

## STELLAR PHOTOMETRY AT THE CROSSROADS OF THE TWO CENTURIES

V. Straizys

*Institute of Theoretical Physics and Astronomy, Vilnius University,  
Goštauto 12, Vilnius, LT-01108, Lithuania*

Received November 15, 2003.

**Abstract.** In the last century photometry was recognized as a powerful method for investigation of physical parameters of stars and of interstellar matter. Photometric investigations now cover the spectral range from the far ultraviolet to the far infrared. The article describes the most important landmarks in development of photometric classification of stars and the number of photometric survey projects accomplished by ground-based and space telescopes and including millions of point sources. The success of the future LSSD and Gaia projects will depend on the use of optimum photometric passbands.

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

### 1. INTRODUCTION

Since Hipparchus (180–125 BC), the magnitude of a star alongside with its coordinates served the only purpose of simplifying the identification of the star on the celestial sphere. However, at the beginning of the 20th century astronomers understood that the radiation of stars is a physical quantity which bears much more information. For example, it was realized that a comparison of the radiation intensity of a star in two spectral regions (colors) can give its temperature. This fact stimulated appearance of the first two-color photometric systems. The necessity to get more information has led to an increase of the number of measured spectral passbands and to narrowing of their widths. The result was a great variety of

currently existing photometric systems for photometric classification and quantification of stars (see Moro & Munari 2000). The systems have very different capabilities in determining physical parameters of stars, each system being most effective in certain temperature and luminosity ranges. Some of them are more or less capable of eliminating interstellar reddening effects. Photometric systems can contain from one to more than ten passbands.

Strömgren (1963a) has introduced the classification of systems in broad-band, medium-band and narrow-band systems. In this review we will use somewhat revised band-widths. 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 narrow-band systems  $\Delta\lambda < 10$  nm. The systems with  $\Delta\lambda > 100$  nm sometimes are called super-broad-band systems.

The author is not ready to give here an exhaustive review of astronomical photometry. Instead of this, the main landmarks in the development of stellar photometry will be given, together with some prospects for the near future. A detailed historical description of the main photometric systems is given in author's monograph "Multicolor Stellar Photometry" (Straizys 1992).

## 2. THE FIRST TWO-COLOR PHOTOMETRIC SYSTEMS

The pioneers of two-color photometry were Schwarzschild (1912), Parkhurst (1912) and King (1915). They made series of observations of the photographic magnitudes  $m_{pg}$  which, combined with the visual magnitudes  $m_V$  or with the photovisual magnitudes  $m_{pv}$ , formed a two-color system or one color index. Subsequent work by Edward Pickering and Henrietta Leavitt at Harvard, as well as by Frederick Seares at Mount Wilson, led to the establishment of the standard North Polar Sequence (NPS) which contained nearly one hundred stars of various spectral types covering the magnitude range from 2.5 to 20. The list of standard magnitudes of these stars was confirmed at the 1st IAU General Assembly in 1922 as the International  $IPg$ ,  $IPv$  system (Seares 1922). 206 Kapteyn Selected Areas (SA) taken around the sky at every  $15^\circ$  in declination and every 1 h in right ascension served as secondary standards of the International system (Seares, Kapteyn & van Rhijn 1930). In the Southern hemisphere, R. H. Stoy, J. W. Menzies and A. W. J. Cousins established a similar system called  $SPg$ ,  $SPv$  (see the review by Stoy (1956)).

However, the photographic photometry obtained in these pioneering works was of low accuracy. A photographic emulsion is a very non-linear light detector, and the sensitivity variations across the plate surface are of the order of 5%. Additionally, there are difficult problems with the tie-up to standard areas and the account of the variable atmospheric extinction. Therefore, later it was realized that the magnitude scale of the International system contained considerable systematic errors – the non-linearity of the magnitude scale was up to 0.2 mag among the brightest and the faintest stars. Also, the magnitudes and color indices were affected by systematic errors in the transformation process of instrumental magnitudes of different observers to the standard system due to non-linearity and luminosity dependence of the equations.

