Baltic Astronomy, vol. 8, 505–534, 1999.

PHOTOMETRIC SYSTEMS AND STELLAR PARAMETERS *

V. Straižys

Institute of Theoretical Physics and Astronomy, Goštauto 12, Vilnius 2600, Lithuania

Received December 15, 1999.

Abstract. Information on temperatures, gravities, metallicities, peculiarities and interstellar reddening of stars can be obtained by photometry of their light in a certain photometric system. A review of some photometric systems currently in use is given. The review includes the broad-band system *UBV* and its extension *RI*, the revised *WBVR* system and the medium-band *Vilnius* and *Strömvil* systems.

Key words: methods: observational – techniques: photometric – stars: classification, physical parameters, interstellar reddening

1. INTRODUCTION

Temperatures, gravities, metallicities and other physical parameters of stars can be determined either by the analysis of their spectra or by multicolor photometry using a certain photometric system. Such a system means a set of spectral passbands defined by response functions in which stellar intensity measurements give us certain information about their physical parameters. A photometric system can contain from one to tens of passbands. Strömgren (1963a) has suggested the classification of photometric systems in broad-band, medium-band and narrow-band systems. In this review we will use the same classification of systems but with somewhat revised bandwidths. Broad-band systems have their half-widths $\Delta\lambda > 50$ nm, for medium-band systems $\Delta\lambda$ is between 10 and 50 nm and for

---

* Communication at the Nordic-Baltic Research Course in Applied Astrophysical Photometry, Molėtai Observatory, August–September 1999

narrow-band systems $\Delta\lambda < 10$ nm. The systems with $\Delta\lambda > 100$ nm sometimes are called super-broad-band systems.

Among broad-band photometric systems most popular is the *UBV* system introduced by Johnson and Morgan (1953) and its extension to the red-infrared spectral range proposed by Cousins (1976, 1980). Till now a big variety of medium-band systems have been used. The systems having the largest number of observations are: the *Strömgren* four-color system, the *Geneva* seven-color system, the *Vilnius* seven-color system, the *DDO* six-color system and the *Walraven* five-color system. All these systems are described in detail in the Straižys (1992a) monograph. Here we give the updated description of the broad-band *UBVRI* system and the medium-band *Vilnius* and *Strömvil* systems.

2. THE *UBV* AND *WBV* SYSTEMS

The *UBV* system was introduced by Johnson and Morgan (1953) as a standard three-color system for approximate classification of stars, the determination of their interstellar reddening and for the determination of star cluster ages. The blue (B) and green (V) passbands with mean wavelengths at 442 nm and 550 nm respectively were chosen to repeat as closely as possible the response functions of the International photographic (*IPg*) and photovisual (*IPv*) system which was in use since 1922. The positions of passbands of this system are quite accidental: the position of *IPg* is defined by the sensitivity of unsensitized photographic emulsions, while the position of *IPv* approximately corresponds to the spectral sensitivity curve of the human eye.

However, an important improvement of the blue passband B has been made. In his earlier investigation Johnson (1952) found that *IPg* systems of various authors showed non-linear color equations, caused by inclusion of different amounts of the ultraviolet radiation into the passband. Therefore, Johnson decided to cut by a special filter (Schott GG 13) the wavelengths shorter than 380 nm to exclude the influence of the Balmer jump on the blue passband. From the side of long wavelengths, the response function of the passband was formed by another (blue) filter Corning 5030.

The yellow passband V was accomplished by a yellow filter Corning 3384 cutting wavelengths shorter than 490 nm. From the red

Table 1. Mean wavelengths and half-widths of passbands of the *UBV* system from Ažusienis & Straižys (1969).

Passband	*U*	*B*	*V*
λ_0 (nm)	364	442	550
$\Delta\lambda$ (nm)	44	96	83

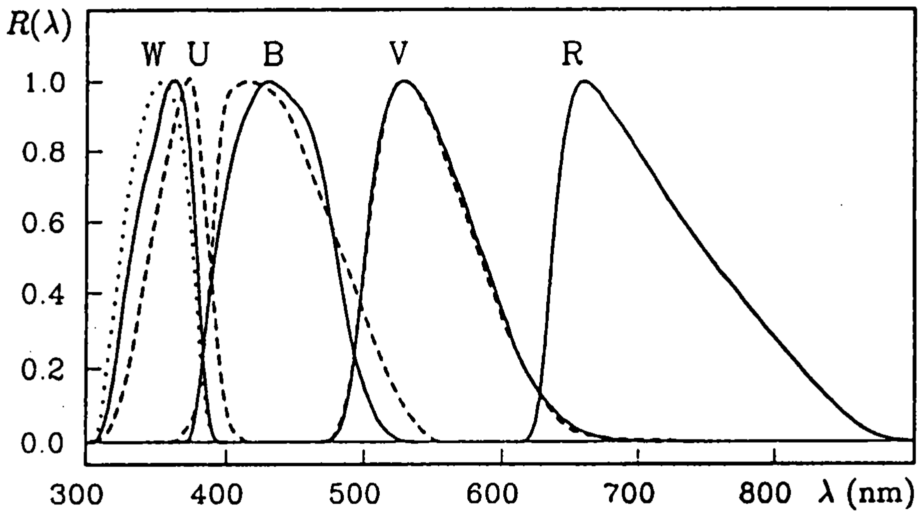

Fig. 1. Normalized response functions of the *UBV* (dashed lines) and *WBVR* (solid lines) photometric systems.

side the passband was formed by declining sensitivity curve of the antimony-caesium RCA 1P21 photomultiplier.

The ultraviolet passband *U* was introduced to make possible the measurement of height of the Balmer jump in B–A–F stars by the color index *U–B*. For this Johnson has used Corning 9863 filter which has its transmittance curve between 300 and 400 nm, i.e., mostly shortward of the Balmer jump.

The response functions of the *UBV* system are shown in Fig. 1. Mean wavelengths and half-widths of the passbands are given in Table 1. Intrinsic color indices $(U-B)_0$ and $(B-V)_0$, the ratios of color excesses E_{U-B}/E_{B-V}, the ratios of interstellar extinction to reddening A_V/E_{B-V} and the interstellar reddening-free parameters

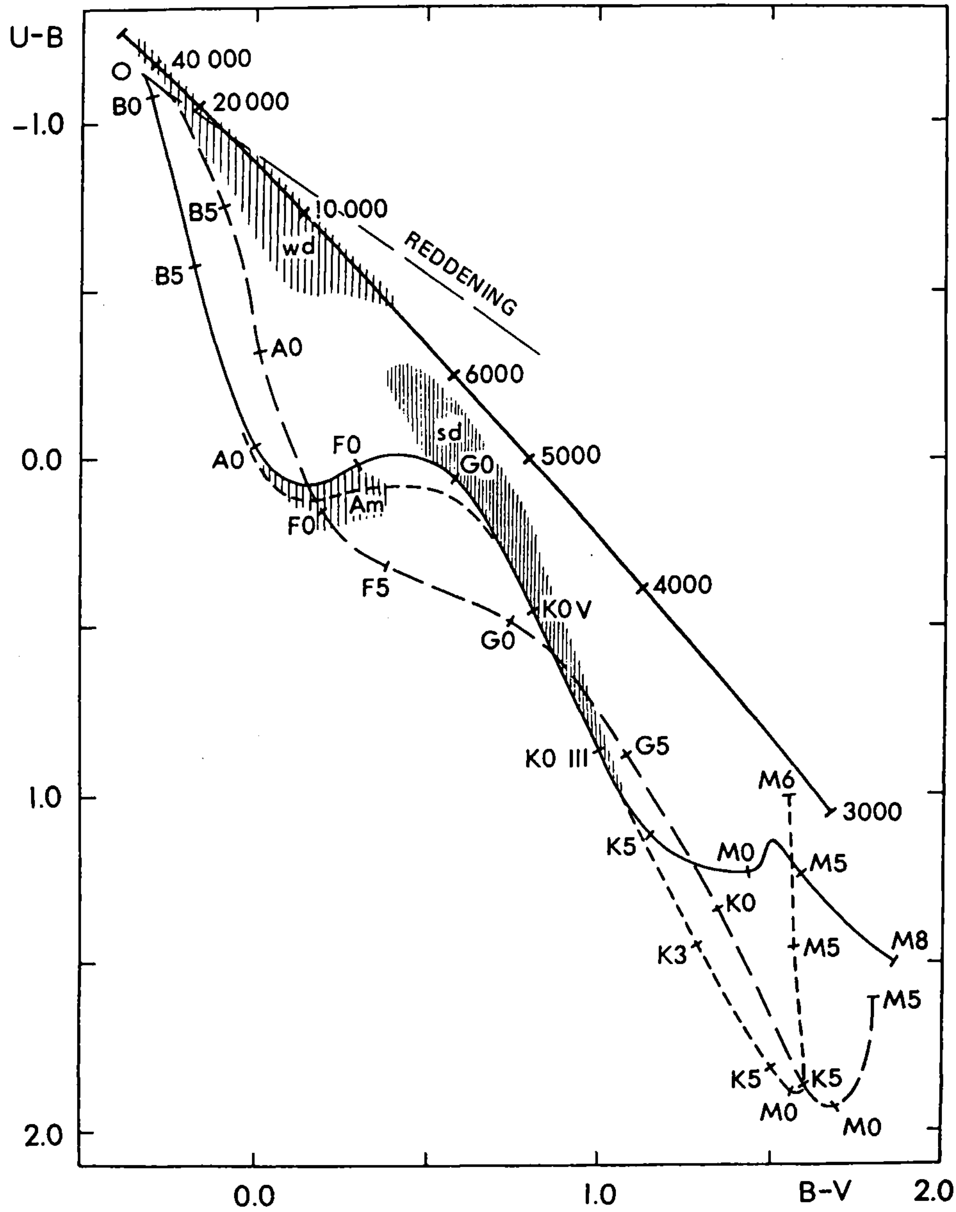

Fig. 2. The U–B, B–V diagram with sequences of luminosity V (solid line), III (short-dashed line) and I (long-dashed line) stars, the black-body line with temperature ticks and the positions of white dwarfs, metallic-line stars and subdwarfs.

