CCD PHOTOMETRY AND CLASSIFICATION OF STARS IN THE NORTH AMERICA AND PELICAN NEBULAE REGION. I. MOLĖTAI PHOTOMETRY

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Abstract. Magnitudes and color indices in the Vilnius seven-color system are measured for 690 stars down to ∼13.2 mag in the area of the North America and Pelican nebulae. Spectral types, absolute magnitudes, color excesses, interstellar extinctions and distances of the stars are determined. The plots of interstellar extinction $A_V$ versus distance for the North America Nebula and for the dark cloud L935 show that both areas are covered by the same absorbing cloud, situated at a distance of 600 pc. The maximal extinction in the area of the nebula is ∼3 mag, while in the dark cloud L935 it is much greater.

Key words: stars: fundamental parameters, classification, multi-color photometry, Vilnius photometric system – ISM: dust, extinction, individual objects: cloud L935

1. INTRODUCTION

This work continues the investigation of the area containing the North America and Pelican nebulae complex, using photometry of stars in the Vilnius seven-color photometric system and their two-dimensional classification. In the first paper (Straižys, Meištas, Vansevičius & Goldberg 1989a, Paper I) the results of photoelectric photometry of 249 stars down to 11 mag, their two-dimensional classification, color excesses, interstellar extinctions and distances have been given. In the second paper (Straižys, Goldberg, Meištas & Vansevičius 1989b, Paper II) interstellar extinction in the area was
investigated. The dark cloud L935, separating the North America and Pelican nebulae, was found to be at a distance of 550 pc. In the third paper (Straižys, Kazlauskas, Vansevičius & Ėčernis 1993, Paper III) the cloud distance was revised to 580 pc, using photometry and classification of additional 564 stars down to 12.5 mag. In the above papers, the scale of absolute magnitudes of stars was based on the Hyades distance modulus $V - M_V = 3.2$. If we accept the new distance modulus of 3.3 (Perryman et al. 1998), the cloud distance determined in the last paper changes to 610 pc.

The present paper starts a new series of investigations of the North America and Pelican nebulae complex, using CCD photometry in the Vilnius system obtained with the 35/51 cm Maksutov telescope of the Molėtai Observatory in Lithuania and with the 1 meter Ritchey telescope at the US Naval Observatory at Flagstaff, Arizona. The present paper is based on the Molėtai observations only.

2. OBSERVATIONS

CCD frames were obtained in 2000 and 2002 with the 35/51 cm Maksutov telescope at the Molėtai Observatory in Lithuania. The camera, loaned from the Tromso University Observatory (Norway), was fixed in the Newtonian focus, having the scale of $2.87''/\text{mm}$ or $4.25''/\text{pixel}$. The field size was $25\times25 \text{ mm}^2$ or $1.2\times1.2 \text{ sq. degrees}$. The camera has a thinned back-illuminated Tektronix $1012 \times 1012$ pixel chip with 25 $\mu\text{m}$ pixels and with a thermoelectric cooling down to $-40^\circ\text{C}$.

The focal sizes of images are very small: even at a seeing of $3''$ they are $17 \mu\text{m}$ only, i.e., smaller than the CCD pixel size. Therefore, the exposures were made with a small defocusing. Usually a star image contained from 4 to 9 pixels. A set of round (60 mm diameter) filters of the Vilnius system was used. The ultraviolet filters $U$ and $P$ are glass filters and $X$, $Y$, $Z$, $V$ and $S$ are interference filters. The exposure times in different filters were from 0.5 to 4 min. Each night in each filter several twilight flats were obtained. The centers of the exposed areas were shifted aiming to cover the $2\times2 \text{ sq. degree}$ field bounded by the coordinates (2000.0): $RA = 20^\text{h}51.5^m - 21^\text{h}00^m$, $DEC = +43^\circ30' - +45^\circ30'$. A schematic map of the investigated area is given in Figure 1 with the contours of the dark cloud corresponding to $A_V = 5 \text{ mag}$ according to Cambrésy et al. (2002).
Additionally, we have measured magnitudes and color indices of 150 stars in the *Vilnius* system photoelectrically. The observations were done with the 165 cm telescope of the Moletai Observatory in 1999.

