

A STUDY OF ATMOSPHERIC EXTINCTION BY STELLAR PHOTOMETRY IN THE VILNIUS SYSTEM

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Abstract. An analysis of the Earth's atmospheric extinction over the Molėtai and Maidanak observatories is performed using photometric observations of stars in the *Vilnius* seven-color system, which were obtained during the periods 1993–1999 and 1978–1998, respectively. We present for each site the maximum and median values of the observed extinction coefficients for all color indices and investigate correlations between extinctions at different wavelengths. It is found that at Maidanak the aerosol extinction is mainly neutral, whereas at Molėtai both the selective and the neutral aerosol extinctions are almost equally frequent. We show that models with appropriate parameters for the total aerosol extinction ($\alpha_{ae} = A_0 \lambda^{-b}$) and those which include the selective aerosol extinction ($\alpha_{ae} = \alpha_n + A_{0s} \lambda^{-b_s}$) are equally good and permit us to calculate the extinction coefficients to the same degree of accuracy as observations.

Key words: atmospheric effects – methods: observational – techniques: photometric: Vilnius photometric system

1. INTRODUCTION

The Earth's atmosphere attenuates the intensity of stellar light and changes its spectral energy distribution. Therefore, at the Earth's surface, starlight must be corrected for the influence of the atmosphere, what is not an easy task to perform, because the atmospheric transmission is not always constant but often varies with time. Transparency variations appear to be irregular and are not

the same at different wavelengths. The character and amplitude of these variations depend on the site.

The most stable atmosphere keeps above isolated mountain peaks such as those of the western coast of Chile or some ocean islands (e.g., Hawaii and Canary Islands). In this respect, Maidanak Observatory in Uzbekistan, where two Lithuanian telescopes, among others, are sited, can also be attributed to a category of the best sites (see Ehgamberdiev et al. 2000 and references therein).

Lithuania is in a zone of unstable climate and we therefore need to apply special methods for reducing the influence of rapid variations of atmospheric transparency on observations performed from here. At Molėtai Observatory, for example, the number of nights with atmospheric conditions acceptable for photometry is very limited, but it can be considerably increased by means of simultaneous or quasi-simultaneous measurements of the intensity of light in different parts of the spectrum. Observations with modern panoramic receivers such as CCDs, where the light of hundreds of stars can be registered at the same time, are optimum for sites with variable transparency of the atmosphere. Still, in the case of CCD observations with large telescopes, where observing time is at a premium, most observers make no special observations for the determination of atmospheric extinction and use, as a rule, the average values of extinction coefficients for a given site. This approach is, however, correct only for sites with a stable atmospheric extinction and cannot be applied in the case of Molėtai Observatory.

Astronomical aspects of the question of the Earth's atmospheric extinction have been addressed in a number of papers. To facilitate such investigations, a model for atmospheric extinction which assumes three components, i.e., Rayleigh scattering, aerosol extinction and molecular absorption, is usually used (see, e.g., Hayes & Latham 1975; Gutiérrez-Moreno et al. 1982, 1986; Reimann et al. 1992; Manfroid 1993; Forbes et al. 1996; Zdanavičius & Pakštienė 1997).

It appears that the most stable component of the atmospheric extinction is Rayleigh scattering by air molecules, which was first described by Lord Rayleigh a hundred years ago (see Manfroid 1993). Approximately, the Rayleigh component of extinction is proportional to λ^{-4} . As a wavelength exponent, Burki et al. (1995) use, for instance, -4.05 , the value given by Allen (1973). In fact, the exponent depends slightly on the wavelength itself (Frohlich & Shaw 1980).

The most unstable component of the atmospheric extinction is that due to aerosols, including dust and salt particles, water droplets and pollutants of anthropogenic origin. A detailed description of the aerosol extinction was first given by Ångström (1929) who found it to be proportional to λ^{-b} , where the wavelength exponent b is equal approximately to 1.3. Different investigators give differing b values, mostly from 0.5 to 1.8 (see, e.g., Hayes & Latham 1975, Gutiérrez-Moreno et al. 1986, or, for an extensive review, Manfroid 1993). It follows from many investigations that values of b are site-dependent and that at low altitudes above sea level the aerosol extinction is larger and values of b are smaller. Analyzing a very extensive set of data, Laulainen (1977) found that the mean visual extinction is minimal at maritime sites (0.11–0.17 mag), medium at continental sites (0.17–0.24 mag) and the largest at urban sites (0.27–0.42 mag).

