Baltic Astronomy, vol. 7, 513–524, 1998.

FOUR-CHANNEL STELLAR PHOTOMETER WITH DICHROIC BEAM-SPLITTERS

V. G. Kornilov

Sternberg Astronomical Institute, Moscow University,
Universitetskij Prospect 13, Moscow 119899, Russia

Received April 27, 1998.

Abstract. An optical design of a four-channel *WBVR* photometer based on dichroic mirrors is described. The key properties of dichroic mirrors and features of beam-splitters used are considered. Under certain conditions, the *WBVR* photometric system with characteristics very close to the standard system can be set up. Polarization effects in the photometer are investigated.

Key words: instrumentation: stellar photometer – *WBVR* photometric system

1. INTRODUCTION

A four-channel stellar photometer with beam splitting to four channels by semitransparent aluminum films was described by Kornilov & Krylov (1990). This device has been designed for multicolor photometric measurements of bright (down to 8–9 mag) stars. A photometric survey of bright northern stars was carried out using this device during 1985–1989 at the Tien-Shan Observatory of the Sternberg Astronomical Institute (Kornilov et al. 1991).

The design of this photometer was used to construct a four-channel stellar photometer with beam-splitters based on dichroic mirrors. The dichroic mirror is a multilayer dielectric structure which reflects almost completely the radiation with wavelengths shorter than a certain λ_s (light splitting boundary) and transmits all the remaining light. A combination of such mirrors makes possible to direct almost all the radiation of some spectral range to a corresponding photometric channel. In this case the photometer is suitable for simultaneous multicolor observations of faint astronomical objects. The advantages of simultaneous measurements in a few spectral bands were discussed earlier (Serkowski 1970, Zdanavičius et al. 1978).

A prototype of such a photometer was constructed during 1988–1989, and three operating devices have been produced. The first test observations with one of these four-channel photometers were made on the Zeiss-600 telescope of the Maidanak Observatory in 1992. From 1994, regular photometric observations with the second instrument have been carried out at the Tien-Shan Observatory (Kusakin & Mkrtichian 1996, Goransky et al. 1998).

Fig. 1 shows the results of observations of the star SAO 94526 ($V \approx 5.1$ mag, G0) during its occultation by the Moon. The photometric measurements were carried out with the third sample of the photometer on the 0.7 m telescope in Moscow (Zaitsev et al. 1998).

In this paper we explain the features of dichroic beam-splitters and the optical layout of the four-channel photometers. We also present some investigations of this instrumentation. At the beginning, some basic properties and features of light transmission and reflection by multilayer dielectric structures will be reviewed.

2. BASIC FEATURES OF A DICHROIC MIRROR

A dichroic mirror is a structure consisting of alternative thin dielectric films with high and low refractive indices evaporated on a transparent base in vacuum. In fact, it is the same dielectric mirror which is used in interference filters and Fabry-Perot interferometers but for a wider spectral band including the maximum reflection range (as in the case of dielectric mirror) and the adjacent maximum transmission range.

A typical spectral reflectivity function $R(\lambda)$ for a dichroic mirror is shown in Fig. 2. The main feature of this curve is a certain wavelength λ_s at which $R(\lambda)$ falls down sharply and remains low at longer wavelengths. (It is possible to produce a dichroic mirror with the opposite behavior of $R(\lambda)$, but such a mirror has worse characteristics). On the other hand, the transmittance function $T(\lambda)$ increases sharply at this wavelength. This boundary can be more definitely determined from the condition $R(\lambda_s) = T(\lambda_s)$.