### 3. THE FIRST PHOTOELECTRIC SYSTEMS

Photoelectric photometry makes it possible to measure the star brightness with an accuracy of 1%, if the atmospheric extinction and its variations are taken into account. This method appeared at the beginning of the 20th century, at once after the sufficiently sensitive photoelements were invented (Stebbins 1910, Guthnik 1913). At first, only the brightest stars in integrated light were accessible. In 1924 with a 38 cm refractor Stebbins (1928) was able to observe the stars as faint as 7th mag. Since then and until the appearance of photomultipliers the sensitivity of potassium photoelements remained more or less constant. In the period between 1920 and 1940, hundreds of stars were measured photoelectrically in a number of two-color photometric systems. Unfortunately, each of these works was made in its own system with somewhat different response functions. Therefore, at present these numerous observations are only of historical interest.

Stebbins & Whitford (1938, 1948), Eggen (1950, 1951), Johnson (1950), Stebbins, Whitford & Johnson (1950) made attempts to set up the International system photoelectrically. Since 1947, instead of photoelements, very sensitive RCA 1P21 photomultipliers came into use. For some period the two-color system of Stebbins, Whitford and Johnson, named as the  $P,V$  system, was most popular. However, this system was soon also abandoned due to transformation difficulties. Observations of various authors in the system were found to show non-linear color equations (Johnson 1952, 1955) caused by inclusion

of different amounts of ultraviolet radiation into the  $P$  response function. Kron & Smith (1951) introduced a two-color system with the passbands in the red ( $R$ ) and infrared ( $I$ ) spectral regions. Sometimes the  $PV$  and the  $RI$  systems were considered as parts of one four-color system.

Two-color systems gave the possibility to form a color index and to estimate stellar temperatures. It was expected that the color index must be a function of spectral class. However it was found that for the stars of the same spectral class color indices are very different, especially for O- and B-type stars; this confirmed the presence of interstellar reddening and extinction.

#### 4. THREE-COLOR PHOTOMETRY

The first three-color photometric system, later named as the  $RGU$  system, was introduced by Becker (1938, 1942, 1946). When selecting the positions of response functions of the system, Becker already knew about approximate energy distributions in stellar spectra of different spectral classes and the interstellar extinction law. Unfortunately, the system was set up by photographic techniques, and the accuracy of photometry was rather low.

Becker was the first to apply three-color photometry in the study of open clusters. He introduced the ultraviolet passband shortwards from the Balmer jump and showed its usefulness for the classification of B–A–F type stars. He proposed a new method to determine cluster reddening and photometric distances (Becker 1951). As early as in 1938 Becker suggested a “color-difference” method which is a prototype of the currently known “Q-method”. To determine cluster reddening, Becker used a diagram in which the parameter  $(U - G) - \alpha(G - R)$  is plotted against  $G - R$ . Becker’s idea was to select the positions of his passbands so as to have  $\alpha=1$ . In this case a difference of color indices turns into an interstellar reddening-free parameter. However, the attempt was not successful. Therefore, since 1947 Becker and his group used the parameter  $(U - G) - 1.18(G - R)$  where the factor 1.18 has been derived accepting the  $\lambda^{-1}$  interstellar extinction law. However, this assumption was not correct: the value of the coefficient should be 0.70 to obtain the really reddening-free parameter.

Despite the difficulties with interstellar reddening, Becker was the first who found a way for determining stellar luminosities from

their three-color photometry. Approximately at the same time for luminosity determination of early-type stars Barbier & Chalonge (1939, 1941) applied a spectrophotometric method which uses two gradients of energy distribution on both sides from the Balmer jump and the position of the jump.

The definition of the interstellar reddening-free  $Q$ -parameter was first introduced by Johnson & Morgan (1953) in the  $UBV$  system:

$$Q_{UBV} = (U - B) - (E_{U-B}/E_{B-V})(B - V),$$

where the ratio of color excesses slightly depends on intrinsic color indices and color excesses (Ažusienis & Straižys 1966). This parameter is extremely useful in photometric classification of stars, and it is in use in many photometric systems.

The  $UBV$  system soon became the dominant among all broad-band systems. It appeared to be very useful for the investigation of photometric effects of temperature, luminosity, age, metallicity and axial rotation. Namely,  $UBV$  photometry of F–G subdwarfs has been used for the first photometric determination of metallicity blanketing and metallicity (Morgan et al. 1953, Roman 1954). Hundreds of open and globular clusters, associations, stellar areas and tens of thousands of separate stars have been measured in the system.