Molecular absorption is also unstable and therefore difficult to determine. This component manifests itself in absorption lines and bands, of which the ozone, water and O₂ bands are major contributors to the extinction. Their mean intensities can be taken from the literature (e.g., from Handbook of Geophysics 1965). Specially observed spectrograms can also be used to extract the intensities of molecular absorption bands (Gutiérrez-Moreno et al. 1986). Also, attempts were made to express the intensities by equations, for instance, for O₂ absorption by Pierluissi (1986) and for water absorption by Yamanouchi & Tanaka (1985). The mean atmospheric extinctions due to Rayleigh scattering, aerosol scattering and molecular absorption can be calculated using special codes (Nitschelm 1988).

Time variations of the atmospheric extinction may be both irregular and periodic. The periods may differ in the range from parts of a second to months (seasonal changes). As a rule, the aerosol extinction is the largest in summer. A detailed study of seasonal variations was carried out by Laulainen et al. (1977). Extinction variations with a period of one day are conditioned by the Solar motion through the sky, which causes the aerosol convection in the daytime and its sedimentation during the night. Short-term variations are due to changes of the aerosol scattering properties, whereas long-term and seasonal extinction variations may be linked with meteorological and hydrodynamical changes in the Earth's atmosphere. Irregular long-term extinction variations may be also due to volcanic eruptions (Burki et al. 1995). Most thoroughly the influence of me-

teorological conditions on the atmospheric extinction was studied by Reimann et al. (1992) and Sterken & Manfroid (1992).

The first investigations of the atmospheric extinction at Maidanak Observatory by means of seven-color *Vilnius* photometry were done by Zdanavičius & Sūdžius (1978) and Zdanavičius & Macijauskas (1980). Since then, a large amount of observational data in the *Vilnius* system has been accumulated, which prompted us to carry out a more detailed and accurate analysis of the extinction at this site.

In our first paper in this series (Zdanavičius & Pakštienė 1997; hereafter referred to as Paper I), the mean extinction coefficients in the seven passbands of the *Vilnius* system were determined for certain observing runs at Molėtai, Maidanak, Mount John (New Zealand) and Cerro Tololo, together with the mean parameters A_0 and b of the total aerosol extinction. Also, the relationships between the monochromatic aerosol extinction and its model parameters as well as between different model parameters were analyzed and the use of separating the neutral aerosol extinction from the selective one was shown.

In this paper, we present a long time analysis of the extinction coefficients in the passbands of the *Vilnius* photometric system, which were determined at Molėtai Observatory over a period of seven years (1993–1999) and at Maidanak Observatory during twenty years (1978–1998). The primary purpose of our analysis is to determine for both sites the regularity of extinction variations, to give the highest and the lowest values of the observed extinction coefficients for color indices, and to find a set of appropriate values of model parameters, which match the observed extinction and which later could be used to evaluate the variations of the second-order extinction coefficients. We also attempt to establish the relationships between the extinction coefficients in different passbands as well as between the extinction coefficients and model parameters and to estimate errors which arise when the atmospheric extinction is approximated by a model.

2. OBSERVATIONS

Photometric observations of the extinction stars were carried out from two different sites, Molėtai Observatory in Lithuania (longitude $25^{\circ}34'$, latitude $55^{\circ}19'$, elevation 200 m) and Maidanak Observatory in Uzbekistan (longitude $66^{\circ}54'$, latitude $38^{\circ}41'$, elevation 2550 m).

Table 1. Mean wavelengths and FWHM of the response functions of the *Vilnius* photometric system.

	<i>U</i>	<i>P</i>	<i>X</i>	<i>Y</i>	<i>Z</i>	<i>V</i>	<i>S</i>
λ_0 , nm	345	374	405	466	516	544	656
FWHM, nm	40	26	22	26	21	26	20

At both sites, the observations were done in seven spectral regions (Table 1) defined by the filters of the *Vilnius* photometric system (Straizys and Zdanavičius 1970).

At Molėtai Observatory, 570 observations of eight bright stars of spectral classes O9–B6 were obtained in 1993–1997 (Paper I) on the 63 cm telescope, using an eight-channel automated photometer with a permanently rotating filter wheel for quasi-simultaneous measurements (for a description of the photometer, see Paškevičius et al. 1987). In addition, a few extinction stars of spectral classes F5–G2 were observed by us in 1998–1999 (216 measurements) with a new quasi-simultaneous photometer (Janulis & Skipitis 1996) attached to the Molėtai 165 cm telescope. Quasi-simultaneous observations in all spectral regions made it possible to obtain color indices (and extinction values) of good accuracy even when observing through thin clouds or when the extinction was variable.

At Maidanak, the measurements of the extinction stars, all of which are of spectral classes F5–G2, were carried out by S.B. in 1978–1998 (about 600 nights) with the 48 cm and 100 cm telescopes, using a classical single-channel photometer.

The magnitudes and color indices of the extinction stars outside the atmosphere were determined using Nikonov's method modified by Zdanavičius (1996). Having the extra-atmospheric data, we calculated the instantaneous extinction coefficients (atmospheric extinction at the zenith, in magnitudes) for the magnitude *V* and the six color indices. For Maidanak, the extinction coefficients are determined more reliably than for Molėtai where the periods of clear sky were mostly short.