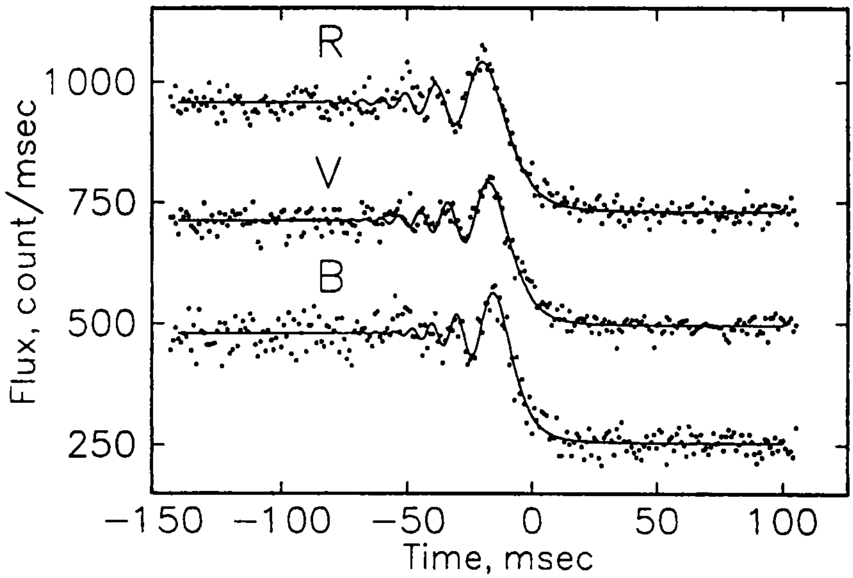

Fig. 1. The *B*, *V* and *R* light curves of occultation of the star SAO 94526 by the Moon on March 15, 1997. The time resolution is 1 ms. Zero time corresponds to the geometric occultation moment. The positions of *V* and *R* curves are shifted vertically. The solid curves are the light curves predicted theoretically.

For the calculation of optical properties of multilayer dielectric structures an algorithm described in the book of Kondrashov (1976) was used. A computer model of dichroic structure was composed from dielectric materials with high ($n_{\rm H} = 2.4$) and low ($n_{\rm L} = 1.38$ refractive indices. Such indices are inherent to ZnS and MgF_2, usually employed in the visual range. The refractive index dependence on wavelength and light absorption in these materials were neglected.

It is known that the spectral function of reflectivity (or transmittance) in the case of inclined incidence of light beam on multilayer structures is shifted to shorter wavelengths than in the case of normal incidence (see e.g. Clarke et al. 1975). To separate spatially the incoming and reflected light, the beam-splitters with inclined incidence are used. We have studied numerically the dependence of the shift $\Delta\lambda_s$ on incident angle. The shift almost does not depend on the number of layers. It depends on the refractive indices of dielectric

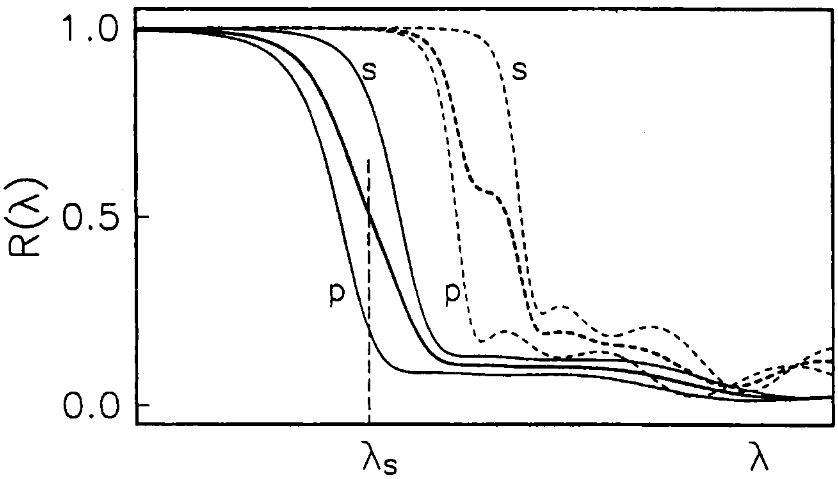

Fig. 2. The calculated reflectivity function $R(\lambda)$ for a 15-layer dichroic mirror model and 22.5° incident angle. The thick line shows non-polarized light, the thin lines are for p- and s-polarized light. The dashed lines show the same for a 21-layer mirror.

materials and quadratically on the incident angle. For example, in the case of a 15-layer dichroic mirror the shift reaches 40 nm at 25° in glass (or $\sim$ 39° in the air) for $\lambda_s = 520$ nm.