![Fig. 1](image)

**Fig. 1.** Schematic map of the investigated area and its surroundings. The angles mark the corners of the investigated area. The broken line shows the contours of the North America Nebula. The solid line shows the contours of the dark cloud corresponding to $A_V = 5$ mag according to Cambrésy et al. (2002). The grid of the coordinates is for 2000.0.

3. **REDUCTIONS**

For obtaining the instrumental magnitudes of stars the multi-aperture method of the IRAF program package was used. The size
of the aperture used was 15–20″. Instrumental $V$ magnitudes and color indices were transformed to the standard Vilnius system by color equations obtained by comparing about 60–100 standard stars in the same field observed photoelectrically and taken mostly from Straižys et al. (1993).

Transformation equations obtained from observations were verified by synthetic photometry, calculating the magnitude differences between the standard and the CCD systems by the equation:

$$m_{st} - m_{CCD} = -2.5 \log \frac{\int F(\lambda)R_{st}(\lambda)\tau^x(\lambda)d\lambda}{\int F(\lambda)R_{CCD}(\lambda)\tau^x(\lambda)d\lambda} + \text{const,} \quad (1)$$

where $m_{st}$ and $m_{CCD}$ are magnitudes defined by the response functions $R_{st}(\lambda)$ and $R_{CCD}(\lambda)$, $F(\lambda)$ is the energy flux distribution function in the spectrum of a star, $\tau^x(\lambda)$ is the transmittance function of interstellar dust of $x$ unit masses (interstellar extinction law). The energy distribution curves for 25 stars of various spectral classes and luminosity classes V–IV–III were taken from Straižys & Sviderskienė (1972) with the corrected ultraviolet, as described by Straižys et al. (1996). The response curves of the standard Vilnius system were taken from the Straižys (1992) monograph, Table 59. The response curves of the CCD system were obtained by multiplying the sensitivity function $s(\lambda)$ of the CCD chip, the transmittance functions of the filters $f(\lambda)$ and the meniscus lens of the telescope $m(\lambda)$, and the reflection functions of two aluminized mirrors $a^2(\lambda)$. For the ultraviolet filter the mean atmospheric transmittance function $p(\lambda)$ at zenith was taken into account. The functions are taken from the following sources: $s(\lambda)$ – from the manufacturer’s description of the Tektronix 1024×1024 CCD camera, $f(\lambda)$ – from the measurements with a photoelectric spectrometer, $m(\lambda)$, $a(\lambda)$ and $p(\lambda)$ – from Straižys (1983).

The coefficients of synthetic color-equations for indices $P-V$, $Y-V$, $Z-V$ and $V-S$ are close to those of the equations determined from observations. For color indices $U-V$ and $X-V$ some nonlinearity of the synthetic equations was found. The response curve of the instrumental magnitude $U$ is shifted toward long wavelengths by the meniscus lens. This lens is made from ultraviolet transmitting glass; however it is $\sim$30 mm thick and this makes its transmittance in the ultraviolet wavelengths $<330$ nm rather low. This causes the mentioned nonlinearity in the transformation equation of $U-V$. 
In case of $X-V$, the nonlinearity originates from the shift of the transmittance curve of the filter onto the Hδ line.

The accuracy of the final magnitudes and color indices is seen from Figure 2 which shows the instrumental errors given by the IRAF package.

![Graph showing instrumental errors of magnitudes and color indices as a function of magnitude V.](image)

**Fig. 2.** Instrumental errors of magnitudes and color indices as a function of the magnitude $V$. The “sequences” of dots seen in the graph are due to slightly different exposure times and background intensities on different frames.

