AN OPTIMUM EIGHT-COLOR PHOTOMETRIC SYSTEM FOR A SURVEY SATELLITE

V. Straižys[1] and **E. Høg**[2]

[1]Institute of Theoretical Physics and Astronomy,
Goštauto 12, Vilnius 2600, Lithuania (straizys@itpa.fi.lt)

[2]Copenhagen University Observatory,
Østervoldgade 3, DK-1350, Copenhagen K, Denmark (erik@astro.ku.dk)

ABSTRACT

Addition to the Strömgren photometric system *uvby* of three bandpasses at 374, 516 and 656 nm from the Vilnius photometric system gives a more universal combined system. This system, called *Stromvil,* is able to classify stars of all spectral types in the presence of interstellar reddening. This property of the system is especially important in photometric surveys, making possible the photometric classification in three or more dimensions (temperature, luminosity, metallicity, peculiarity) of stars as faint as 20 mag both in unreddened and reddened areas of the sky. We propose the Stromvil system for a survey satellite of the GAIA type. For more exact determination of temperature for late-type stars, the system is supplemented by a blanketing-free infrared passband I. The resulting eight-color system, *Stromvil+I,* has the following mean wavelengths: 350, 374, 411, 467, 516, 547, 656 and 812 nm. A preliminary calibration of the reddening-free diagrams of the system in terms of spectral classes (and temperatures), absolute magnitudes (and surface gravities) and metallicities is available. We estimate limiting magnitudes of the survey, standard errors of the photometry and the precision of the photometric classification. It is shown that precision classification of stars with $V \leq 16$ mag will be achieved.

Keywords: space photometry; stellar classification; GAIA satellite.

1. INTRODUCTION

An astrometric scanning survey satellite, GAIA, has been described by Lindegren & Perryman (1994). The satellite should be used as a CCD photometer for obtaining precision multicolor photometry of tens of millions of stars down to 16 mag. To make the photometric results most useful, one should use an optimal photometric system, allowing to classify stars of all spectral types, subject to various interstellar reddening, surface temperatures and surface gravities, metallicities, and sometimes belonging to peculiar spectral types. For this purpose, the medium-band photometric systems are most effective.

In the 1960es, a number of medium-band photometric systems were proposed for two- and three-dimensional classification of stars. Among them were the Strömgren four-color system and the Vilnius seven-color system. Both systems and their possibilities were recently described by one of the authors (Straižys 1992a).

The Strömgren system with the mean wavelengths 350, 411, 467 and 547 nm was suggested for determination of temperatures and luminosities of B-A-F and early G-type stars and metallicities for A-F-G-type stars (Strömgren 1963a,b, 1966). Lateron, the system was supplemented by two additional narrow passbands, measuring the intensity of the Hβ line in order to obtain a more precise determination of luminosities of B-type stars (Crawford and Mander 1966).

The Vilnius photometric system with the mean wavelengths 345, 374, 405, 466, 516, 544 and 656 nm was suggested for photometric classification of stars of all spectral types in the presence of interstellar reddening (Straižys 1963, 1965; Straižys and Zdanavičius 1965). Optimum passbands of this system were selected using energy distributions in the spectra of stars of different spectral and luminosity classes and on the interstellar reddening law.

The passbands of both systems are shown in Fig. 1. One can see that four passbands of the *uvby* system have their analogues in the Vilnius system. Let us repeat the description of the main purposes of these passbands given by Straižys et al. (1994).

The ultraviolet passbands of both systems (u and U) measure the radiation intensity to the ultraviolet side of the Balmer jump. The violet passbands of both systems (v and X) measure the radiation intensity to the red side of the Balmer jump. For B-A-F type stars the color indices $u - v$ and $U - X$ give the Balmer jump height, which depends both on temperature and luminosity. Additionally, for A-F-G type stars the violet magnitudes of both systems measure blanketing by metallic lines, and thus are important for a photometric determination of the [Fe/H] ratio.

The blue magnitudes b and Y in combination with the green magnitudes y and V give color indices $b - y$ and $Y - V$ which are almost blanketing-free for A, F and early G stars. Additionally, the blue passbands of both systems are close to the break-point of interstellar reddening law. For this reason, all color indices which include b and Y magnitudes show the maximum possible effect of the temperature reddening and the interstellar reddening

Figure 1: Comparison of passbands of the Vilnius (solid lines) and Strömgren (broken lines) photometric systems.

difference.