This shift of the boundary does not much complicate the usage of dichroic mirrors in inclined beams: it can be calculated and taken into account when the coating is produced. However, the situation is complicated by the fact that these shifts are different when the light is polarized in parallel with the incidence plane (p) and perpendicularly to it (s).

In Fig. 2 the $R(\lambda)$ functions for different plane polarizations are presented. One can see that the split boundary for s-polarized light disagrees with the boundary for p-polarized light. In our case the difference between them exceeds 20 nm.

This displacement determines the slope of $R(\lambda)$ curve near λ_s for natural light. A further increase in number of layers does not increase this slope, giving rise only to the appearance of characteristic ledges and waves. In the case of linearly polarized light, such a displacement leads to a change of spectral characteristics of light split depending on the orientation of the polarization plane.

The size of the polarization displacement can be decreased by using other dielectric materials. For example, the use of materials with $n_{\rm H} = 2.3$ and $n_{\rm L} = 1.8$ decreases this effect by more than three times and its magnitude becomes ~6 nm only. However, twice as many layers should be used to obtain the necessary characteristics of the dichroic mirror.

The difference between the reflectivity functions for different plane polarizations is unimportant if non-polarized light passes through the beam-splitter. The radiation from astronomical objects can be partially linearly polarized; this case will be discussed below in more detail.

3. BEAM-SPLITTER UNIT

Usually, astronomical multichannel photometers (see e.g. Giovannelli et al. 1980, Baron et al. 1983) include a dichroic mirror coated on a glass or quartz plate which is placed in the light beam under 45° angle. Such an optical design has two substantial disadvantages which are well known to constructors of color TV cameras (Furman 1977). The large incident angle (~ 28° in glass) gives rise to pronounced polarization effects and strong distortion of the reflection curve (see Fig. 2 in Serkowski 1975). The use of glass plates produces a parasitic light from the second side in the direction of the reflecting beam, independently of the dichroic mirror location (on front or back side). Due to this factor, about 15 % of long-wave radiation falls within a short-wave beam and this imposes restrictions on the filters forming the spectral passband.

To decrease polarization splitting, the incident angle must be as small as possible. The spatial separation of the incoming and reflected beams requires larger angles. A compromise is achieved with an incident angle of about 20°.

A diagram of the beam-splitter unit for a working incident angle of 22.5° is presented in the insert in Fig. 3. The unit consists of two prisms cemented together: an oblique-angled prism with 112.5° and 45° angles and a right-angled prism with an angle of 67.5°. The dichroic mirror is evaporated onto the right-angled prism hypotenuse. This location of the mirror requires special ultraviolet transmitting optical cement.

To turn the incoming beam, the total internal reflection effect is used. This limits the working and divergence angles. The incident angle 22.5° is close to the minimum possible angle for a focal ratio of 1/12. A very precise installation of the beam-splitter with respect to the incoming beam is required. The prisms are made of quartz or crown glass depending on the spectral range.

It should be noted that glass plates may be successfully used for incident angles of about 20–25° (13–17° in glass) if the parasitic light is suppressed by an antireflection coating.

4. OPTICAL LAYOUT OF THE FOUR-CHANNEL PHOTOMETER

The optical layout of the four-channel photometer with dichroic beam-splitters is shown in Fig. 3. The light beam from the telescope (top of the Figure) passes through the diaphragm (1) in the focal plane and falls on the first beam-splitting "blue/red" unit (I). The reflected "blue" ($\lambda < 500$ nm) light passes through the turning prism (2) and falls on the second beam-splitter "W/B" (II) which separates the light between the W channel (reflected radiation with $\lambda < 380$ nm) and the B channel (transmitted light with $\lambda > 380$ nm). The prism is required to turn the beam into the horizontal plane.