Q_{UBV} for stars of various spectral and luminosity classes are given by Straižys (1992a).

In Fig. 2 the intrinsic U–B, B–V diagram is presented, with lines of the main sequence, giants and supergiants, the line of black bodies and the areas occupied by white dwarfs, metallic-line stars and metal-poor subdwarfs, as well as the reddening line of O-type stars. The reddening line is of slightly parabolic form due to the band-width effect on color excesses. This diagram makes it possible to classify approximately unreddened stars in spectral types in the parts of diagram where intrinsic sequences of various luminosities do not intersect. In the places near intersections, the classification is multivalued. The U–B, B–V diagram is very useful for the determination of interstellar reddening of open clusters by the amount of the shift of the main sequence along reddening lines.

Two color indices and the color excess ratio of the UBV system may be combined into the interstellar reddening-free quantity

$$Q_{UBV} = U - B - \frac{E_{U-B}}{E_{B-V}}(B - V).$$

Here the color excess ratio shows only small variations with spectral class and luminosity due to the band-width effect. The dependence of Q_{UBV} on B–V is shown in Fig. 3. Due to interstellar reddening stars in this diagram move along reddening lines which are parallel to X-axis. This means that this diagram may be used for estimation of color excess E_{B-V} of the star but for this we must know its luminosity class.

Unfortunately, from the very beginning of its introduction the UBV system, especially the ultraviolet passband, had some faults. Here they are.

(1) The main shortcoming of the U–B index was its incorrect transformation to outside the atmosphere which neglected the dependence of the extinction coefficient on spectral class, luminosity and interstellar reddening of the star. As a result, the U–B color index differs from that which would be measured with the same filter from outside the atmosphere. The system of the U–B color index is not uniform, depending on the zenith distance, the period of observations and the altitude of the observatory. In other words, each star from the list of primary standards of the UBV system has its own color system corresponding to the mean zenith distance at which this star has been observed. Consequently, Johnson's U magnitudes cannot be measured from space.

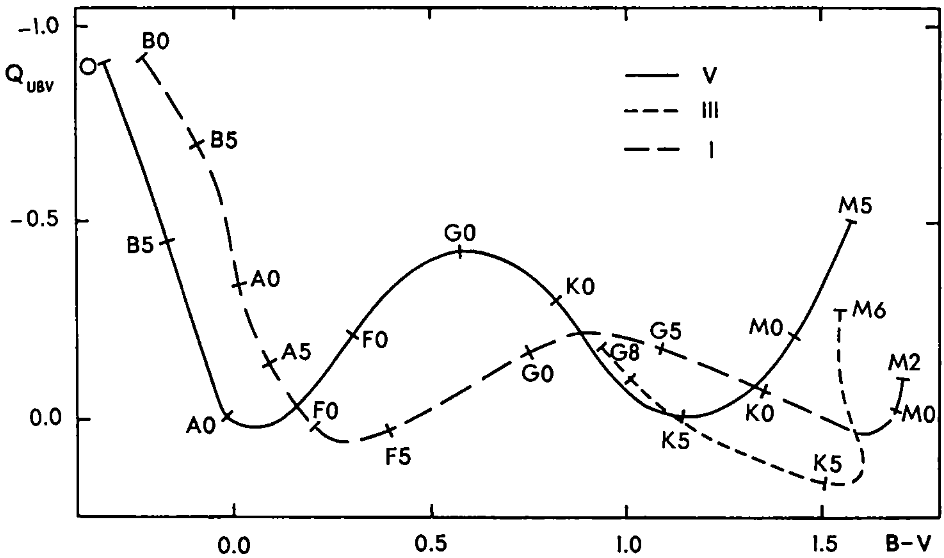

Fig. 3. The reddening-free parameter Q_{UBV} as a function of intrinsic $B-V$ color index. Luminosity class designations are the same as in Fig. 2.

(2) Moreover, the U magnitude does not serve as a measure of the radiation intensity of a star beyond the Balmer jump, since its response function includes the rising part of the jump. The mean wavelength λ_0 of the U passband is at 364 nm, i.e., it almost coincides with the Balmer limit. A considerable part of radiation on the rising part of the energy distribution curve at 380–400 nm is included.

(3) The Corning 9863 glass filter, which has been used to realize the U passband, has a considerable transmittance in the red part of the spectrum at 700 nm ("red leak"). Some $SbCs_3$ cathode photomultipliers have a long sensitivity tail which gives a considerable red sensitivity depending on the temperature. To have a precise knowledge of this effect, one must measure the red leak for every intrinsically red star or a star reddened by interstellar dust. As a result, a three-color UBV system becomes a four-color one.

Thus, due to the ill definition of the system and the inaccurate transformation of the $U-B$ color index to outside the atmosphere, the high accuracy of photometric observations is lost. Systematic errors of various catalogs can be as large as 0.05 mag. $U-B$ errors

Table 2. Mean wavelengths and half-widths of passbands of the *WBVR* system from Kornilov & Krylov (1990).

Passband	*W*	*B*	*V*	*R*
λ_0 (nm)	354	438	551	712
$\Delta\lambda$ (nm)	46	87	89	122

are the largest for F–G supergiants which show extreme deviation of the extinction coefficient from that for the majority of luminosity V and III stars. For some supergiants the errors can be as large as 0.1 mag and even more.

Ažusienis and Straižys (1969) suggested the following measures to revise the *U* passband: (1) to limit filter transmittance from the red side to exclude the influence of the rising energy curve at the Balmer jump; (2) to exclude the red leak of the filter; (3) to determine accurate response functions of the photometer which will be used to measure standard stars; (4) to transform the U–B index to outside the atmosphere with the extinction coefficient dependent on spectral class, luminosity and interstellar reddening of stars.

An ultraviolet passband *W* satisfying these requirements has been described by Straižys (1973, 1977, 1983). The filter has maximum transmittance at 345 nm and a half-width of 56 nm. The system *WBV* was tested by Meištas et al. (1975). Color indices were transformed to outside the atmosphere by Zdanavičius (1975) method which uses the extinction coefficients dependent on energy distribution in stellar spectra. The method gives the extra-atmospheric W–B values with the accuracy of ± 0.01 mag. The description of the method in English is given by Straižys (1992a).

Standard stars of the *WBVR* system (here *R* is the broad passband at 643 nm with $\Delta\lambda = 90$ nm) and 13 586 stars down to $V = 7.2$ mag north of $-15°$ in declination have been observed by Kornilov et al. (1991) at the Tien-Shan Observatory in Kazakhstan. The system is described by Mironov et al. (1984), Khaliullin et al. (1985) and Kornilov & Krylov (1990) and the method of reduction to outside the atmosphere used is described by Moshkalev & Khaliullin (1985). The newest response functions of the system are given in Kornilov et al. (1991). The parameters of the response functions are given in Table 2. The response functions of the *UBV* and *WBVR*

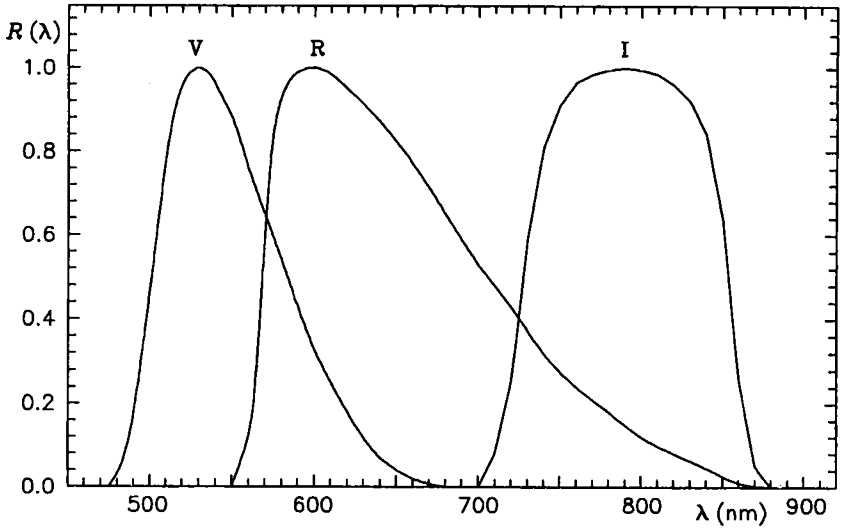

Fig. 4. Response functions of the Cousins *V,R,I* photometric system.

systems are intercompared in Fig. 1. Intrinsic color indices of stars of various spectral luminosity classes are determined by Vansevičius & Straižys (1994). This system gives real extra-atmospheric values of color indices of high accuracy. This system is recommended to use in future instead of Johnson's *UBV* system. The filters of the *WBVR* system are available from the Institute of Theoretical Physics and Astronomy, Vilnius.