The stars which had double or multiple images in the CCD frames were omitted from photometry. However, the binary stars (both physical and optical) with a separation of $< 5''$ are unresolvable in our CCD images and seem as single stars. Trying to find more binaries, all stars down to the limiting magnitude (13.2 mag in $V$)
were verified for duplicity on the Internet’s virtual telescope SkyView of NASA based on the DDS (Digital Sky Survey) scans of the Palomar atlas red and blue plates (http://skyview.gsfc.nasa.gov). About 80 stars showing double or multiple images or close neighbour stars were also rejected from further analysis.

4. THE CATALOG AND CLASSIFICATION OF STARS

The final catalog will be published elsewhere. It contains 690 stars down to \( V = 13.2 \) mag observed by CCD and 150 stars down to \( V = 12.0 \) mag observed photoelectrically, 130 stars are common. For 27% of stars all color indices are available, 53% of stars are without \( U-V \) and 20% – without both \( U-V \) and \( P-V \).

For the stars with all six color indices available, spectral types were determined by using the method of matching of 14 different interstellar reddening-free \( Q \)-parameters of a program star to those of about 8300 standard stars of various spectral and luminosity classes, metallicities and peculiarity types from the General Photometric Catalog of Stars Observed in the Vilnius System (Straižys & Kazlauskas 1993). The \( Q \)-parameters are defined by the equation:

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

where \( m \) are the magnitudes in four (sometimes three) passbands, \( m_1 - m_2 \) and \( m_3 - m_4 \) are the two color indices and \( E_{12} \) and \( E_{34} \) are the corresponding color excesses. The \( E_{12}/E_{34} \) ratio slightly depends on spectral type, and this dependence is taken into account by iterations. The ratios are taken for the Cygnus interstellar reddening law which, according to the study of Straižys, Corbally & Laugalys (1999), is valid in the North America and Pelican nebulae area.

The matching of \( Q \)-parameters leads to a selection of some standard stars with a set of \( Q \)s most similar to those of the program star. The match quality is characterized by

\[
\sigma Q = \pm \sqrt{\frac{\sum n \Delta Q_i^2}{n}},
\]

where \( \Delta Q \) are differences of corresponding \( Q \)-parameters of the program star and the standard, \( n \) is a number of the compared \( Q \)-parameters (in our case, \( n = 14 \)). For the stars observed with an accuracy of \( \pm 0.01 \) mag, the \( \sigma Q \) value is of the order of \( \pm 0.01–0.02 \).
mag. In such a case the match is considered to be sufficiently good, and the spectral type (spectral class + luminosity class) of the standard star may be prescribed to the program star. In our case, for the program star we have accepted the average spectral and luminosity classes of the three to five best matching stars. Since the errors of the observed color indices for a part of the stars is $>0.01$ mag, their classification accuracy is lower. If the matching accuracy was of the order of $\pm0.03$ mag or larger, the star was not classified at all. There are 30 such stars ($\sim4\%$) in the catalog. Some of them may be unresolved binaries or peculiar stars. The known binary stars with $\rho \leq 15''$ and $\Delta V \leq 3$ mag were also not classified.

The accepted spectral types are in the table available from the authors in electronic form. Table also contains spectral types found in other publications, mostly in Schwassmann & van Rhijn (1938), Metik (1960), Kharadse et al. (1964) and Eglitis (2002). In all these cases spectral classification has been done from low dispersion objective prism spectra and is of low accuracy.

In the case when one or two ultraviolet color indices of a star were missing, we have used the same method, but the number of the $Q$-parameters was smaller: in the absence of $U-V$, $n$ was 10, in the absence of $U-V$ and $P-V$, $n$ was 7. Naturally, the accuracy of classification in these cases for B–A–F–G stars was lower, especially in luminosity classes. For two-dimensional classification of K and M stars the ultraviolet color indices are not essential.

For the estimation of the classification accuracy in the range of spectral classes B0–K0, we have made the following test. The real program stars were replaced by the test stars having the mean intrinsic color indices instead of the observed ones. After that the matching classification method was applied, taking $\sigma Q$ values $\leq 0.02$ mag.