The "red" light ($\lambda > 500$ nm), transmitted through the beam-splitter I, falls on the third beam-splitter "V/R" (III). The light transmitted through this unit ($\lambda > 610$ nm) is directed into the R channel and the reflected light ($\lambda < 610$ nm) falls into the V channel.

Beam-splitter I works in the spectral range from 300 nm to 900 nm. To ensure such a wide range, the dichroic mirror is made of two quasi-independent dichroic structures with different λ_s. In the case of this beam-splitter, all three beams lie in the vertical plane.

Beam-splitters II and III were calculated and fabricated for use in the spectral ranges 300–550 nm and 450–900 nm, respectively. The beam planes of both splitters are horizontal.

In each photometric channel, the light beam goes further through a filter (3) forming the photometric band, a Fabry lens (4), a mirror turning the light by 90° (5) and then falls on the photocathode of a photomultiplier tube (6).

To increase total transmission of the optical channels, the surfaces of all the optical components (except filters) were covered with an antireflection coating in their spectral ranges. It is a hard problem for the first surface of the unit I, so this surface was covered with coating which is effective in the spectral interval 300–400 nm only, where a shortage of light usually exists.

The remaining parts of the optical layout are not connected with photometric channels. They include a wide-field eyepiece and a diaphragm eyepiece. The former has a turned mirror (7), a plate with crosshairs (8) and a Kellner eyepiece with 90 mm focus (9). The field of view of this eyepiece is 10 arcmin for a telescope with the 14 m focus. The second eyepiece with a field of view of 1.2 arcmin consists of a moving total internal reflection prism (10), a symmetrical transfer objective (11) and 20× symmetrical lens (12).

A diaphragm unit includes eight round diaphragms with diameters ranging from 3 to 75 arcsec and two mutually perpendicular narrow slits (2 arcsec in width and 90 arcsec in length). The diaphragms are placed on a wheel which is precisely turned by a stepper motor, and the diaphragm can be positioned with a 0.5 arcsec step and with a 0.2 arcsec accuracy.

Thus, one can do photometric measurements of extended astronomical objects or multiple stars in a scanning mode with different apertures. The scanning of a star image by two mutually perpendicular slits makes it possible also to center a star image in the diaphragm.

5. SPECTRAL RESPONSE FUNCTIONS OF THE PHOTOMETRIC CHANNELS

The characteristics of the dichroic mirrors have been calculated so that a photometric system as close as possible to the *WBVR* system could be realized. The astrophysical advantages of this system over the *UBV* system are described by Straižys (1973, 1977, 1992). This system is also easier to set up with a dichroic beam-splitter since the *W* and *B* bands overlap much less than Johnson's *U* and *B* bands do.

For each photometric channel of the device, the light passes two beam-splitters and their total transmission is described by the following expressions:

$$T_W(\lambda) = R_{\rm I}(\lambda) \cdot R_{\rm II}(\lambda), \qquad T_B(\lambda) = R_{\rm I}(\lambda) \cdot T_{\rm II}(\lambda),$$

$$T_V(\lambda) = T_{\rm I}(\lambda) \cdot R_{\rm III}(\lambda), \qquad T_R(\lambda) = T_{\rm I}(\lambda) \cdot T_{\rm III}(\lambda),$$