3. THE V, R_C, I_C SYSTEM

The first broad-band photoelectric systems in the red and near infrared were introduced by Stebbins & Whitford (1943), Kron & Smith (1951), Kron, White & Gascoigne (1953), Johnson & Mitchell (1962), Johnson (1965). However, these systems are not sufficiently accurately defined and not used any more. In the seventies new types of photomultipliers, using the GaAs and InGaAsP photocathods, have appeared. They have high sensitivity up to 0.9 and 1.1 μm, respectively. They make possible to measure stars in all passbands the *UBVRI* system with a single tube. The *R,I* system proposed by Cousins (1976, 1980) has become very popular among observers, since it can be easily set up by CCD detectors.

The Cousins system R_C and I_C in 1976 was set up with the GaAs photomultiplier. The filters and transformations in 1978 have suffered some changes (Cousins 1978). The R passband is set with the Schott glasses OC 570 (2 mm) and KG 3 (2 mm). The I passband is set with the Schott RGN9 glass (3mm) and the cut-off of the photomultiplier at about 920 nm. The final response curves are given by Cousins (1980) and Bessell (1979, 1983). They are shown in Fig. 4. The mean wavelengths of the R_C and I_C response functions are 658 nm and 812 nm, the half-widths of both passbands are 166 nm. If the Cousins system is set by a CCD camera, then the I_C filter must contain a glass or interference layer cutting wavelengths longer than 900 nm. Additionally to the R and I passbands, Cousins has always used the green V passband almost coinciding with Johnson's V.

The intrinsic color indices of the system are determined and analyzed by many authors which are listed by Straižys (1992). The relations between the Cousins system and other R, I systems in most cases are nonlinear and luminosity-dependent. However, the linear transformation in many cases is adequate to give an accuracy of ± 0.01 mag. Standard stars of the system are described in Straižys (1992).

4. THE VILNIUS SYSTEM

Most of the photometric systems cannot give two-dimensional classification and quantification of stars over the whole stellar temperature range, from the hottest to coolest stars, with interstellar reddening present. Each system is either restricted to stars of certain spectral and luminosity range or gives classification if the interstellar reddening is absent. Consequently, these systems are not applicable for classification of stars in the galactic field areas containing stars of different temperatures, luminosities, peculiarities and interstellar reddenings.

In 1962 at the Vilnius Observatory we started investigations aiming to select the optimum multicolor photometric system for classification of stars of any spectral class, luminosity and interstellar reddening (Straižys 1963). The selection of passbands of the optimum system was based on detailed energy distributions in spectra of stars of different types and on the interstellar extinction law.

If the temperature reddening and interstellar reddening followed the same law, say, λ^{-1} law, we would have no possibility to separate intrinsically red and reddened stars by photometric data alone. Fortunately, both temperature and interstellar reddening deviate from the λ^{-1} law, and in a different manner. The greatest deviation of energy distribution curves from the λ^{-1} law is caused by the Balmer jump in early-type stars and by blends of atomic lines and molecular bands in spectra of late-type stars. The interstellar reddening also does not completely follow the λ^{-1} law. These differences make reddening lines in two color index diagrams not coincide, as a rule, with sequences of unreddened stars. Only sometimes, the positions of the passbands being especially selected, these lines may coincide.

The selection of optimum passbands has been carried out with the help of the synthetic two color and Q, Q diagrams, by varying positions, widths and shapes of the response functions. The whole process may be followed in detail in a series of works published by Straižys (1963, 1964a,b, 1965), Straižys & Zdanavičius (1965), Zdanavičius & Straižys (1964), Straižys & Kurilienė (1981). Here only the final results will be described.

4.1. Selection of passbands for early-type stars

It was decided at the very beginning that the system should be medium-band one, to ensure possibility of measuring faint stars. Although narrow-band photometric systems are more informative, their limiting magnitude is too bright.

The classification of early-type stars in temperature is based on measurement of the Balmer jump. Spectra of hot stars have no other feature which would be so convenient for their classification in spectral classes and for determination of effective temperature. To measure the Balmer jump photometrically, we must have two passbands, one placed in the ultraviolet shortwards the jump (the passband U) and the other placed longwards the jump (the passband X). In B and A stars the spectrum shortwards the Balmer jump is rather smooth, with no strong spectral lines. The most serious obstacle here is the presence of a strong time-variable atmospheric extinction caused by the ozone and extending from 330 to 300 nm. Consequently, we do not have much space in the ultraviolet to place a passband of medium width. The U passband with the mean wavelength 345 nm and a half-width of 40 nm has been selected between the Balmer limit and

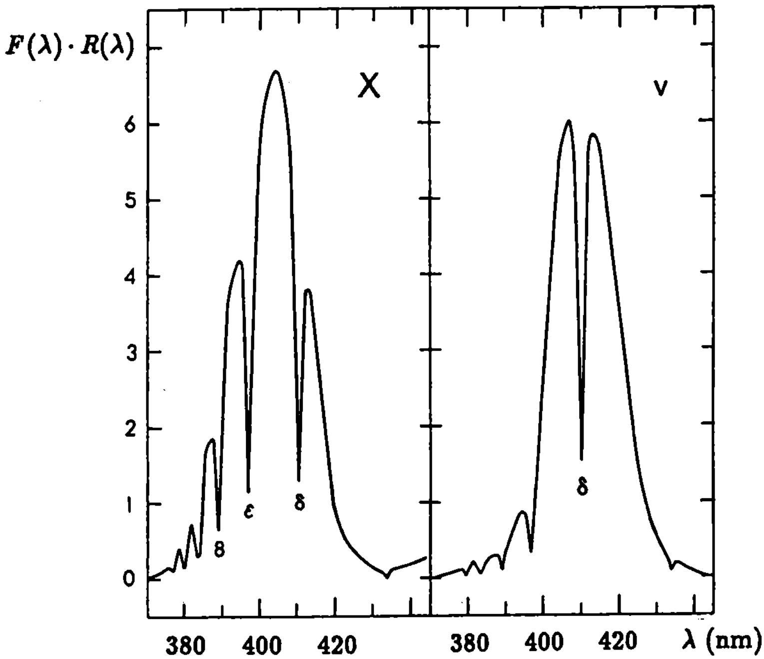

Fig. 5. The spectrum of α Lyrae convolved with the response functions of the X passband of the *Vilnius* system and the v passband of the *Strömgren* system. The Balmer lines Hδ, Hϵ and H8 are seen.

the strongest ozone absorption bands. It almost coincides with the u passband of the Strömgren *uvby* system.

The space before the Balmer jump for the X passband is even more limited. We almost have no choice here, as the only line-free place is between the Hδ and Hϵ lines (Fig. 5). Even this "window" is not broad enough to place here a passband of medium width. Strömgren has placed his v magnitude exactly on the Hδ line. However, this position is worse, since color index $U-v$ is not so good measure of the height of the Balmer jump. Also, the inclusion of a strong line into the passband causes difficulties in repeating the same photometric system with other set of filters: even a small shift of the filter transmittance function causes a nonlinear and luminosity-sensitive color equation. Also, there are other reasons against pushing the X passband towards longer wavelengths.

The above listed factors have determined the choice of the X passband before the Balmer jump at 405 nm, i.e. between the Hδ and Hϵ lines. The N magnitude of the Borgman (1960, 1963) system is exactly in the same position.