The green passbands, y and V, have their mean wavelengths close to the mean wavelength of the broad V passband of the UBV photometric system. This makes an easy transfer of the broad-band V magnitudes into the medium-band system and vice versa.

In comparison with the Strömgren system, the Vilnius system contains three more passbands P, Z and S which are important in the classification of stars in luminosities as well as for detection of the Hα line emission. These three passbands are designed for the following purposes.

(1) The passband P at 374 nm is placed on the crowding of the higher members of the Balmer series, near its limit. As a result, P magnitudes are very sensitive to luminosity for early-type stars.

(2) The passband Z at 516 nm is placed on a wide and deep absorption feature in spectra of G-K-M stars, created by a crowding of metallic lines, of which the Mg I triplet is the strongest. Additionally, in late K-type dwarfs and M-type dwarfs the Z passband contains strong MgH molecular bands. Both Mg I lines and MgH bands show a strong negative luminosity effect. Therefore color indices containing a Z magnitude are good luminosity discriminators for G, K and M-type stars.

(3) The passband S is placed on the Hα line and for all types of stars it indicates the presence of this emission. In the case of normal absorption spectra, the S magnitude can be combined into the temperature sensitive color indices $Y-S$ or $V-S$ with only a small blanketing effect.

It was demonstrated by Straižys et al. (1994), that the addition to the Strömgren photometric system of three passbands at 374, 516 and 656 nm from the Vilnius system makes the combined Stromvil system more universal. The system becomes capable of classifying stars in spectral classes and luminosities (or determining their temperatures and surface gravities) everywhere in the HR diagram. This property of the Stromvil system is especially important in CCD photometry, since a photometric classification of stars as faint as 20 mag becomes possible (Straižys 1992b). The Stromvil system was recommended for the photometric classification of faint stars where it is difficult or even impossible to obtain narrow-band Hβ photometry and where the classification of G-K-M stars is needed in the presence of interstellar reddening. The Stromvil system should be as good as the parent systems in determining the metallicities and peculiarities of stars.

Parameters of the passbands of the Stromvil system are given in Table 1. In the further text we will designate these passbands by 35, 37, 41, 47, 52, 55, 66 where the numerals are the rounded mean wavelengths.

Table 1: Mean wavelengths and half-widths (FWHM) of passbands of the Stromvil photometric system

Passband Name	35 u	37 P	41 v	47 b	52 Z	55 y	66 S
λ_0 [nm]	350	374	411	467	516	547	656
$\Delta\lambda$ [nm]	30	26	19	18	21	23	20

2. DIAGRAMS FOR CLASSIFICATION OF NORMAL STARS AFFECTED BY INTERSTELLAR REDDENING

Interstellar reddening-free Q-parameters suitable for the classification of stars in two dimensions can be calculated from color indices by the equation

$$Q(1234) = (m_1 - m_2) - \frac{E_{12}}{E_{34}}(m_3 - m_4) \qquad (1)$$

where magnitudes 2 and 3 in most cases coincide. Color excess ratios, $E12/E34$, must be calculated for every star individually to make the Q parameters really independent of interstellar reddening. The following Q-parameters are most useful for determining spectral classes (or temperatures) and absolute magnitudes (or surface gravities) of stars of solar chemical composition: Q(35,37,47), Q(37,47,55), Q(41,47,55), Q(35,41,47), Q(35,37,47,55), Q(41,52,66), Q(41,47,52).

Figure 2: The $Q(35,37,47)$, $Q(37,47,55)$ diagram for classification of B-type stars of luminosities V-III and B-A-F supergiants. Symbols: dots for luminosity V stars, crosses for luminosity III stars, and circles for supergiants.

Figure 3: The $Q(35,37,47)$, $Q(41,47,55)$ diagram for classification of A-F-G type stars. Symbols are the same as in Fig. 2.

Figure 4: The $Q(35,37,47)$, $Q(41,52,66)$ diagram for classification of G and K stars. Symbols are the same as in Fig. 2.

Figure 5: The $Q(41,52,66)$, $Q(41,47,52)$ diagram for classification of K and M stars. Symbols are the same as in Fig. 2.