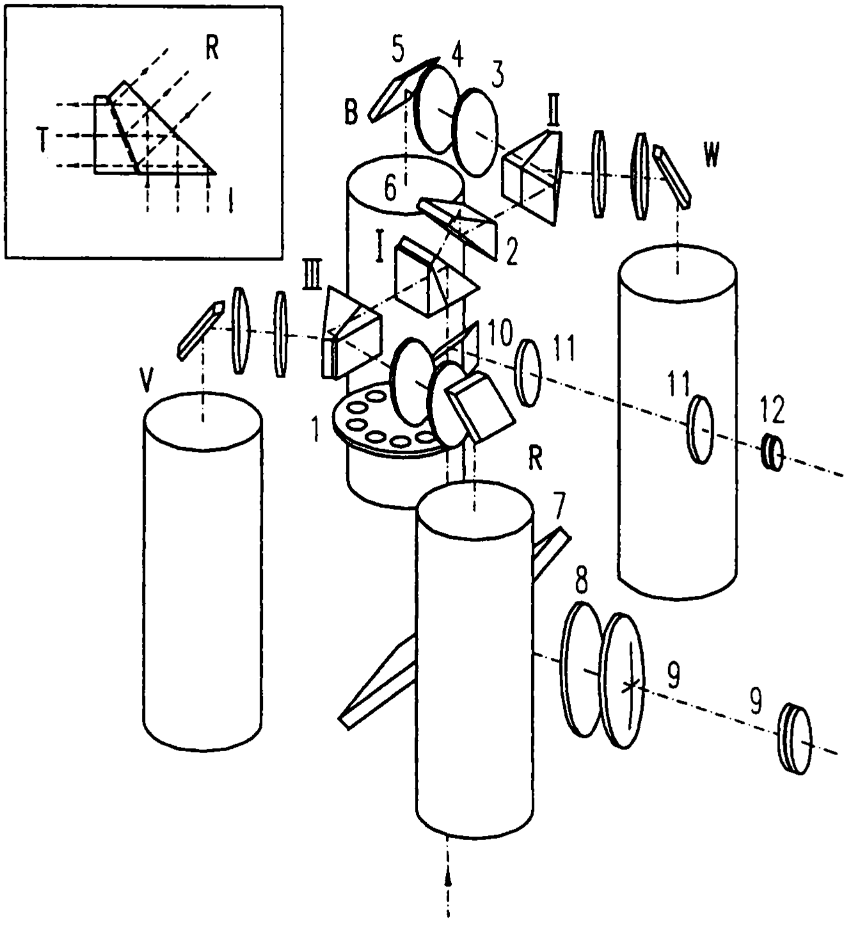

Fig. 3. The optical layout of the four-channel photometer with dichroic beam-splitters. See designations of the units in the text. The dash-dotted line shows the axis of the light beams. In the insert the beam-splitting unit is shown. The surface with the dichroic mirror is marked by a dashed line. The following light paths are shown: I – incoming beam, R – reflected beam, T – transmitted beam.

where subscripts I, II, III denote the functions related to the corresponding beam-splitters.

These expressions explain the optical layout. The use of such layout leads to minimum losses in the W channel (where the fluxes from