It is known that the interstellar extinction law in the $A(\lambda)$, λ^{-1} plot in the 300–800 nm range can be approximated by two straight lines which intersect at about 435.5 nm. If we consider the temperature reddening of stars to follow the λ^{-1} law, then the maximum separation between interstellar and temperature reddening in the two color $X-Y$, $Y-Z$ diagram is achieved when the Y passband is situated on the knee-point of the interstellar extinction law, and the two other passbands X and Z are placed on both sides of it. If unreddened stars lie on the $X-Y$, $Y-Z$ diagram along a single line without any bends, the diagram would present a method of determining spectral types of stars, irrespective of their reddening and using the reddening-free Q_{XYZ} parameter. The farther we place the X passband from the knee-point, the greater is the basis of the $X-Y$ color index and the greater is variation of the Q parameter with advancing spectral type. At the same time, the angle between the reddening line and the unreddened main sequence in the $X-Y$, $Y-Z$ diagram increases. However, the shift of the X passband towards short waves is restricted by the Balmer jump. If the X passband includes at least a part of the radiation of the falling part of energy distribution or beyond the jump, a bend of the main sequence line in the $X-Y$, $Y-Z$ diagram immediately appears. The position of the X passband at 405 nm seems to be optimum, giving a sufficient scale of the $X-Y$ index and avoiding the appearance of a considerable bend on the main sequence.

What concerns the Y passband, when it is shifted farther from the knee-point of the interstellar extinction law, the angle between the reddening lines and the unreddened main sequence gradually diminishes. On the other hand, the Y passband should avoid the interstellar absorption band at 443 nm and the Hα line. Therefore, we have decided to place the Y passband near 460 nm. The passband M of the *Borgman* system and b of the *Strömgren* system are close to the Y passband.

In the $X-Y$, $Y-Z$ diagram the intrinsic sequences of luminosity V, IV, and III stars almost coincide and the reddening-free Q_{XYZ} parameter is an one-to-one function of spectral classes (Fig. 6). However, the early-type supergiants form a separate sequence and any shifts of passbands cannot eliminate the luminosity effect. Thus, the

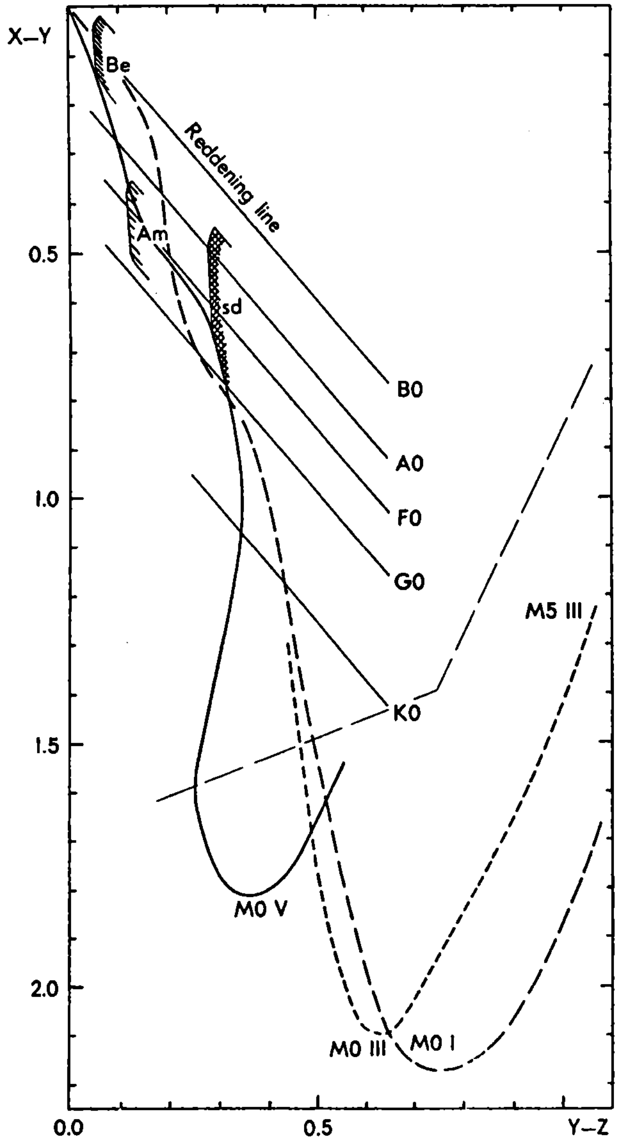

Fig. 6. The schematic X–Y, Y–Z diagram. The solid curve is the main sequence, the short-dashed line is the giant sequence, the long-dashed line is the supergiant sequence, the parallel straight lines are reddening lines of B0 V, A0 V, F0 V, G0 V and K0 V stars. the two intersecting broken lines separate the area in which M-type stars of various luminosities are met. The blue limits of Be and Am stars and subdwarfs are shown.

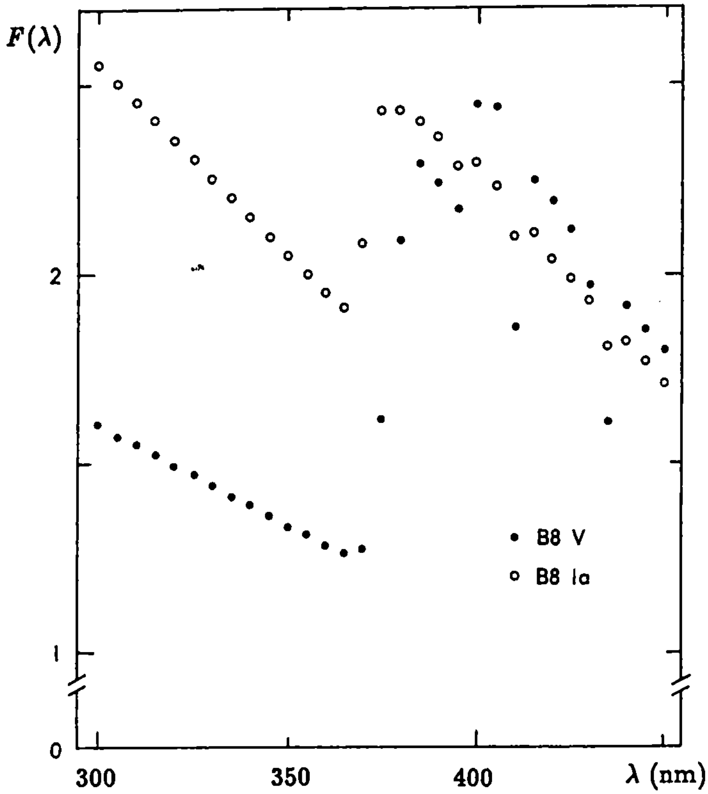

Fig. 7. The energy distribution in the region of the Balmer jump of a main sequence star and a supergiant of spectral class B8.

knowledge of luminosity is necessary before the photometric classification. This information can be obtained by introducing one more passband P placed on the crowding of higher members of the Balmer series near the Balmer limit.

The difference of shapes of energy distributions of a main sequence star and a supergiant of the same spectral class in the region of the Balmer jump is seen in Fig. 7. It is evident that with increasing luminosity the Balmer jump decreases and moves towards shorter wavelengths.

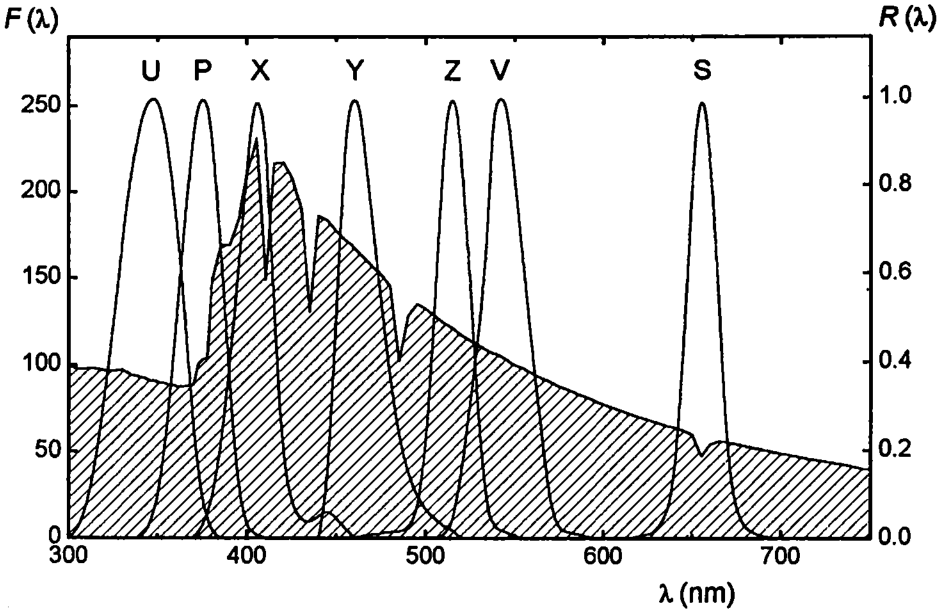

Fig. 8. The energy distribution in the spectrum of α Lyrae with the positions of the *Vilnius* system passbands.