Table 2: For the the visual magnitudes V are given the predicted standard errors in [mmag] for a B0 star; see explanations in Sect. 4

V mag	*W*	*35*	*37*	*41*	*47*	*52*	*55*	*66*	*81*
2	–	0.0	0.0	–	–	–	–	–	–
4	–	0.0	0.1	0.0	0.0	0.0	0.0	0.0	–
6	–	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0
8	0.0	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
10	0.0	0.6	0.5	0.3	0.3	0.2	0.3	0.3	0.1
12	0.0	1.5	1.2	0.7	0.7	0.6	0.6	0.8	0.3
14	0.1	3.8	3.1	1.7	1.6	1.6	1.6	2.0	0.9
16	0.2	9.8	7.9	4.2	4.2	4.0	4.0	5.1	2.2
18	0.6	28.9	22.5	11.2	11.3	10.9	11.0	14.4	6.1
20	2.0	–	–	39.5	41.7	40.3	41.2	57.3	21.9
λ_0 [nm]	–	350	374	411	467	516	547	656	812
$\Delta\lambda$ [nm]	–	30	26	19	18	21	23	20	166
Peak transm. [%]	–	40*	42*	60	70	80	80	80	90
QE of CCD	–	0.68	0.72	0.74	0.78	0.77	0.76	0.73	0.62

* Transmission of glass filters

Table 3: Predicted standard errors in [mmag] for a G0 star

V mag	*W*	*35*	*37*	*41*	*47*	*52*	*55*	*66*	*81*
2	–	0.0	0.0	–	–	–	–	–	–
4	–	0.1	0.0	0.1	0.0	0.0	0.0	0.0	–
6	–	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
8	0.0	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.0
10	0.0	0.8	0.7	0.4	0.3	0.3	0.3	0.3	0.1
12	0.0	2.0	1.7	1.0	0.8	0.7	0.6	0.7	0.3
14	0.1	5.1	4.4	2.5	1.9	1.6	1.6	1.8	0.7
16	0.2	13.4	11.5	6.5	4.8	4.2	4.2	4.6	1.7
18	0.6	47.7	39.5	18.2	13.3	11.5	11.0	12.5	4.6
20	2.0	–	–	–	51.4	43.2	41.2	47.8	14.9

Table 4: Predicted standard errors in [mmag] for a M0 star

V mag	*W*	*35*	*37*	*41*	*47*	*52*	*55*	*66*	*81*
2	–	0.1	0.1	0.0	–	–	–	–	–
4	–	0.1	0.1	0.1	0.1	0.0	0.0	0.0	–
6	–	0.3	0.2	0.1	0.1	0.0	0.0	0.1	–
8	0.0	0.8	0.6	0.3	0.2	0.1	0.1	0.1	0.1
10	0.0	2.0	1.4	0.8	0.4	0.3	0.3	0.2	0.1
12	0.0	5.1	3.6	2.1	1.0	0.7	0.6	0.6	0.2
14	0.1	13.4	9.4	5.3	2.4	1.8	1.6	1.4	0.5
16	0.2	47.7	27.7	14.6	6.3	4.6	4.0	3.6	1.1
18	0.5	–	–	55.6	18.3	12.8	11.0	9.6	3.0
20	1.6	–	–	–	–	49.9	41.2	33.9	8.7

Synthetic Q, Q-diagrams of the Stromvil system for classification of solar chemical composition stars are plotted in Figs. 2–5. The color indices and Q-parameters are calculated by convolution of the energy distribution functions in stellar spectra and the response functions of the photometric passbands, as described by Straižys et al. (1994). Each of these diagrams is usable for classification of stars in different intervals of spectral classes, after calibration in terms of physical parameters.

Methods of recognizing metal-deficient dwarfs, subgiants and giants and determination of the metallicity using the Vilnius photometric system are described in detail by Straižys (1992a). Since the passbands of the Stromvil system are quite similar, the same methods may be applied for this system. The Stromvil system is also capable of identifying the following types of stars: F-G-K-(M) subdwarfs, metal-deficient G-K-(M) giants, Be-stars, Am and Ap stars, white dwarfs, carbon and barium stars, Herbig Ae/Be stars, T Tauri-type stars, many types of unresolved binary stars.

3. REALIZATION OF THE STROMVIL SYSTEM ON A SATELLITE

We propose to implement on the scanning survey satellite the eight color system consisting of seven passbands of the Stromvil system and one additional infrared passband. An infrared band combined with a passband in the green part of the spectrum would give a blanketing-free color index suitable for temperature determination of late-type stars. The infrared passband may be I from the RI system of Cousins (1980) with a mean wavelength at 812 nm and a half-width of 166 nm.