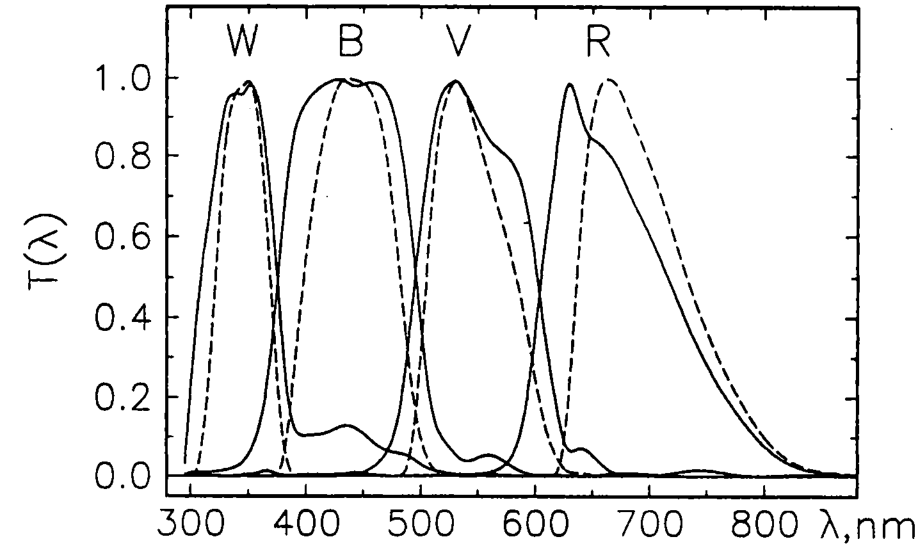

Fig. 4. The normalized response functions $F(\lambda)$ for all photometric channels of the device with (the dashed line) and without (the solid line) forming filters.

stars are small), because the efficiency of beam-splitting is higher for the reflected beam (see Fig. 2). On the other hand, the long-wave radiation with $\lambda > 550$ nm is suppressed twice in the W channel.

The relative response functions $F(\lambda)$ of the four-channel photometer prototype are shown in Fig. 4. The curves were measured with a monochromator calibrated against an optical radiometer. The form of these curves is defined only by the spectral characteristics of the beam-splitting units since light filters are not used. The fall of response with decreasing wavelength in the W channel and with increasing wavelength in the R channel is predetermined by the PMTs used. The real positions of the beam-splitting boundaries are at somewhat shorter wavelengths than calculated.

Our measurements confirm the simulation results. In particular, for the W channel the parasitic transmittance of light in the 650–700 nm spectral range (where the UV color glasses used for the UV photometric bands have a secondary transmittance rise) is smaller than 0.001. This makes it possible to refrain from using the $CuSO_4$ crystal in the W passband even if a PMT with a multialkali photocathode is used. In general, the measurement results demonstrate the possibility of using the four-channel photometer without light filters. This property of the photometer is very important if we prefer to increase the signal-to-noise ratio for faint stars rather than to set up precise passbands of the photometric system.

For setting up the *WBVR* system, the glass filters described by Meištas et al. (1975) can be used. In Fig. 4 the resulting response functions obtained by the beam-splitting alone, as well as with the glass filters are presented. The photometric passbands defined by filters are slightly narrower than the standard ones. For example, the half-widths of the *B* and *V* passbands are 82 nm and 75 nm, in comparison with 95 nm and 80 nm for the corresponding bands from Meištas et al. (1975).

If we shift the beam-splitting boundaries near 380 nm and 610 nm to longer wavelengths, our instrumental *WBVR* system becomes closer to the standard one. This correction has been made when new dichroic mirrors for other samples of the device were ordered. The investigation also shows that the dichroic mirrors have some individual peculiarities which are not important in defining the response functions.

6. AN ESTIMATE OF THE POLARIZATION EFFECTS

It is known that all optical devices with reflecting elements partially polarize the passing light. The measurements of light fluxes made with such devices may be affected by systematic errors if the starlight is linearly polarized.

As follows from the physics of dichroic mirrors, the beam-splitter produces maximum polarization near the splitting boundary (see Fig. 2). The light filter which forms the photometric band strongly reduces this effect, since the splitting boundary and the filter transmission boundary overlap. Still, this effect cannot be neglected. An additional linear polarization of about 3–5 % is produced by the turning mirrors.

To investigate the effects in the passbands, calculations using the above dichroic model for the real orientation of beam-splitters and mirrors were made for stellar energy distributions from Sviderskienė (1988).

On the average, the degree of instrumental linear polarization varies from 5 % in *W* to 12 % in the *B* channel. The laboratory measurements show values of about 14 %, 10 %, 9 % and 11 % in the corresponding channels for incandescent lamp as a source of light. More precise values can be obtained only from the observations of stars.