The best position of the P passband on the Balmer jump was selected by analyzing the synthetic U–P, P–Y diagrams computed at various positions of the P passband. The position of P at 375 nm proved to be optimum. It corresponds to nearly maximum intensity in spectra of supergiants and to nearly minimum intensity in spectra of main sequence stars. Therefore, those color indices which include the P magnitude are very sensitive both to the height of the Balmer jump and to its position and give for B–A stars a nice separation of the luminosity classes. However, the sensitivity of the P magnitude to luminosity decreases when we make its passband wider. It seems that it is safe to use the half-width up to 25 nm. Borgman (1960, 1963) in his seven-color system has used a passband at the same position but having the half-width of only 11 nm.

The optimum positions of the passbands U, P, X and Y with respect to the energy distribution of α Lyrae are shown in Fig. 8.

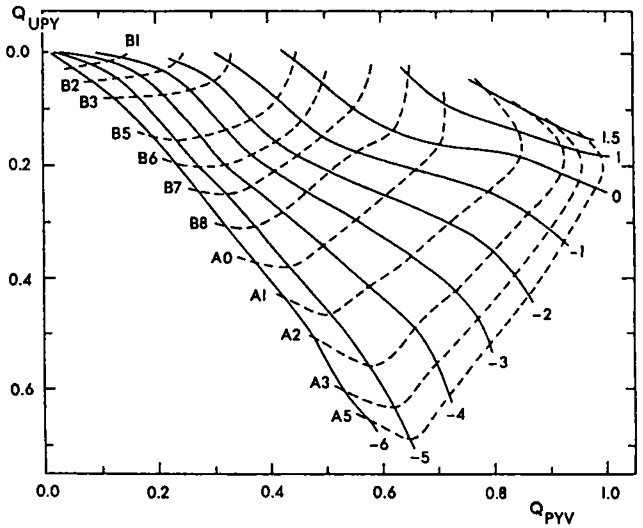

Fig. 9. The reddening-free diagram Q_{UPY}, Q_{PYV} calibrated in spectral classes and absolute magnitudes. The diagram can be used for the classification of B stars of luminosities V–III and B–A–F supergiants.

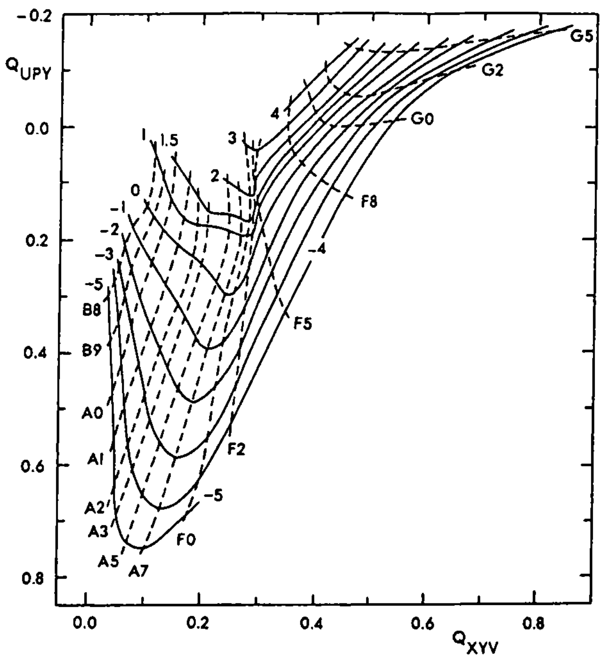

Fig. 10. The reddening-free diagram Q_{UPY}, Q_{XYV} calibrated in spectral classes and absolute magnitudes. The diagram can be used for the classification of A–F–early G stars, except of A V–III stars.

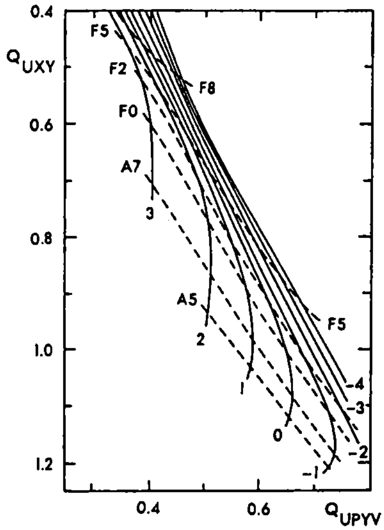

Fig. 11. The reddening-free diagram Q_{UXY}, Q_{UPYV} calibrated in spectral classes and absolute magnitudes. The diagram can be used for the classification of A–F stars of all luminosities.

The best reddening-free diagrams for two-dimensional classification of early-type stars are: Q_{UPY}, Q_{PYV} (Fig. 9) for B-type stars and A–F supergiants and Q_{UPY}, Q_{XYV} (Fig. 10) for A–F–early G type stars. Here V is the magnitude measured in the passband at 540 nm. Since the absolute magnitude isolines in the diagram of Fig. 10 for A-type stars close to the main sequence overlap, for their classification we use the diagram Q_{UXY}, Q_{UPYV} (Fig. 11).

4.2. Selection of passbands for late-type stars

For two-dimensional classification of K- and M-type stars one may use a Q, Q diagram in which one Q-parameter is a function of spectral type, while the other one is more sensitive to luminosity. A good criterion of spectral type or temperature is the parameter Q_{XYZ} where $\lambda\,(X)$=405 nm and $\lambda\,(Y)$=460 nm and the Z passband is taken within 500 and 600 nm. For another parameter which is most sensitive to luminosity, we took Q_{XZS} where $\lambda\,(S)$ can be taken within 600 and 700 nm. This parameter is defined by the X–Z, Z–S diagram where the sequences of G–K stars of different luminosities are well separated and more or less parallel. The reddening lines in this diagram run almost along the intrinsic sequences, hence, the Q_{XZS} parameter is a luminosity-sensitive.

The analysis of tens of diagrams of the Q_{XZS}, Q_{XYZ} type with various positions of Z and S passbands proved the passbands with $\lambda(Z)$=515nm and $\lambda(S)$=655 nm to be the optimum choice.

The optimum position of the Z passband coincides with a broad absorption feature in the spectra of G, K and M stars which is formed by a blend of absorption lines including the strong Mg I triplet at the wavelengths 516.7, 517.2 and 518.3 nm. In M-type dwarfs the same blend contains a MgH absorption band. The Z depression has negative dependence on star's luminosity: dwarfs have deeper absorption than giants and giants – deeper than supergiants. As a result, the X–Z color index has a more positive value for a giant than for a dwarf of the same effective temperature. This is caused by two reasons: (1) color temperature of a giant is lower than that of a dwarf of the same spectral type and (2) a dwarf has a deeper depression in the 515 nm region than a giant. We would have a still greater effect replacing the X magnitude by the U magnitude. However, it is not practical to use the ultraviolet passband for so cool stars. The dependence of the color index Z–S on luminosity is much smaller but its action is such that it strengthens the luminosity dependence of Q_{XZS}.

The final positions of the passbands of the Vilnius system plotted on the energy distribution curve of a K5 V star is shown in Fig. 12.

The two best diagrams for the classification of G–K stars are Q_{UPY}, Q_{XZS} (Fig. 13) and Q_{XZS}, Q_{XYZ} (Fig. 14). In the first of them the luminosity isolines are well separated starting from G0 spectral class, but the diagram contains the ultraviolet U and P magnitudes. The second diagram does not contain any ultraviolet magnitude, but the luminosity separation starts only at G8 or K0 spectral class. The unrequirement of U and P magnitudes for the classification of the reddest stars is important since these stars are very faint and difficult to measure in the ultraviolet.

However, M-type stars in the Q_{XZS}, Q_{XYZ} diagram return back overlapping K-type stars. This happens due to color index X–Y which increases with transition from O to M0 stars but in M stars it starts to decrease with decreasing temperature due to strong absorption in TiO bands within the Y passband. As a result, M stars of all luminosities turn back in the Q_{XZS}, Q_{XYZ} diagram and overlap

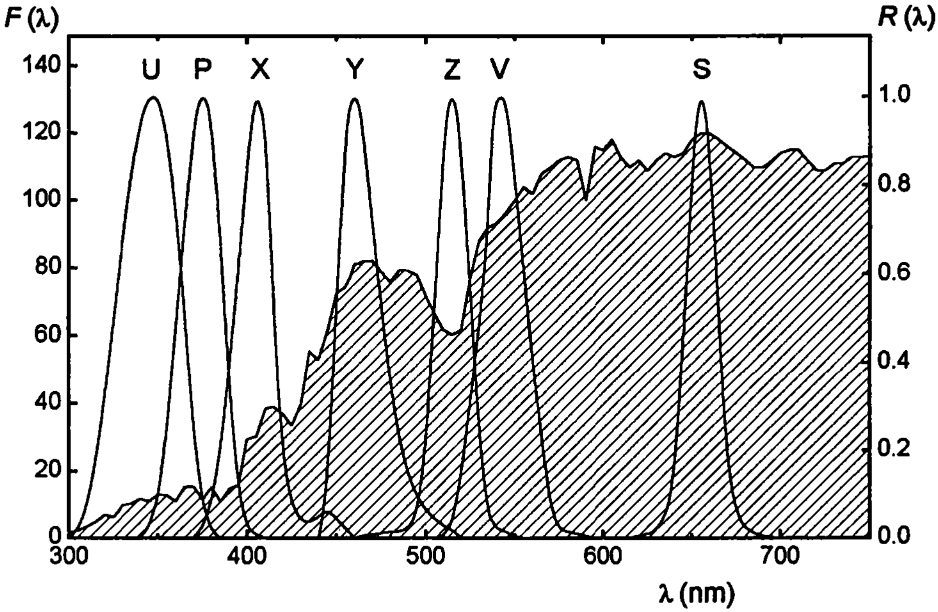

Fig. 12. The energy distribution in the spectrum of a K5 V star with the positions of the *Vilnius* system passbands.