3. EXTINCTION DATA ANALYSIS

For the analysis of atmospheric extinction at Molėtai Observatory, the individual extinction observations for nights with the most reliable extinction determinations are used. Included in the Maidanak data analysis are the mean nightly extinction values and only for nights during which the extinction variations for color indices were less than 0.01 mag.

3.1. Mean extinctions and seasonal variations

The mean extinction coefficients and the extremities of the nightly means for the entire periods of observations at Molėtai and Maidanak are compared in Fig. 1. It is evident that the degree of scatter in the values of nightly extinction coefficients for color indices depends on the difference between the wavelengths of the magnitudes which form a given color index. Lower extinction values for Maidanak are primarily due to its high altitude, but in the visible they are also conditioned by smaller aerosol scattering. Larger extinction variations at Molėtai can be explained as the result of larger aerosol variations over this site.

In Table 2 we present the mean extinction coefficients for both sites, together with the minimal (Rayleigh) and maximal nightly extinction values. For comparison, the bottom line in Table 2(a) gives the largest extinction variations by night for Molėtai Observatory. (At Maidanak, nightly extinction variations are much smaller and are therefore not given in the table.)

The present values of the mean extinction coefficients for color indices agree well with those determined earlier by Zdanavičius & Macijauskas (1980), but the magnitude-extinction coefficients are larger by 0.02 mag for Maidanak and by 0.05 mag for Molėtai. This is not surprising, because, differently from the paper cited, nights with large (nearly gray) extinction were specially used in the present study.

It is perhaps worth noting that the mean visual extinction at Molėtai, $\alpha_V = 0.356$ mag, is remarkably close to the mean value $\alpha_V = 0.355$ mag obtained by Reimann et al. (1992) for the low-altitude Großschwabhausen observing station (elevation 356 m) of Jena University Observatory. At Maidanak, the mean magnitude-extinction coefficients are slightly larger than those observed at the

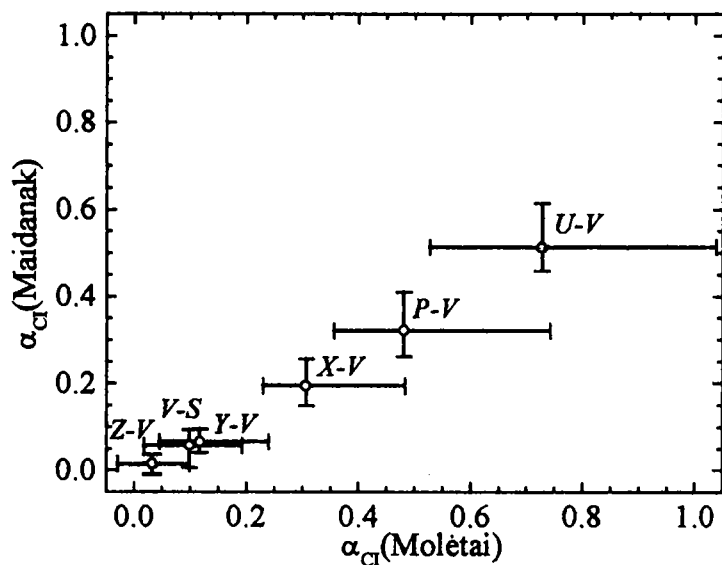


Fig. 1. Comparison of the observed extinction in color indices for Molėtai (the period 1993–1999) and Maidanak (the period 1978–1998).

Table 2. Mean extinction over all nights, minimal (Rayleigh) and maximal nightly extinctions, and largest extinction variations ($\Delta\alpha$) during the night.

(a) Molėtai (the period 1993–1999)

	α_V	α_{U-V}	α_{P-V}	α_{X-V}	α_{Y-V}	α_{Z-V}	α_{V-S}
mean	0.356	0.714	0.469	0.298	0.111	0.033	0.096
min (Rayleigh)	0.110	0.636	0.409	0.263	0.098	0.027	0.057
max	0.712	0.976	0.683	0.483	0.210	0.081	0.156
$\Delta\alpha$ by night	0.520	0.100	0.090	0.070	0.050	0.040	0.060

(b) Maidanak (the period 1978–1998)

	α_V	α_{U-V}	α_{P-V}	α_{X-V}	α_{Y-V}	α_{Z-V}	α_{V-S}
mean	0.210	0.513	0.321	0.194	0.065	0.014	0.057
min (Rayleigh)	0.082	0.452	0.299	0.188	0.072	0.019	0.042
max	0.451	0.614	0.409	0.255	0.095	0.036	0.093