However, from the beginning the  $UBV$  system suffered from the ill-defined ultraviolet magnitude. The main shortcoming was the incorrect transformation of  $U-B$  to outside the atmosphere, neglecting the dependence of the extinction coefficient on temperature, luminosity and interstellar reddening. The response function of the system has been changed in the process of measurements of the standard stars, and the transformation to the unique system was affected by non-linearity errors. These and other drawbacks of the system were investigated and described by Ažusienis & Straižys (1969) and Straižys (1973, 1977, 1983, 1992). The corrected  $WBVR$  system was tested by Meistas et al. (1975). Almost 14 000 stars in the  $WBVR$  system were measured by Kornilov et al. (1991).

## 5. BROAD-BAND MULTICOLOR SYSTEMS

The first really multicolor system was introduced by Stebbins & Whitford (1943). It contained six broad passbands with the mean

wavelengths at 353, 422, 488, 570, 719 and 1030 nm. For a long time this was the only multicolor system in use, therefore, it is related to several important discoveries. This system enabled astronomers to investigate with photoelectric accuracy the interstellar reddening law in various areas of the Milky Way (Stebbins & Whitford 1943, 1945). Günther (1950) made a detailed analysis of the two-color  $U - B$ ,  $B - I$  diagram and investigated the effect of the Balmer jump and interstellar reddening. Nikonov (1954) was the first to show the possibility of photometric classification of B-type stars in this system. Kron (1958, 1960) applied the system for the classification of F–G supergiants. The red and infrared color indices were found useful for the photometric determination of the effective temperatures of stars. The ultraviolet and violet color indices have been used for evaluation of the blanketing and metallicities of F–G–K stars. However, the shortcoming of the system was in its great widths and the overlapping of passbands: it gave only a coarse representation of the spectral energy distribution. With the introduction of a more advanced  $UBVRI$  system, the Stebbins-Whitford system lost its former significance.

In 1962–1965 Harold Johnson and his group at the University of Arizona supplemented the  $UBV$  system by nine red and infrared passbands  $R$ ,  $I$ ,  $J$ ,  $H$ ,  $K$ ,  $L$ ,  $M$ ,  $N$  and  $Q$  covering spectral range from 0.7 to 20  $\mu\text{m}$  (see references in Straižys 1992). Later the passbands of the Arizona system were changed many times. Instead of Johnson's  $R$  and  $I$ , the modified and better defined passbands  $R_C$  and  $I_C$  were introduced by Cousins (1976, 1978, 1980). The infrared passbands at longer wavelengths were revised by Young et al. (1994). Actually, a variety of broad-band infrared systems exists, but color indices of most of them are inter-transformable.

## 6. NARROW- AND MEDIUM-BAND MULTICOLOR SYSTEMS

Broad-band photometric systems make it possible to measure both bright and faint stars, but their information content is rather low. They are insensitive to individual spectral lines, bands or small intensity jumps in the continuous spectrum. Consequently, the usefulness of broad-band photometry for classification of stars is rather limited. In this respect most informative are the narrow-band systems.

The pioneers of narrow-band photometry are Bengt Strömgren and Kjeld Gyldenkerne who in 1950 started test observations of stars through 26 narrow-band ( $\Delta\lambda$  between 8 and 12 nm) interference filters. Since then tens of different narrow-band photometric systems have been used. They are listed in Tables 55 and 56 of the Straižys (1992) monograph. Different color indices or their combinations of the systems usually are used for the determination of temperatures, absolute magnitudes, gravities, element abundances, emission-line strengths and other physical parameters of stars. However, narrow-band systems suffer from the low penetrating power (limiting magnitude).

