the accuracy of the decontamination corrections is low. Trying to increase the fluxes of the Gaia BP spectra in the ultraviolet (and their accuracy), we decided to test a broader passband \( W \) covering the wavelength range from 338 to 385 nm (see Figure 1). Figure 4 shows the \( T_{\text{eff}} \) vs. \( \log g \) diagrams for the 11-color system, where two passbands at 350 nm and 374 nm are replaced by the \( W \) passband with the mean wavelength at 362 nm. Due to this change, the sizes of ellipses increase by a factor of \( \sqrt{2} \) in all temperature and gravity ranges.

If we reject the ultraviolet part of the BP spectrum completely (Figure 5 left), the sizes of the ellipses increase even more, mostly in the temperature range of B-type stars. For the temperature range of F- and G-type stars the errors increase mostly in gravities.

The situation is much worse when we change the intrinsic color indices to interstellar reddening-free \( Q \)-parameters defined by the equations:

\[
Q_{123} = (m_1 - m_2) - (E_{12}/E_{23})(m_2 - m_3),
\]

and

\[
Q_{1234} = (m_1 - m_2) - (E_{12}/E_{34})(m_3 - m_4),
\]

where \( m_1 - m_2, m_2 - m_3 \) and \( m_3 - m_4 \) are color indices, \( E_{12}, E_{23} \) and \( E_{34} \) are corresponding color excesses.

In Figure 2 (right) the following 10 parameters are compared: \( Q_{350,545,820}, Q_{374,545,820}, Q_{405,545,820}, Q_{465,545,820}, Q_{516,545,820}, Q_{657,820,545,820}, Q_{715,820,545,820}, Q_{750,820,545,820}, Q_{820,940,545,820} \) and \( Q_{820,940,545,820} \). Although the forms of the ellipses in Figure 2 (right) are similar to those for the standard Vilnius system (Straižys et al. 1998a), their sizes for the Gaia system are somewhat larger, i.e., the classification accuracy is lower. The addition of the broad-band parameter \( Q_{BP,RP,RVS} \) (Figure 3, right) leads to a small increase of the classification accuracy for early spectral classes. However, the replacement of the 350 nm and 374 nm passbands to a single \( W \) (Figure 4, right) leads to a complete impossibility to classify B, A, F and G stars in two dimensions. Only for K and M stars the situation remains more or less satisfactory. When we remove all the ultraviolet magnitudes (Figure 5, right), the situation remains hopeless for the classification of B, A, F and G stars, even in the range of K and M stars the classification accuracy becomes lower.

For further analysis of the classification accuracy, we will take the system with the following 11 passbands: \( W, 405, 465, 516, 545, 657, 715, 750, 820, 875 \) and 940 (hereafter “the system \( W+10 \)” since only in this case BP/RP photometry is expected to give a reasonable accuracy. It is evident, however, that even in this system the determination of physical parameters of stars in many cases is not single-valued, especially when the interstellar reddening is present.

The accuracy of the determination of \( T_{\text{eff}} \) and \( \log g \) can be estimated quantitatively by using the \( \sigma T_{\text{eff}} \) vs. \( T_{\text{eff}} \) and \( \sigma (\log g) \) vs. \( T_{\text{eff}} \) plots for different
Fig. 6. The $W+10$ system, quantification by intrinsic color indices: errors of the effective temperatures are plotted as functions of $T_{\text{eff}}$ for two values of $\log g$ (4.0 and 3.0) and three values of observational errors of color indices ($\pm 0.01$, 0.02 and 0.03 mag).
Fig. 7. The W+10 system, quantification by intrinsic color indices: errors of the gravity logarithms are plotted as functions of $T_{\text{eff}}$ for two values of log $g$ (4.0 and 3.0) and three values of observational errors of color indices ($\pm 0.01$, 0.02 and 0.03 mag).
Fig. 8. The $W+10$ system, quantification by $Q$-parameters: errors of the effective temperatures are plotted as functions of $T_{\text{eff}}$ for two values of $\log g$ (4.0 and 3.0) and three values of observational errors of $Q$-parameters ($\pm 0.02$, 0.03 and 0.04 mag).
Fig. 9. The W+10 system, quantification by $Q$-parameters: errors of the gravity logarithms are plotted as functions of $T_{\text{eff}}$ for two values of $\log g$ (4.0 and 3.0) and three values of observational errors of $Q$-parameters ($\pm 0.02$, 0.03 and 0.04 mag).
observational errors calculated by the following equations (Straižys & Lazauskaitė 2002):

\[ \sigma_{T_{\text{eff}}} = \sqrt{\frac{\sum (T_{\text{eff}} - T_{\text{eff}}^\text{ref})^2}{100}} \]  

(3)

and

\[ \sigma(\log g) = \sqrt{\frac{\sum (\log g - \log g^\text{ref})^2}{100}}. \]  

(4)

The \( \sigma_{T_{\text{eff}}} \) and \( \sigma(\log g) \) values for the system \( W+10 \), obtained by comparing the intrinsic color indices (Figure 4), for different temperature ranges, for two values of \( \log g \) (4.0 and 3.0) and for three values of photometry errors (±0.01, 0.02 and 0.03 mag) are plotted in Figures 6 and 7. When comparing these values of \( \sigma_{T_{\text{eff}}} \) and \( \sigma(\log g) \) with the sizes of the confidence ellipses in Figure 4 (left panels), one should bear in mind that the ellipses are about three times larger (3\( \sigma \)).