K-type stars. Therefore, two-dimensional classification of late-type stars requires first to separate M-type stars from the hotter ones.

This may be done by checking photometrically the presence of the TiO band absorption. Whether the TiO absorption is present or not, we may learn from any color index whose short-wavelength passband is situated on one of intensity peaks in M-type spectra, while the long-wavelength passband is placed on the intensity minimum following the peak. If this index is very small or even negative, this means that the star has TiO bands and belongs to M-type. Intensity peaks are at 580, 610, 660 and 700 nm (Fig. 15). Our S passband is close to one of them (660 nm). Intensity minima are at 590, 625, 675 and 715 nm. We may combine our S passband with those at 675 or 715 nm. However, the band at 675 nm is rather shallow, and the use of 715 nm passband is more preferable. The $m_{660} - m_{715}$ index should be a nice indicator of the presence of the TiO band.

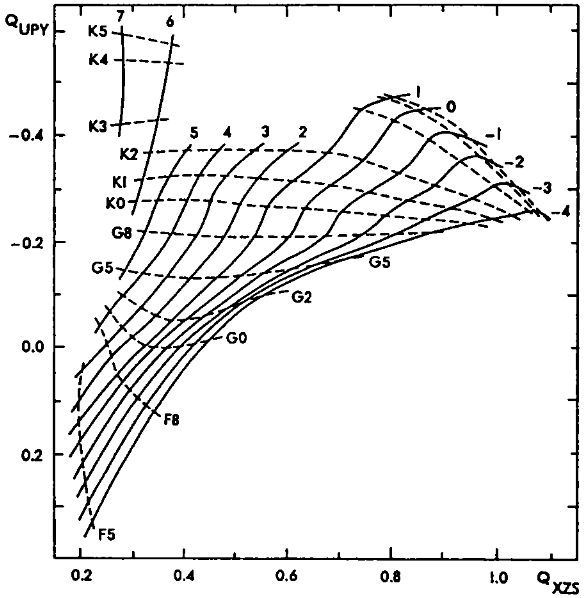

Fig. 13. The reddening-free Q_{UPY}, Q_{XZS} diagram calibrated in spectral classes and absolute magnitudes. The diagram can be used for the classification of G–K stars of all luminosities.

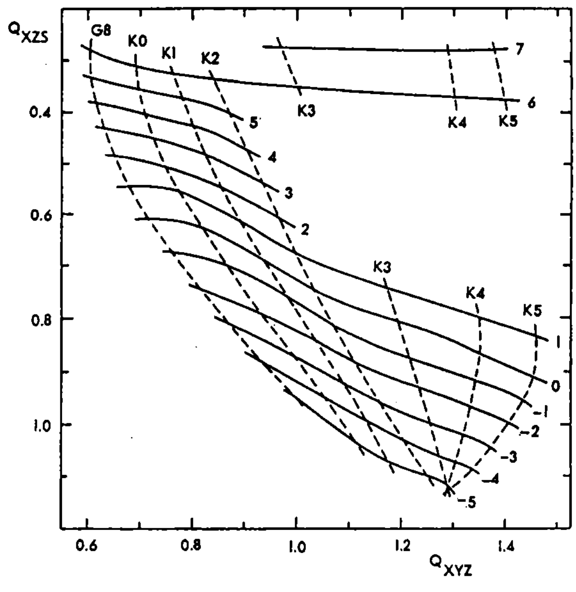

Fig. 14. The reddening-free Q_{XZS}, Q_{XYZ} diagram calibrated in spectral classes and absolute magnitudes. The diagram can be used for the classification of G8–K stars of all luminosities.

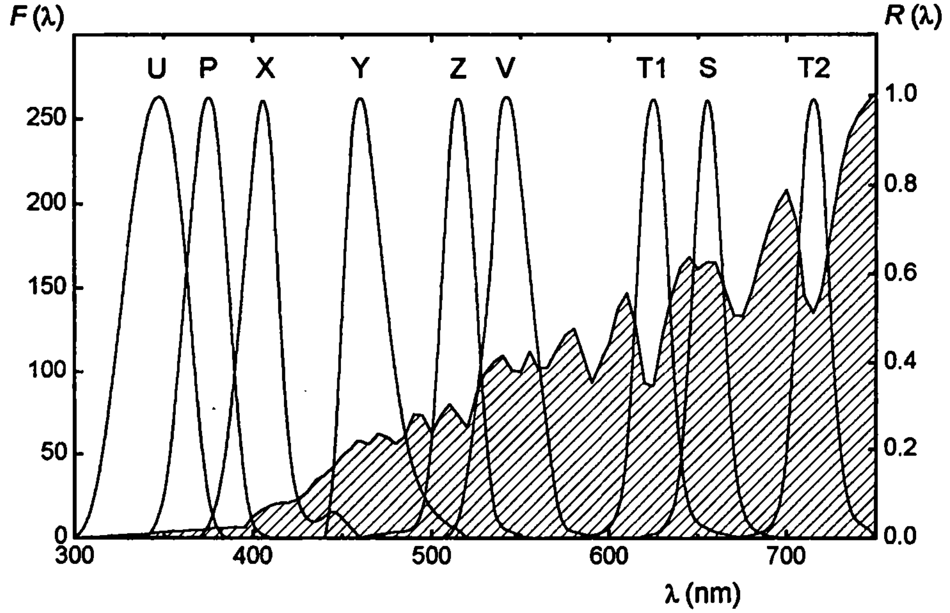

Fig. 15. The energy distribution in the spectrum of a M3 III star with the positions of the *Vilnius* system passbands.

However, multialkali photomultipliers are of low sensitivity at 715 nm, and we decided to take a passband within the TiO band on the short-wavelength side from S, at 625 nm. In this case color index $m_{625} - m_{660}$ cannot give the final answer whether the TiO band is present or not, if the star is affected by interstellar reddening. In this case, instead of color index we must use a reddening-free Q-parameter. If we denote the magnitude situated on the TiO absorption band by T, the Q_{YTS} and Q_{ZTS} parameters are excellent criteria in recognizing M-type stars (Fig. 16). These parameters are nearly constant for G- and K-type stars, while for M-type stars they strongly decrease with transition to later M subclasses. Thus, the knowledge of Q_{ZTS} for any star answers the question if that star is of spectral type M or not.

The T passband is essential only for detection of M-type stars of early subclasses. Stars of spectral type M3 stars and later can be recognized with the help of other Q parameters affected by TiO

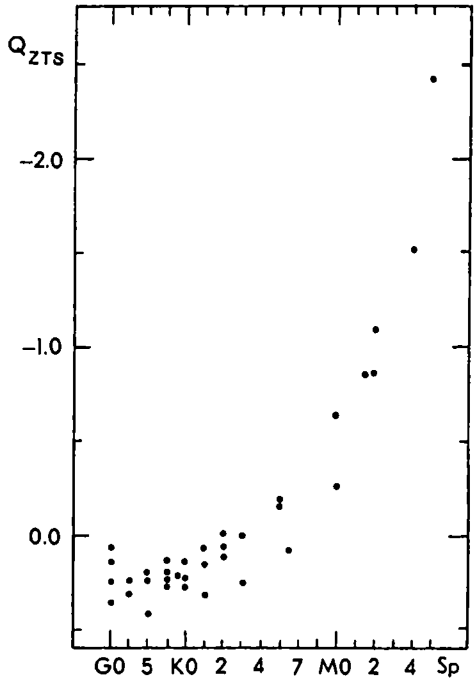

Fig. 16. Reddening-free Q_{ZTS} parameter as a function of spectral class.

bands. One of such parameters is Q_{YSYV} which is ≥ 0.13 for M-type stars and ≤ 0.12 for the remaining ones.

It is important to add one more passband at 545 nm which we denote V. The mean wavelength of its response function nearly coincides with λ_0 of the V passband of the UBV system. The Q_{XZS} and Q_{XZV} parameters were found to have similar properties, consequently, both the Q_{XZS}, Q_{XYZ} and Q_{XZV}, Q_{XYZ} diagrams may be used for two-dimensional classification of late-type stars. Although color index $Z-V$ has a very short scale, it measures the depth of the depression near the Mg I triplet lines.