Medium-band systems with  $\Delta\lambda$  between 10 and 50 nm are most useful for the photometric classification of stars. Their information content is sufficiently high, and they can reach sufficiently faint stars even with telescopes of moderate size. The first medium-band multicolor systems were proposed at the beginning of 1960s: the five-color *Walraven* system (Walraven & Walraven 1960), the seven-color *Borgman* system (Borgman 1960, 1963), the four-color *Strömgren* system (Strömgren 1963a,b, 1964, 1966), the seven-color *Geneva* system (Golay 1963) and the seven-color *Vilnius* system (Straižys 1963, 1964a,b, 1965; Straižys & Zdanavičius 1965; Zdanavičius & Straižys 1964). The *Walraven* and the *Geneva* systems were not completely medium-band systems: they contained also some broad passbands.

## 7. THE VILNIUS SYSTEM

The selection of passbands of the *Vilnius* system was based on energy distribution functions of stars of various spectral and luminosity classes obtained by the photoelectric scanning method. Willstrop (1965) provided his extensive energy distribution catalog before publication. The interstellar reddening law was taken from Whitford (1958). From the beginning we tried to find a minimum number of passbands which would give two-dimensional classification (temperature and luminosity) of stars situated on all sequences of the HR diagram. The selection of optimum passbands was based on the synthetic two-color and  $Q, Q$  diagrams, by varying positions, widths and shapes of the response functions. The details of the selection process are described in Straižys (1977, 1992, 1999b).

The *Vilnius* system contains seven passbands with the mean wavelengths and half-widths listed in Table 1. These passbands are

**Table 1.** Mean wavelengths and half-widths of passbands of the *Vilnius* photometric system (with *T* passband).

| Passband             | <i>U</i> | <i>P</i> | <i>X</i> | <i>Y</i> | <i>Z</i> | <i>V</i> | <i>T</i> | <i>S</i> |
|----------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| $\lambda_0$ (nm)     | 345      | 374      | 405      | 466      | 516      | 544      | 625      | 656      |
| $\Delta\lambda$ (nm) | 40       | 26       | 22       | 26       | 21       | 26       | 20       | 20       |

sufficient to determine spectral classes and absolute magnitudes of single stars of the main spectral classes of solar chemical composition, in the presence of various amounts of interstellar reddening. Together with two-dimensional classification, the interstellar reddening and extinction for each star can be obtained.

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

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

Additionally, the system makes it possible to identify many types of peculiar stars, including F–G–K subdwarfs, G–K metal-deficient giants, white dwarfs, Ap, Am, carbon, barium and CH stars, emission-line stars of the types Be, Herbig Ae/Be, T Tauri, WR, many types of unresolved binaries.

The *Vilnius* photometric system is capable of classifying any collection of single stars without additional information from their spectra. These stars may be of different temperatures, luminosities, metallicities, O/C ratios, most types of peculiarities, and affected by different amounts of interstellar extinction. This property of the system makes possible its use for investigation of stellar population in

the distant and dusty parts of the Galaxy. Till the end of 2003 about 10 000 stars have been observed with photoelectric photometers and about 2000 stars by CCD detectors. Among them there are bright stars of different spectral and luminosity classes for calibration of the system, stars in open and globular clusters and associations, metal-deficient F–G–K subdwarfs, subgiants and giants, horizontal-branch stars, carbon and barium stars, white dwarfs, emission-line stars (Be, Ae/Be, T Tauri stars), peculiar and metallic-line A stars, cepheids and RR Lyrae type stars, novae. A number of sky areas containing dust and molecular clouds have been investigated.

## 8. OTHER VARIETIES OF THE VILNIUS SYSTEM

The *Vilnius* and the *Geneva* systems have some passbands with close positions. After some theoretical investigation at both observatories it was decided to propose the new *VILGEN* system consisting of the four passbands from the *Vilnius* system and three passbands of the *Geneva* system. This system had the same star classification properties as both original systems. At the same time it had a fainter limiting magnitude due to broader passbands. Description of the *VILGEN* system, its preliminary intrinsic color indices and its calibration in terms of spectral types and absolute magnitudes was given by Straizys et al. (1982). Peculiar stars in the *VILGEN* system were investigated by North et al. (1982).

Another joint system, the *Strömvil* system, consisting of four passbands from Strömgren's *uvby* system and three passbands from the *Vilnius* system was proposed by Straizys, Crawford & Philip (1996). The properties of the system are as good as of the parent systems in classifying normal stars of different spectral types, in determining metallicities and peculiarities of stars. The calibration of the *Strömvil* system in terms of temperatures, absolute magnitudes and gravities is described by Kazlauskas et al. (2003) in the present publication.