These estimates show that observations using the four-channel photometer have systematic errors of < 0.01 mag if the linear polarization of light is less than 10 %. Most stars have smaller polarization. Only some peculiar stars and strongly reddened ($A_V > 3$ mag) stars (Serkowski et al. 1975, Coyne et al. 1979) can be polarized to a higher degree.

In any case one must consider the polarization effects. A few methods are known to decrease the degree of the instrumental polarization. A depolarizer in the device is able to reduce polarization by an order of magnitude. Another way is to use a narrower forming glass filter. But it is always recommended to use the photometer at a constant position angle.

7. CONCLUSIONS

The main goal of our work in designing four-channel photometers with dichroic beam-splitters was precision *WBVR* photometry. Therefore we have concentrated on the key properties of dichroic mirrors which define the instrumental photometric system. To obtain the response functions close to the standard ones and to avoid some systematic errors, the following points should be taken into account.

(1) The slope of reflectivity (or transmittance) function near the splitting boundary is determined by two factors: the incident angle of the light beam and the number of layers in the dichroic structure; for an incident angle of 22.5° and usual dielectric materials, a mirror with 15–17 layers is an optimum choice.

(2) To depress undesirable polarization effects, the incident angle must be as small as possible; the usage of dielectric materials with a small difference in refractive indices seems to be promising.

The described four-channel *WBVR* photometer has the following properties:

(1) the instrumental photometric system is very close to the standard *WBVR* system;

(2) in principle, it is possible to observe faint objects without forming glass filters; this gives an additional gain in sensitivity;

(3) the main advantages of this photometer are a high total transmittance and a possibility of simultaneous measurements in four passbands.

ACKNOWLEDGMENTS. The author thanks A. Krylov and Yu. Zajtsev for their help in solving technical problems. The author also acknowledges the contribution of the staff of the Vavilov Optical Institute in fabricating the dichroic mirrors.

REFERENCES

Baron R. L., Dunkam E. W., Elliot J. L. 1983, PASP, 95, 925
Clarke D., McLean I. S., Wyllie H. A. 1975, A&A, 43, 215
Coyne G. V., Tapia S., Vrba F. J. 1979, AJ, 84, 356
Furman Sh. A. 1977, Optical Thin Coatings (Design and Production), Mashinostroenie Publ. House, Leningrad, p. 3–200
Giovannelli F., Auriemma G., Costa E. et al. 1980, Acta Astron., 30, 565
Goransky V. P., Esipov V. F., Cherepashchuk A. M. 1998, AZh, 75, 240
Kondrashov V. E. 1976, Optics of Photocathodes, Nauka Publishing House, Moscow, p. 7
Kornilov V. G., Krylov A. V. 1990, AZh, 67, 173 = Soviet Astron., 34, 90
Kornilov V. G., Volkov I. M., Zakharov A. I. et al. 1991, Catalogue of WBVR Magnitudes of Bright Stars of the Northern Sky, Transactions of the Sternberg Astron. Inst., Moscow University, Vol. 63
Kusakin A. V., Mkrtichian D. E. 1996, IBVS, No. 4314, 1
Meištas E., Zdanavičius K., Straižys V., Gurklytė A. 1975, Bull. Vilnius Obs., No. 42, 3
Serkowski K. 1970, PASP, 82, 908
Serkowski K., Mathewson D. S., Ford V. L. 1975, ApJ, 196, 261
Straižys V. 1973, A&A, 28, 349
Straižys V. 1977, Multicolor Stellar Photometry, Mokslas Publishing House, Vilnius, p. 126–129
Straižys V. 1992, Multicolor Stellar Photometry, Pachart Publ. House, Tucson, Arizona
Sviderskienė Z. 1988, Bull. Vilnius Obs., No. 80, 3
Zajtzev A., Kornilov V., Trunkovsky E. 1998, in preparation
Zdanavičius K., Meištas E., Daukša S. et al. 1978, Bull. Vilnius Obs., No. 45, 3