The V passband is also useful from other points of view. This medium-band magnitude shows no color equation with respect to the V magnitude of the UBV system over a wide temperature range down to M stars of early subclasses (Straižys 1973). This property allows to transfer directly the scale of stellar magnitudes from the UBV into the *Vilnius* system thus saving the work for measuring new standards of stellar magnitudes. The *V* passband is also useful in a number of classification diagrams (see further).

4.3. The final system and its implementation

Summarizing the results for selecting the optimum positions of passbands of a medium-band photometric system intended for photometric classification of stars of all spectral types, we conclude that the system must include eight passbands at 345, 375, 405, 460, 515, 540, 625 and 655 nm. However, not all passbands are always necessary. For two-dimensional classification of early-type stars the passbands at 345, 375, 405, 460 and 515 (or 545) nm are sufficient. For two-dimensional classification of late-type stars the passbands at 405, 460, 515, 625 and 655 nm are sufficient. If we know which stars are of spectral class M, the passband at 625 nm need not be used.

The positions of most of the passbands have been selected by computation of the synthetic color indices using the response functions with shapes similar to those of interference filters with a half-width of 20 nm. The computation of color indices with various half-widths of passbands proved that most of them retain their classification properties, if their half-widths are within 10–40 nm. Only the passbands *P* and *Z* require their half-widths not to exceed 25 nm.

The system is set up with glass filters which are sandwiches of different color glasses made in Russia, cemented with a Canadian balsam. The transmittance curves of the separate components and the cemented filters are given by Straižys & Zdanavičius (1970). Since no suitable glasses can be found to set up the *T* and *S* passbands, interference filters have been taken. As a detector, we have used a FEU-79 photomultiplier with multialkali S-20 photocathode. Response functions of the system are tabulated in Straižys & Zdanavičius (1970) and Straižys (1977, 1992) and shown in Fig. 17. Mean wavelengths and half-widths of the response functions are given in Table 3. The color glasses made in Russia may be replaced by the Schott or other glasses. Glass filters may be replaced by interference filters which have higher transmittance but are less stable. For CCD work, several sets of large interference filters have been made. Some sets contain round filters of 5 cm and 6 cm diameter. The largest filters are squares of 9 × 9 cm size. Both glass and interference filters are being produced by two laboratories in Vilnius. Due to technical difficulties, only glass version of the *U* and *P* filters can be made at the present time.

Table 3. Mean wavelengths and half-widths of passbands of the *Vilnius* photometric system (with *T* passband).

Passband	*U*	*P*	*X*	*Y*	*Z*	*V*	*T*	*S*
λ_0 (nm)	345	374	405	466	516	544	625	656
$\Delta\lambda$ (nm)	40	26	22	26	21	26	20	20

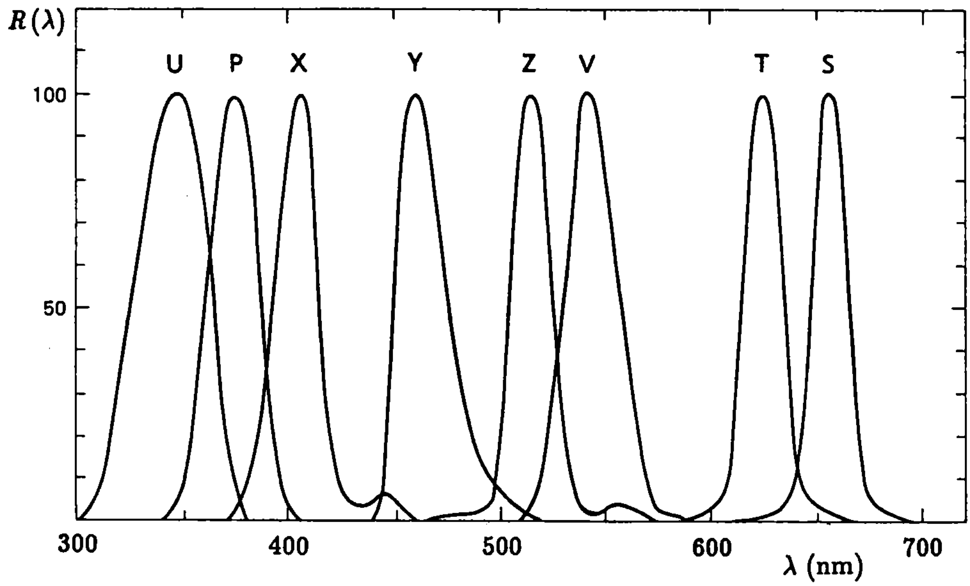

Fig. 17. Response functions of the *Vilnius* photometric system.

All color indices of the system have been normalized to satisfy the condition

$$U - P = P - X = X - Y = Y - Z = Z - V = V - S = T - S = 0$$

for unreddened O-type stars. Since all O-stars are more or less reddened, the normalization constants were derived by subtracting color excesses from color indices of the stars S Mon (O7), 10 Lac (O9), 68 Cyg (O8) and ξ Per (O7) and then averaging their intrinsic color indices. This method of the zero-point definition is rather convenient, as color indices of all normal stars of any spectral type are positive.

Till the end of 1999 more than 10 000 stars have been observed in the *Vilnius* system. Among these stars are bright stars of different spectral types and luminosity classes selected for the calibration of the system, stars in open and globular clusters and associations, field stars in a number of sky areas, metal-deficient subdwarfs, giants and horizontal branch stars, Be, Ap, Am, Ba, CH, R, N, S stars, white dwarfs and other peculiar stars, cepheids, RR Lyrae-type stars, T Tauri-type stars, novae, etc. As the regional standards we use 5–7 mag stars of different spectral types in the Cygnus and Aquila standard regions (Zdanavičius et al. 1969; Zdanavičius & Černienė 1985). Other regional standards are BS stars within 15° from the North Celestial Pole and a number of Kapteyn Selected Areas which contain standards down to V=9 mag (Zdanavičius et al. 1978, Černis 1986, Černis & Jasevičius 1992, Janulis 1996). For the winter sky the Orion standard region has been established (Černis et al. 1998). In 1993–1994, a number of standard stars in the southern hemisphere were measured (Forbes et al. 1993, 1994, 1997; Zdanavičius et al. 1994, 1995). Most of the observations are collected in the general catalogue of stars observed in the *Vilnius* photometric system and its Supplement (Straižys & Kazlauskas 1993, 1998). These catalogs contain lists of all the papers containing observations in the *Vilnius* system.

The accuracy of determination of the physical stellar parameters by *Vilnius* photometry, when the accuracy of photometry is ±0.01 mag, is:

- spectral class: ±0.8 decimal subclass;
- temperature: from ±2000 K for hot stars to ±200 K for cool stars;
- absolute magnitude M_V:
  ±(0.4–0.6) mag for luminosity V–III stars,
  ±(0.8–0.9) mag for supergiants;
- surface gravity $\log g$: ±(0.2–0.5) dex;
- metallicity [Fe/H]: ±(0.15–0.2) dex;
- color excess E_{B-V}: ±(0.02–0.03) mag;
- interstellar extinction A_V: ±0.1 mag;
- distance d: ±25 % for luminosity V–III stars.

For automatic classification of stars several programs are created. For each star they usually use from 7 to 14 various reddening-free Q-parameters.

Table 4. Mean wavelengths and half-widths of passbands of the *Strömvil* photometric system.

	u	P	v	b	Z	y	S
λ_0 (nm)	350	374	411	467	516	547	656
$\Delta\lambda$ (nm)	30	26	19	18	21	23	20

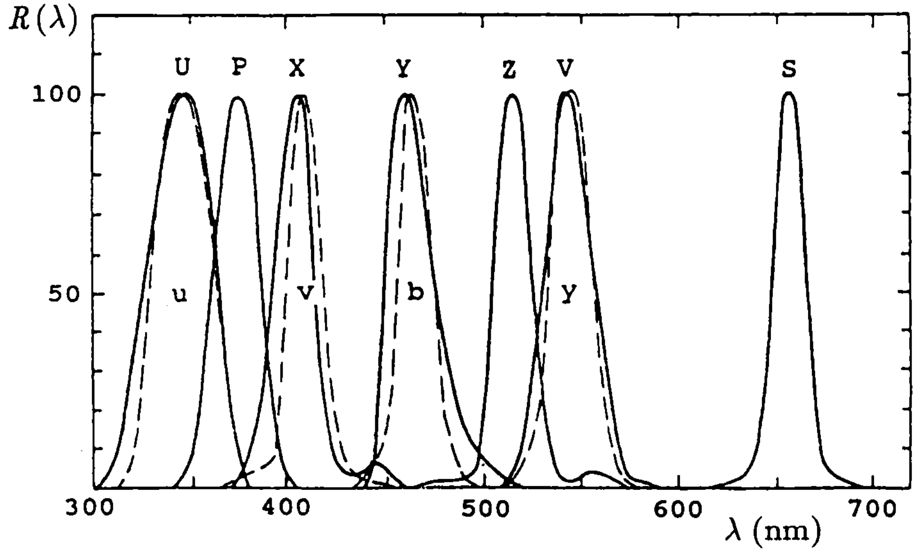

Fig. 18. Comparison of passbands of the *Vilnius* (solid lines) and *Strömgren* (broken lines) photometric systems.