The *Strömvil* system was proposed for the *Gaia* orbiting observatory of ESA planned for launch in 2010–2012 (Straizys & Høg 1995, Høg et al. 1999, 2000a,b). For this project the response functions 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 (Straizys 1998, 1999a).

## 9. PHOTOMETRIC SKY SURVEYS

At the end of the 20th century a number of photometric sky surveys in different spectral ranges were accomplished or progressing. Here is their short description.

1. *The Hipparcos-Tycho survey*. Photoelectric  $B$  and  $V$  magnitudes of 1 million stars down to 12 mag were measured by the *Tycho* photometer aboard the *Hipparcos* orbiting observatory of ESA. Unfortunately, the *Tycho* filters differed from the standard  $B$  and  $V$  filters, and the transformation to the standard system was multivalued. The accuracy of color indices is 0.02 mag down to  $V = 9$ . For fainter stars the accuracy is much lower.

2. *The Digital Palomar Observatory Sky Survey* (DPOSS, Djorgovski et al. 1998). This survey is based on the POSS-II photographic sky atlas. The survey covers the entire sky north of  $\delta = -3^\circ$  in three passbands photographed with J (blue-green), F (red) and N (near infrared) plates. Typical limiting magnitudes reached are  $B_J \sim 22.5$ ,  $R_F \sim 20.8$  and  $I_N \sim 19.5$ . The photographic magnitudes are calibrated to the Gunn  $g,r,i$  CCD system. The survey contains about 2 billion stars and 50 million galaxies. The accuracy of magnitudes is of the order of 0.05–0.10 mag.

3. *The SuperCosmos Sky Survey* (SSS). The extension of the DPOSS to the southern declinations. SSS is based on the scanned photographic plates of the UKST blue (J), red (F) and infrared (N) surveys, the ESO red (F) survey and the POSS-I red (E) survey.

4. *The Sloan Digital Sky Survey* (SDSS). The CCD sky survey in five broad passbands  $u,g,r,i,z$  with the mean wavelengths 355, 477, 623, 762 and 913 nm on the 2.5 meter telescope at the Apache Point Observatory. 100 million objects with Galactic latitude  $>30^\circ$  will be measured down to 23 mag in the  $g$  passband. The project will be finished in 2005.

5. *The infrared IRAS and COBE/DIRBE surveys*. In 1983, photometry of 350 000 point sources has been done with a 60 cm telescope on the IRAS orbiting observatory in the broad passbands at 12, 25, 60 and 100  $\mu\text{m}$ . Additionally, IRAS has made the full-sky maps of the diffuse background radiation in the same four passbands.

The IR point sources and the diffuse background were also observed in 10 infrared passbands (between 1.25 and 240  $\mu\text{m}$ ) with the DIRBE radiometer on the COBE orbiting observatory in 1989–1991. Both surveys of the infrared background at 100–240  $\mu\text{m}$  are very useful for investigation of dust distribution in the Galaxy, since the emission intensity map may be converted to a map of the dust column density (Schlegel et al. 1998).

6. *The infrared 2MASS survey.* A photometric survey of all-sky objects in the  $J$ ,  $H$  and  $K$  passbands with two 1.3 meter telescopes at Mount Hopkins and Cerro Tololo observatories (1997–2001). The  $3\sigma$  limiting magnitudes are 17.1 mag at  $J$  and 16.4 mag at  $H$ . The final catalog contains 300 million stars and more than 1 million galaxies.

7. *The infrared DENIS survey.* A photometric survey of the southern hemisphere in the  $I$ ,  $J$  and  $K$  passbands with a 1 meter telescope of ESO (1996–2001). The limiting magnitudes are 18.5, 16.5 and 14.0 in the  $I$ ,  $J$  and  $K$  passbands, respectively. The final catalog contains 195 million point sources.

Most of the listed sky surveys are included in the Internet's Virtual Telescope SkyView of NASA Goddard Space Flight Center (<http://skyview.gsfc.nasa.gov>).