The conclusion is made that spectral classes of B–A–F stars are determinable with acceptable accuracy when all color indices are available or only color indices $U-V$ are missing. In the case if $U-V$ and $P-V$ color indices are missing, the accuracy of spectral classes of these stars is very different in various spectral class ranges. We shall return to a discussion of this accuracy later.

The luminosity classification of B, A and F stars of luminosity classes V–IV–III is ambiguous even at the presence of all color indices. The reason is a lack of one-to-one dependence between MK spectral types and intrinsic color indices. Even the unreddened stars of the same spectral and luminosity classes always exhibit so-called
“cosmic dispersion” of their color indices and spectral line intensities. As a result, both MK and photometric classification of B–A–F stars of luminosities V–III always have an ambiguity of the order of ±1 of spectral subclass and ±1 of luminosity class. When both ultraviolet color indices are not available, the luminosity classification of B–A–F–early G stars is impossible. In this case for late F and early G stars we accepted that all of them are of luminosity V, which statistically is not far from reality (F and early G giants of Population I fall into the Hertzsprung gap in the HR diagram). These stars were used in the investigation of interstellar extinction, paying attention to the lower accuracy of their luminosity classes.

![Diagram](image.png)

**Fig. 3.** The dependence of the interstellar reddening-free parameter $Q_{XYV}$ on spectral class for luminosity V stars. Crosses are for luminosity III stars.

In the absence of $U-V$ and $P-V$ color indices, the best criterion of spectral class is the $Q_{XYV}$ parameter. Its dependence on spectral class is shown in Figure 3. The width of the area between the two broken lines corresponds to the observed “cosmic scatter” of the parameter. In the B8–A3, F6–G0 and especially in G5–K5 spectral ranges the $Q_{XYV}$ parameter shows a gradient which is sufficient for the classification of stars with an accuracy of 1–2 spectral subclasses. However, in the range of A5–F5 classes the classification is of very low accuracy.
5. COLOR EXCESSES, EXTINCTIONS AND DISTANCES OF THE STARS

Color excesses $E_{Y-V}$, extinctions $A_V$ and distances $r$ of the stars were calculated by the equations:

\[ E_{Y-V} = (Y - V)_{\text{obs}} - (Y - V)_0, \]  
\[ A_V = R_{YV}E_{Y-V}, \]  
\[ 5 \log r = V - M_V + 5 - A_V, \]

where the intrinsic color indices $(Y-V)_0$ for different spectral and luminosity classes were taken from Straižys (1992, Tables 66-69). The coefficient $R_{YV}$ for the normal interstellar extinction law is 4.16. Absolute magnitudes $M_V$ were taken from Straižys (1992, Appendix 1), according to their spectral and luminosity classes, with a correction of $-0.1$ mag, adjusting the old $M_V$ scale to the new distance modulus of the Hyades $(V-M_V = 3.3$, Perryman et al. 1998). The extinction values and distances of the stars are available in electronic form from the authors.

The following values of standard deviations $\sigma$ for the determined quantities are expected (including the cosmic dispersion): $\pm 0.03-0.04$ mag for color excesses, $\pm 0.15$ mag for extinctions and $\pm 25\%$ for distances.

6. DISTANCES TO THE DUST CLOUDS

We have divided the investigated area into two parts: one part is relatively transparent and includes a part of the North America Nebula, another one embraces the dark cloud L935. For both areas the diagrams $A_V$ versus $r$ are shown in Figures 4, 5 and 6. Figures 4 and 5 are for the same area, but for different limiting distances. The stars with lower classification accuracy and the late F – early G stars classified without the ultraviolet color indices are shown as crosses. On all figures they are scattered in the same area, as the stars with all color indices available or with only $U-V$ missing. Additionally, in the diagrams we plotted 105 brighter stars of the same area investigated in Papers I and III on the ground of their photoelectric photometry. Their distances determined in Papers I and III are multiplied by 1.05 to place them on the same scale. As a result, total number of stars plotted in Figures 4/5 and 6 are 354 and 242, respectively.
The dotted curves on the figures show the limiting magnitude effect for the stars of spectral classes B0 V, B2 V, B5 V, A0 V, A5 V, F0 V and F5 V. The stars of these spectral types above the corresponding curves are outside accessibility in the present program.