5. THE STRÖMVIL SYSTEM

The *Strömgren* system with the mean wavelengths 350, 411, 467 and 547 nm was introduced for determination of temperatures and luminosities of B–A–F and early G stars and metallicities for A–F–G stars (Strömgren 1963a,b, 1966). Later on, 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 & Mander 1966).

Straižys, Crawford and Philip (1994) have demonstrated, that the addition to the *Strömgren* photometric system of three passbands at 374, 516 and 656 nm from the *Vilnius* system makes the combined *Strömvil* 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 *Strömvil* system is especially important in CCD photometry, since a photometric classification of stars as faint as 20 mag becomes possible (Straižys 1992b). The *Strömvil* 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 *Strömvil* system is as good as the parent systems in determining the metallicities and peculiarities of stars.

The parameters of the passbands of the *Strömvil* system are given in Table 4. Fig. 18 compares the response functions of the *Vilnius* and *Strömgren* photometric systems. A collection of the u,P,v,b,Z,y,S passbands forms the *Strömvil* system.

About 2000 stars have been observed both in the *Vilnius* and the *Strömgren* systems. These stars were used for the investigation of the properties and for the preliminary calibration of photometric parameters of the combined system (Straižys et al. 1996). At present, a program of photoelectric observations of the calibration stars in the *Strömvil* system is in progress. The behavior of peculiar stars in the *Strömvil* system is described by Straižys, Høg and Philip (1997) and Straižys (1999a).

The *Strömvil* system is proposed to be set in the *Gaia* orbiting observatory of ESA planned for launch in 2009 (Straižys & Høg 1995, Høg, Knude & Straižys 1999, Straižys 1999a). For this the response functions of the system were modified to rectangular shape in order to increase the limiting magnitude. Three passbands in the infrared spectrum (at 810, 875 and 938 nm) were added for measuring the height and position of the Paschen jump in early-type stars and for the identification of M-type and carbon-rich stars (Straižys 1998, 1999b).

ACKNOWLEDGMENT. The author is grateful for the support from the Nordic Research Academy for the Nordic-Baltic Research Course in Applied Astrophysical Photometry and from the NATO Scientific and Environmental Affairs Division linkage grant.

REFERENCES

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

Bessell M. S. 1979, PASP, 91, 589

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

Borgman J. 1960, Bull. Astron. Inst. Netherlands, 15, 255

Borgman J. 1963, Bull. Astron. Inst. Netherlands, 17, 58

Černis K. 1986, Bull. Vilnius Obs., No. 75, 31

Černis K., Bartašiūtė S., Straižys V., Janulis R. 1998, Baltic Astronomy, 7, 625

Černis K., Jasevičius V. 1992, Baltic Astronomy, 1, 168

Cousins A. W. J. 1976, Mem. RAS, 81, 25

Cousins A. W. J. 1978, Monthly Notes Astron. Soc. South Africa, 37, 8

Cousins A. W. J. 1980, Circ. South African Astron. Obs., No. 5, 234

Crawford D. L., Mander J. 1966, AJ, 71, 114

Forbes M. C., Dodd R. J., Sullivan D. J. 1993, Baltic Astronomy, 2, 246

Forbes M. C., Dodd R. J., Sullivan D. J. 1994, Baltic Astronomy, 3, 227

Forbes M. C., Dodd R. J., Sullivan D. J. 1997, Baltic Astronomy, 6, 371

Høg E., Knude J., Straižys V. 1999, Specification of Gaia Photometric Systems, Document SAG-CUO-58 of February 11, 1999

Janulis R. 1996, Baltic Astronomy, 5, 149

Johnson H. L. 1952, ApJ, 116, 272

Johnson H. L. 1965, ApJ, 141, 923

Johnson H. L., Mitchell R. I. 1962, Comm. Lunar and Planetary Laboratory, Univ. of Arizona, 1, 73

Johnson H. L., Morgan W. W. 1953, ApJ, 117, 313

Khaliullin Kh., Mironov A. V., Moshkalyov V. G. 1985, Ap&SS, 111, 291

Kornilov V. G., Krylov A. V. 1990, AZh, 67, 173

Kornilov V. G., Volkov I. M., Zakharov A. I., Kozyreva V. S., Kornilova L. N., Krutjakov A. N., Krylov A. V., Kusakin A. V., Leontiev S. E., Mironov A. V., Moshkaliov V. G., Pogrosheva T. M., Sementsov V. N., Khaliullin Kh. F. 1991, Catalog of WBVR magnitudes of bright stars of the Northern sky, Trudy Astron. Inst. Sternberg, Moscow University Publ. House, Vol. 63

Kron G. E., Smith J. L. 1951, ApJ, 113, 324

Kron G. E., White H. S., Gascoigne S. C. B. 1953, ApJ, 118, 502

Meistas E., Zdanavičius K., Straižys V., Gurklytė A. 1975, Bull. Vilnius Obs., No. 42, 3

Mironov A. V., Moshkalev V. G., Khaliullin Kh. F. 1984, Astron. Circular, Moscow, No. 1351, 1

Moshkalev V. G., Khaliullin Kh. F. 1985, AZh, 62, 393 = Soviet Astron., 29, 227
Stebbins J., Whitford A. E. 1943, ApJ, 98, 20
Straižys V. 1963, Bull. Vilnius Obs., No. 6, 1
Straižys V. 1964a, AZh, 41, 750 = Soviet Astron., 8, 596
Straižys V. 1964b, Bull. Vilnius Obs., No. 11, 11
Straižys V. 1965, Bull. Vilnius Obs., No. 15, 3
Straižys V. 1973, A&A, 28, 349
Straižys V. 1977, *Multicolor Stellar Photometry*, Mokslas Publishers, Vilnius, Lithuania
Straižys V. 1983, Bull. Inform. CDS, No. 25, 41
Straižys V. 1992a, *Multicolor Stellar Photometry*, Pachart Publishing House, Tucson, Arizona
Straižys V. 1992b, Baltic Astronomy, 1, 107
Straižys V. 1998, Baltic Astronomy, 7, 571
Straižys V. 1999a, Baltic Astronomy, 8, 109
Straižys V. 1999b, Baltic Astronomy, 8, 489
Straižys V., Crawford D. L., Philip A. G. D. 1996, Baltic Astronomy, 5, 83
Straižys V., Høg E. 1995, in *Proceedings of a joint RGO-ESA Workshop on Future Possibilities for Astrometry in Space*, Cambridge, ESA SP-379, p. 191
Straižys V., Høg E., Philip A. G. D. 1997, in *Proceedings of the ESA Symposium Hipparcos-Venice 97*, ESA SP-402, p. 761
Straižys V., Kazlauskas A. 1993, Baltic Astronomy, 2, 1
Straižys V., Kazlauskas A. 1998, Supplement to the General Photometric Catalogue of Stars Observed in the Vilnius System, unpublished
Straižys V., Kurilienė G. 1981, Bull. Vilnius Obs., No. 56, 25
Straižys V., Zdanavičius K. 1965, Bull. Vilnius Obs., No. 14, 3
Straižys V., Zdanavičius K. 1970, Bull. Vilnius Obs., No. 29, 15
Strömgren B. 1963a, in *Basic Astronomical Data*, ed. K. A. Strand, Univ. of Chicago Press, p. 123
Strömgren B. 1963b, QJRAS, 4, 8
Strömgren B. 1966, Ann. Rev. Astron. Astrophys., 4, 433
Vansevičius V., Straižys V. 1994, Baltic Astronomy, 3, 426
Zdanavičius K. 1975, Bull. Vilnius Obs., No. 41, 3
Zdanavičius K., Černienė E. 1985, Bull. Vilnius Obs., No. 69, 3
Zdanavičius K., Claria J. J., Piatti A. E., Straižys V. 1994, Baltic Astronomy, 3, 217
Zdanavičius K., Dodd R. R., Forbes M. C., Sullivan D. J. 1995, Baltic Astronomy 4, 25

Zdanavičius K., Gurklytė A., Sūdžius J., Jasevičius V., Kazlauskas A. 1978, Bull. Vilnius Obs., No. 49, 3

Zdanavičius K., Straižys V. 1964, Bull. Vilnius Obs., No. 11, 1

Zdanavičius K., Sūdžius J., Sviderskienė Z., Straižys V., Burnashev V., Drazdys R., Bartkevičius A., Kakaras G., Kavaliauskaitė G., Jasevičius V. 1969, Bull. Vilnius Obs., No. 29, 3