Two important sky surveys are in the project stage:

1. *The LSST Observatory project.* The Large-Aperture Synoptic Survey Telescope (LSST) will be a 8.4 meter survey telescope with a field diameter of 55 cm covered by CCDs (2.3 billion pixels). With a focus length of 10 m the angular diameter of the field is  $3^\circ$ , and its area is 7 square degrees. The filters (60 cm diameter) will set up the  $UBVRI$  system and some medium-band systems. In a run of 3–4 clear nights the fast-slewing telescope will be used to survey the entire visible sky to a limiting magnitude of  $V = 24$  and  $I = 23$ . Alternatively, in 50 hours of observation five color images of a single 7 square degree field could be made to limiting magnitudes  $U = 26.7$ ,  $B = 27.8$ ,  $V = 27.9$ ,  $R = 27.6$  and  $I = 26.8$ . The first light of the telescope is planned for 2011.

2. *The Gaia project.* The astronomical satellite *Gaia* of ESA will contain two telescopes of light collecting area of  $1.4 \times 0.5$  m for astrometry and broad-band photometry, and one telescope of  $0.5 \times 0.5$  m for spectroscopy and medium-band photometry. The photometric systems are not fixed yet, but it is planned that the broad-band system will have 5 passbands and the medium-band system –

about 10 passbands. Among the candidate medium-band systems is the *Strömvil* system supplemented by three infrared passbands (see in Section 8). About 1 billion stars are planned for observation during the five-year period. The success of the project highly depends on the optimum photometric systems set up in the satellite.

## REFERENCES

- Ažusienis A., Straizys V. 1966, Bull. Vilnius Obs., No. 18, 3
- Ažusienis A., Straizys V. 1969, AZh, 46, 402 = Soviet Astron., 13, 316
- Barbier D., Chalonge D. 1939, Ann. d'Astrophys., 2, 254
- Barbier D., Chalonge D. 1941, Ann. d'Astrophys., 4, 30
- Becker W. 1938, Z. f. Astrophys., 15, 225
- Becker W. 1942, Astron. Nachrichten, 272, 179
- Becker W. 1946, Veröff. Sternw. Göttingen, Nos. 79–81
- Becker W. 1951, Z. f. Astrophys., 29, 66
- Borgman J. 1960, Bull. Astron. Inst. Netherlands, 15, 255
- Borgman J. 1963, Bull. Astron. Inst. Netherlands, 17, 58
- Cousins A. W. J. 1976, Mem. RAS, 81, 25
- Cousins A. W. J. 1978, Monthly Notes ASSA, 37, 8
- Cousins A. W. J. 1980, Circ. SAAO, N0. 5, 234
- Djorgovski S. G., Gal R. R., Odewahn S. C. et al. 1998, in *itl Wide Field Surveys in Cosmology*, 14th IAP Meeting, Paris, eds. S. Colombi & Y. Mellier, Editions Frontiers, p. 89 = LANL astro-ph/9809187
- Eggen O. J. 1950, ApJ, 111, 65, 81 and 414; 112, 141
- Eggen O. J. 1951, ApJ, 113, 367 and 657
- Golay M. 1963, Publ. Obs. Geneve, No. 64, 419
- Günther S. 1950, Z. f. Astrophys., 27, 167
- Guthnik P. 1913, Astron. Nachrichten, 196, 357
- Høg E., Knude J., Straizys V. 1999, *Specification of Gaia Photometric Systems*, GAIA Internal Report SAG-CUO-58, February 11, 1999
- Høg E., Knude J., Straizys V. 2000a, *A new photometric system (2G)*, GAIA Internal Report SAG-CUO-72, April 13, 2000
- Høg E., Straizys V., Vansevičius V. 2000b, *The 3G photometric system*, GAIA Internal Report SAG-CUO-78, August 29, 2000
- Johnson H. L. 1950, ApJ, 112, 240
- Johnson H. L. 1952, ApJ, 116, 272