![Graph showing interstellar extinction](image)

**Fig. 4.** The dependence of interstellar extinction $A_V$ on distance up to 1.6 kpc for the North America Nebula area.

Let us discuss the distribution of stars in the $A_V$ vs. $r$ for the North America Nebula region shown in Figures 4 and 5. The following features can be noticed:

1. The stars with zero reddening are met from 100 to 600–700 pc. The same is true for the stars with small reddening, up to $A_V = 0.5$ mag.
2. The upper limit of reddened stars gradually increases with increasing distance, reaching $A_V \sim 0.8$ mag at 400 pc.
3. Approximately at this distance stars with higher extinction start to appear. The upper limit of $A_V$ is $\sim 4$ mag.
4. The area contains 20 OB-type stars and supergiants at distances between 2.0 and 6.5 kpc, their $A_V$ values are between 1 and 4 mag. Most of these stars, if not all, should be inside the Orion spiral arm. Our line of view in this direction leaves this arm at about 4 kpc distance.
**Fig. 5.** The dependence of interstellar extinction $A_V$ on distance up to 6 kpc for the North America Nebula area.

**Fig. 6.** The dependence of interstellar extinction $A_V$ on distance for the area of the dark cloud L935.
Such distribution of stars is consistent with the following model of distribution of interstellar dust. Up to a distance of $\sim 600$ pc we see a general Galactic dust layer with an extinction gradient of $\sim 1.0$ mag/kpc. Approximately at this distance a sharp increase of dust density takes place. If we accept a distance error of stars $\pm 25\%$, at 600 pc it corresponds to $\pm 150$ pc. Due to this error, the expected scatter of stars reddened by the cloud should be observed between 450 and 750 pc. This is not far from reality, since we find the nearest stars with $A_V > 1.0$ mag at $\sim 400$ pc.

A more accurate distance of the dust cloud may be estimated by taking the average of limiting distances to the nearest reddened stars and to the most distant unreddened stars. We suppose, both these limiting distances are caused by the same source – a dust cloud and the distance errors of stars inside the cloud and just behind it. The nearest stars with $A_V > 1.0$ mag are at 400 pc and the farthest stars with $A_V < 0.5$ mag are at 800 pc. The average of these distances is 600 pc. Thus, our results are consistent with the distance of the absorbing dust cloud at 600 pc, in good accordance with the cloud distance determined in Paper III.

Maximum extinction in the direction of the North America Nebula is not high: a lot of faint stars are seen on deep photos. Among the stars with the extinction $A_V > 1.5$ mag, 31 are closer than 1 kpc, 22 are between 1 and 2 kpc and 20 are farther than 2 kpc. Stars which are closer than 1 kpc exhibit the maximum extinction values at $\sim 3$ mag.

Now let us turn to the $A_V$ vs. $r$ graph for stars in the dark cloud area, shown in Figure 6. Although both transparent and dark areas are of comparable apparent size, the last one shows much smaller surface density of stars, and most of them are the foreground objects. Actually both areas are very similar with respect to the number of foreground stars and their distribution on the $A_V$ vs. $r$ diagrams. However, the dark area is very poor of stars with extinctions larger than 1.0 mag at distances farther than 800 pc. In the dark area, the nearest reddened stars with $A_V > 1.0$ mag and the farthest stars with $A_V < 0.4$ mag are almost at the same distances as in the transparent area discussed above: at 400 and 800 pc. Their average distance is 600 pc. It is difficult to estimate the error of the cloud distance since we do not know which stars reside in the cloud and which are behind it. Probably the distance is accurate within $\pm 50$ pc.
Thus, we are safe to accept that the absorbing clouds in both areas are at the same distance. However, in the dark area the extinction is much larger, and here down to 13 mag we see only a few background stars. The majority of reddened stars with $A_V > 1.5$ mag are situated within 400 and 800 pc, the limiting distances for stars residing within the dust cloud. The scarce background stars probably are seen through semitransparent cloud windows. In other directions the cloud in the optical wavelengths is almost black. According to Cambrésy et al. (2002), in some directions of our area the visual extinction may be considerably larger than 5 mag.