In the case of 1\% photometry (\( \sigma = \pm 0.01 \) mag), the accuracy of the temperatures is satisfactory for all spectral ranges, and this ensures the 3\( \sigma \) errors of spectral classes of about ±1 subclass. However, the errors of \( \log g \) (3\( \sigma \)) for B and G stars are larger than 1 dex. Therefore, in these spectral ranges additional information on gravity (or luminosity) of the star is essential. For 2\% accuracy of photometry (±0.02 mag) the errors of \( T_{\text{eff}} \) and \( \log g \) are roughly larger by a factor of 2.

Figures 8 and 9 exhibit the \( \sigma \) errors of \( T_{\text{eff}} \) and \( \log g \) in the case when the reddening-free \( Q \)-parameters are compared (Figure 8). The accepted \( \sigma Q \) values are ±0.02, ±0.03 and ±0.04 mag.

The situation with reddened stars (Fig. 4, right panels) is more complicated since the confidence ellipses are much larger. However, even in this case the 1\( \sigma \) errors of spectral classes are 2–3 subclasses if the accuracy of \( Q \)-parameters is ±0.02 mag. The effect of the accuracy of \( \log g \) on luminosity determination can be estimated conveniently by the \( \log g \) vs. \( T_{\text{eff}} \) plot shown in Figure 10, taken from Straižys & Kurilienė (1981). The errors of gravity do not allow to determine luminosity classes V, IV or III for stars of spectral classes from B to G but K–M dwarfs, giants and supergiants should be easily recognizable.

If we were able to estimate the temperatures and luminosity classes with a reasonable accuracy, then the absolute magnitudes \( M_V \), intrinsic colors, color excesses and interstellar extinctions \( A_V \) can be determined for each star individually. Applying the equation

\[ 5 \log d = V - M_V + 5 - A_V. \]  

(5)

we can determine distances \( d \). The accuracy of the classification can be verified by comparing the photometric distances \( d \) with the distances determined from trigonometric parallaxes.

If the parallaxes of stars are known, for determining of the absolute magnitudes we do not need exact values of \( \log g \). The knowledge of the effective temperatures is sufficient to estimate at least one intrinsic color index which shows a single-valued dependence on the temperature, independent on luminosity (such color index can be, e.g., \( Y-V \) of the Vilnius system or broad-band \( R-I \) color index). In this way we determine the intrinsic color, color excess and \( A_V \). The trigonometric parallax gives the distance \( d \) and the Equation (3) gives \( M_V \) and the luminosity class.
4. CONCLUSIONS

A few medium-band multicolor photometric systems, based on the decontaminated Gaia BP and RP spectra, are analyzed with the aim to determine the effective temperatures and gravities of solar metallicity stars. Due to a very low response of the BP spectrophotometer in the ultraviolet, we form a passband $W$ covering a relatively broad spectral range between 338 nm to 385 nm, with the mean wavelength at 362 nm. A 11-color system with the mean wavelengths of passbands at 362, 405, 465, 516, 545, 657, 715, 750, 820, 875 and 940 nm for solar metallicity stars gives a reasonable accuracy of the effective temperatures corresponding to the errors of 1–3 spectral subclasses, if the measurement errors of color indices $\sigma$ are $\pm 0.01$ mag. Although the classification accuracy of reddened stars is lower, it is sufficient to obtain the effective temperatures with the errors corresponding to 1–3 spectral subclasses.

However, the accuracy of gravities in some temperature ranges is quite low. Since the gravity is related to luminosity of the star, the direct determination of its absolute magnitude becomes impossible. Fortunately, some color indices

---

**Fig. 10.** The $\log g$ vs. $\log T_{\text{eff}}$ diagram with the luminosity sequences, taken from Stražys & Kuriliené (1981).
are insensitive to luminosity, and we can estimate the intrinsic color of the star only from its temperature. Then its color excess and interstellar extinction can be calculated. The absolute magnitude can be obtained by the equation $M_V = V + 5 - A_V - 5 \log d$, where the distance $d$ is known from the trigonometric parallax.

The method of confidence ellipses in the $\log g$ vs. $T_{\text{eff}}$ diagram can be applied for any other set of passbands constructed from the Gaia BP/RP spectra, including a full coverage of the spectra by narrow bands, as this has been done by Elsner et al. (1999). In future, a possibility to estimate the metallicity of F–G–K stars should be investigated. Also, the comparisons of spectral energy distributions (SEDs) of model atmospheres of different authors and of real stars in the temperature range of M-type stars (Straižys et al. 1997; Straižys & Lazauskaitė 2010) show considerable differences. Consequently, we must investigate the classification accuracy of the coolest stars using SEDs of real stars instead of model atmospheres.

ACKNOWLEDGMENTS. The authors are grateful to E. G. Moištas and S. Bartašiūtė for help in preparation of this publication.

REFERENCES
Elsner B., Bastian U., Liubertas R., Scholz R. 1999, Baltic Astronomy, 8, 385
Kurucz R. L. 2001, http://kurucz.harvard.edu/gridP00/fp00k2.pck
Straižys V. 1998, Baltic Astronomy, 7, 571
Straižys V. 1999a, Baltic Astronomy, 8, 491
Straižys V. 1999b, Baltic Astronomy, 8, 505
Straižys V., Lazauskaitė R. 2007, Baltic Astronomy, 16, 477
Straižys V., Liubertas R., Lazauskaitė R. 1998, Baltic Astronomy, 7, 529
Straižys V., Liubertas R., Valiauga G. 1997, Baltic Astronomy, 6, 601