- Johnson H. L. 1955, *Ann. d'Astrophys.*, 18, 292
- Johnson H. L., Morgan W. W. 1953, *ApJ*, 117, 313
- King E. S. 1915, *Ann. Harvard Obs.*, 76, 107
- Kornilov V. G., Volkov I. M., Zakharov A. I. et al. *Catalog of WBVR magnitudes of bright stars of the Northern sky*, Trudy Astron. Inst. Sternberg, Moscow University Publ. House, Vol. 63
- Kron G. E. 1958, *PASP*, 70, 561
- Kron G. E. 1960, *Vistas in Astron.*, 3, 171
- Kron R. G., Smith J. L. 1951, *ApJ*, 113, 324
- Meištas E., Zdanavičius K., Straizys V., Girklytė A. 1975, *Bull. Vilnius Obs.*, No. 42, 3
- Morgan W. W., Harris D. L., Johnson H. L. 1953, *ApJ*, 118, 92
- Moro D., Munari U. 2000, *A&AS*, 147, 629
- Nikonov V. B. 1954, *Izvestija Crimean Obs.*, 12, 134
- North P., Hauck B., Straizys V. 1982, *A&A*, 108, 373
- Parkhurst J. A. 1912, *ApJ*, 36, 169
- Roman N. 1954, *AJ*, 59, 307
- Schlegel D. J., Finkbeiner D. P., Davis M. 1998, *ApJ*, 500, 525
- Schwarzschild K. 1912, *Abhandl. Königl. Ges. d. Wiss. zu Göttingen*, 8, No. 4
- Seares F. H. 1922, *Trans. IAU*, 1, 69
- Seares F. H., Kapteyn J. C., van Rhijn P. J. 1930, *Mount Wilson Catalogue of Photographic Magnitudes in SA 1-139*
- Stebbins J. 1910, *ApJ*, 32, 185
- Stebbins J. 1928, *Publ. Washburn Obs.*, 15, 3
- Stebbins J., Whitford A. E. 1938, *ApJ*, 87, 237
- Stebbins J., Whitford A. E. 1943, *ApJ*, 98, 20
- Stebbins J., Whitford A. E. 1945, *ApJ*, 102, 318
- Stebbins J., Whitford A. E. 1948, *ApJ*, 108, 413
- Stebbins J., Whitford A. E., Johnson H. L. 1950, *ApJ*, 112, 469
- Stoy R. H. 1956, *Vistas in Astron.*, 2, 1099
- Straizys V. 1963, *Bull. Vilnius Obs.*, No. 6, 1
- Straizys V. 1964a, *AZh*, 41, 750 = *Soviet Astron.*, 8, 596
- Straizys V. 1964b, *Bull. Vilnius Obs.*, No. 11, 11
- Straizys V. 1965, *Bull. Vilnius Obs.*, No. 15, 3

- Straizys V. 1973, A&A, 28, 349
- Straizys V. 1977, *Multicolor Stellar Photometry*, Mokslas Publishers, Vilnius, Lithuania
- Straizys V. 1983, Bull. Inform. CDS, No. 25, 41
- Straizys V. 1992, *Multicolor Stellar Photometry*, Pachart Publishing House, Tucson, Arizona
- Straizys V. 1998, Baltic Astronomy, 7, 571
- Straizys V. 1999a, Baltic Astronomy, 8, 489
- Straizys V. 1999b, Baltic Astronomy, 8, 505
- Straizys V., Crawford D. L., Philip A. G. D. 1996, Baltic Astronomy, 5, 83
- Straizys 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
- Straizys V. Jodinskienė E., Hauck B. 1982, Bull Vilnius Obs., No. 60, 50
- Straizys V., Zdanavičius K. 1965, Bull. Vilnius Obs., No. 14, 3
- Strömberg B. 1963a, in *Basic Astronomical Data*, ed. K. A. Strand, Univ. of Chicago Press, p. 123
- Strömberg B. 1963b, QJRAS, 4, 8
- Strömberg B. 1964, Astrophysica Norvegica, 9, 333
- Strömberg B. 1966, Ann. Rev. Astron. Astrophys., 4, 433
- Walraven T., Walraven J. H. 1960, Bull. Astron. Inst. Netherlands, 15, 67
- Whitford A. E. 1958, AJ, 63, 201
- Willstrop R. V. 1965, Mem. RAS, 69, 83
- Young A. T., Milone E. F., Stagg C. R. 1994, A&AS, 105, 259
- Zdanavičius K., Straizys V. 1964, Bull. Vilnius Obs., No. 11, 1