We have no idea how deep is the L935 dust cloud, i.e., is there a single comparatively thin dust sheet or the cloud has extensions along the line of sight. If the cloud is approximately round, its thickness should not exceed 20–30 pc.

7. RESULTS AND CONCLUSIONS

(1) CCD photometry in the Vilnius seven-color system has been done for 690 stars down to 13.2 mag in the 2×2 sq. degree area including the North America Nebula and the dust cloud L935, separating the North America and Pelican nebulae. About 150 of these stars have been observed photoelectrically.

(2) Majority of the stars have been classified in spectral and luminosity classes. Their color excesses, interstellar extinctions and distances have been determined.

(3) The extinction vs. distance graphs have been plotted separately for the area of the North America Nebula and for the dust cloud L935 area. It is shown that the interstellar extinction in both areas up to 600 pc distance is consistent with the general Galactic dust layer with a gradient of $\sim 1.0$ mag/kpc.

(4) A steep increase of extinction is observed in both areas at $\sim 400$ pc, which may be explained by the presence of a dust cloud at about 600 pc distance. In the area of the North America Nebula this cloud is relatively thin, its extinction does not exceed $A_V = 3$ mag. In the area of the dark cloud L935 the extinction is much larger. Due to the limiting magnitude effect, the stars with extinctions greater than 4 mag are not observable in both areas.

(5) This work shows that the Maksutov telescope of the Molėtai Observatory is an excellent instrument for a precise CCD photometry since in one exposure it gives a 1.2×1.2 sq. degree field with a 25×25 sq. mm CCD chip. However, the meniscus lens of the telescope
should be replaced to one, more transparent in the ultraviolet. Also, a CCD chip with enhanced ultraviolet sensitivity is to be used.

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REFERENCES
Cambrésy L., Beichman C. A., Jarrett T. H., Cutri R. M. 2002, AJ, 123, 2559
Eglitis I. 2002, personal communication
Kharadse E. K., Apriamashvili S. P., Kochlashvili T. A. 1964, Bull. Abastumani Obs., No. 31, 3
Metik L. P. 1960, Izvestia Crimean Obs., 23, 60
Perryman M. A. C., Brown A. G. A., Lebreton Y. et al. 1998, A&A, 331, 81
Schwassmann A., van Rhijn P. J. 1938, Bergedorfer Spektral-Durchmusterung der 115 Nördlichen Kapteynschen Eichfelder, Vol. 2, Hamburger Sternwarte in Bergedorf, p. 293 (SA 40)
Straižys V. 1983, Bull. Vilnius Obs., No. 62, 11
Straižys V. 1992, Multicolor Stellar Photometry, Pachart Publishing House, Tucson, Arizona
Straižys V., Corbally C. J., Laugalys V. 1999, Baltic Astronomy, 8, 355
Straižys V., Goldberg E. P., Meičtas E., Vansevičius V. 1989b, A&A, 222, 82 (Paper II)
Straižys V., Kazlauskas A. 1993, Baltic Astronomy, 2, 1
Straižys V., Kazlauskas A., Boyle R. P., Vrba F. J., Smriglio F. 1996, Baltic Astronomy, 5, 165
Straižys V., Kazlauskas A., Vansevičius V., Černis K. 1993, Baltic Astronomy, 2, 171 (Paper III)
Straižys V., Meičtas E., Vansevičius V., Goldberg E. P. 1989b, Bull. Vilnius Obs., No. 83, 3 (Paper I)
Straižys V., Sviderskienė Z. 1972, Bull. Vilnius Obs., No. 35, 3