For implementation of the system, both glass and interference filters may be used. The glass filters are usually sandwiches cemented from two to four pieces of different colored glasses. Glass filters are stable in time, they can be easily and accurately repeated at any time and at any place, and their transmission does not depend on light polarization. Shortcomings of glass filters are their great thickness, low transmission at maximum and the dependence of their transmission functions on the temperature. However, some passbands, especially in the red and infrared, cannot be realized with the existing variety of colored glasses produced by the world companies.

Interference filters have considerably higher transmission in the visible, reaching 80% at maximum. When the interference layer is hermetically sealed, the filters are sufficiently stable. We are using the same interference filter on Hα already about ten years without any change of its transmission curve. However, it is hard to give the interference filters a high transmission in the near ultraviolet (300–400 nm). There are some sets of the Vilnius filters made at the LOMO factory at St. Petersburg with ultraviolet filters having a peak transmission at 60%. Glass filters, realizing the ultraviolet passbands with a halfwidth of 30 nm have a peak transmission of 40%.

4. PRECISION AND LIMITING MAGNITUDE

In this section we shall estimate the precision of the Stromvil+I photometry and the limiting magnitude which can be reached with the six GAIA telescopes of diameter 55 cm during a 5 year period of scanning. The predicted standard errors due to photon noise for stars of three spectral types, B0, G0 and M0, are listed in Tables 2–4. Approximate energy distributions in spectra of these stars are taken from Allen (1973). Filter and CCD characteristics are given at the bottom of Table 2. For the bright stars the minus (–) sign means a non-linear response of the CCD. For the faint stars it means that the signal-to-noise ratio is < 2.0 on a single CCD. Errors are given in millimagnitudes. W means the unfiltered spectral band. Only the incoherent imaging part of the field of GAIA is considered, see Figure 7 of Lindegren & Perryman (1994). See Høg (1995) for more explanation of the calculations.

It appears that down to $V = 14$ mag the precision of magnitudes for all passbands is better than ±0.01 mag for stars of all three spectral types. At $V = 16$ mag this is true only for the stars of G0 and earlier: for the M0 star the precision in the ultraviolet passbands 35 and 37 is ±0.05 and ±0.03 mag, respectively. But the ultraviolet passbands in the Stromvil system are not needed for the classification of M-type stars.

In the Vilnius photometric system, a precision of color indices of the order of ±0.01 mag will produce the following average precision of classification: ±1 subclass for the spectral type, ±0.5 mag for the absolute magnitude M_V and ±0.15 dex for the [Fe/H] determination (Straižys 1992a). The same precision of classification is expected for the Stromvil system. It appears from the three tables that this precision will be obtained for stars as faint as $V = 16$ mag. This expectation is based on the assumption that the standard errors due to photon noise, given in the tables, can be propagated quadratically into the final photometric precision. The experience with the Hipparcos and Tycho projects makes this plausible.

In the Vilnius system about 5% of all field stars are found to have peculiar photometric properties and their classification is problematic. These stars deserve a special photometric and spectroscopic analysis. A part of them can be identified with stars of different spectral peculiarities, a part are unresolvable binary stars. But our experience is based only on the relatively bright stars with V down to 12 or 13 mag. We expect that the same percentage of stars will behave abnormally among the fainter stars. This conclusion is based on the fact that the photometric system is able to classify stars of all spectral and luminosity classes. Consequently, the different relative distribution of stars of different luminosities found among fainter stars, will not increase the classification difficulties.

5. EXPECTED RESULTS IN THE GALAXY

The knowledge of spectral classes, absolute magnitudes, interstellar reddenings and distances of all stars down to 16 mag will give great impetus to the investigation of the structure and evolution of the Galaxy, cf. Høg & Gilmore (1995). The HR diagrams may be constructed for space volumes in different directions and for different heliocentric distances. This will show the variations of the luminosity function in different parts of the Galaxy. More exact values of the galactic radial scale length and the vertical scale height for stars in different evolutionary stages will be obtained. The question of the existence of the thick disk population will be solved. The population differences in the spiral arms, the interarm regions and the central galactic bulge can be analysed. The metallicity gradients can be investigated both in the disk and in the halo. Details of the distribution of the interstellar dust in the disk and the extinction laws in different areas can be investigated. Distances of the dust clouds can be determined. All this information may be used to construct a more realistic model of the Galaxy.

Millions of emission-line stars, chemically peculiar stars, variable stars, carbon stars, white dwarfs and other interesting objects will be discovered. These interesting stars will be subjects for future spectroscopic studies. All known open and globular clusters and stellar associations may be investigated combining the astrometric and photometric data. Probably, many new open clusters and stellar moving groups will be discovered.

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