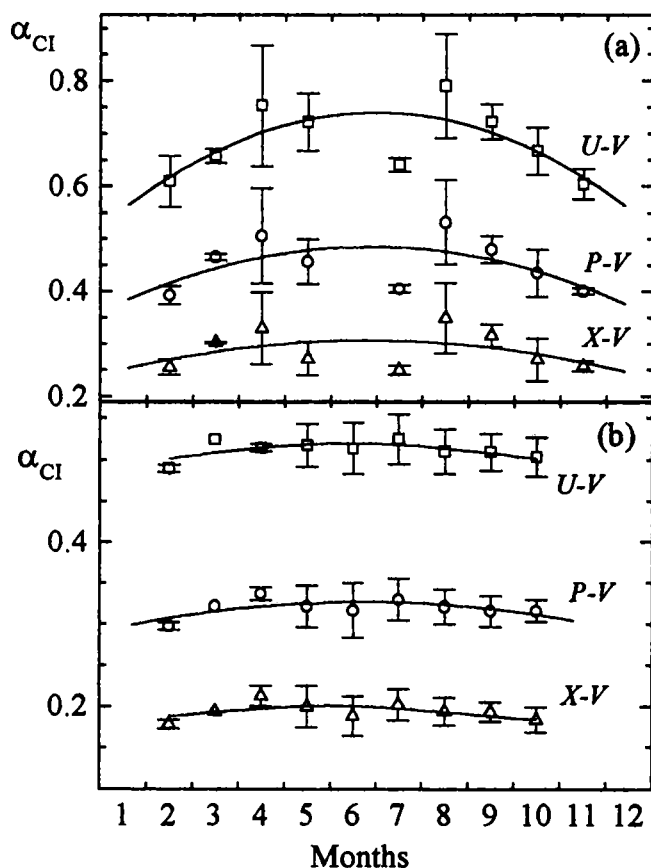


Fig. 2. Seasonal variations of the extinction in color indices for (a) Molėtai (the period 1993–1999) and (b) Maidanak (the period 1978–1998). The limits of the scatter are indicated as error bars. The data for all nights, including non-photometric, are considered.

same wavelengths at La Silla (Rufener 1986, Sterken & Manfroid 1992) and Cerro Tololo (Gutiérrez-Moreno et al. 1967, Gutiérrez-Moreno & Moreno 1970).

As we can see from Fig. 2, the seasonal changes of atmospheric extinction at Maidanak are relatively small, when compared with those at Molėtai, and may be due entirely to aerosol extinction. The Rayleigh extinction variations are negligible and cannot be detected from our data (see, for instance, Fig. 3, where the pointed edge of a wedge-shaped scatter of points shows the Rayleigh extinction).

3.2. Correlations between extinctions at different wavelengths

For practical applications, we made an attempt to establish relationships between the extinction coefficients for different magnitudes and color indices. Some of the typical diagrams are shown in Figs. 3, 4 and 5. On these diagrams, the small points scattered over a wedge-shaped area represent the observed values of the extinction coefficients. The lines and other symbols show model relationships between the extinction coefficients calculated by the equation

$$\alpha(\lambda) = \alpha_R(\lambda, h) + \alpha_{oz}(\lambda, T) + A_0 \lambda^{-b}, \quad (1)$$

where α_R is the Rayleigh extinction, α_{oz} is the ozone (O_3) absorption, and the third term is the total aerosol extinction, i.e.,

$$\alpha_{aei}(\lambda_i) = A_0 \lambda_i^{-b}, \quad (2)$$

where λ_i denotes the effective wavelength of the passband i in μm , and A_0 and b are model parameters.

To calculate α_R and α_{oz} (in magnitudes at the zenith), we used the equations analogous to those given in Paper I:

$$\alpha_{oz}(\lambda, T) = 1.09 T k(\lambda) \quad (3)$$

and

$$\alpha_R(\lambda, h) = 0.0094977 s \left(\frac{1}{\lambda} \right)^4 (n_s)^2 \times \exp \left(\frac{-h}{7.996} \right). \quad (4)$$

In Eq. (3), T is the equivalent thickness of the ozone layer above the observatory in mm at a standard temperature (0°C) and pressure (1 atm), and $k(\lambda)$ is the ozone absorption coefficient taken from Paper I. The thickness of the ozone layer above Molėtai varies from 2.6 mm in autumn to 4.2 mm in wintertime (Girgždys et al. 1999), i.e. over the range close to that found in the literature. For Maidanak, the value of the ozone thickness was taken from Handbook of Geophysics (1965). In Eq. (4), λ is in μm , h is the altitude of the observatory above sea level in km, s is a multiplier (usually, $s=1$) which is suspected to be dependent on temperature and pressure, and n_s is the index-of-refraction term calculated by Eq. (2) from Paper I.

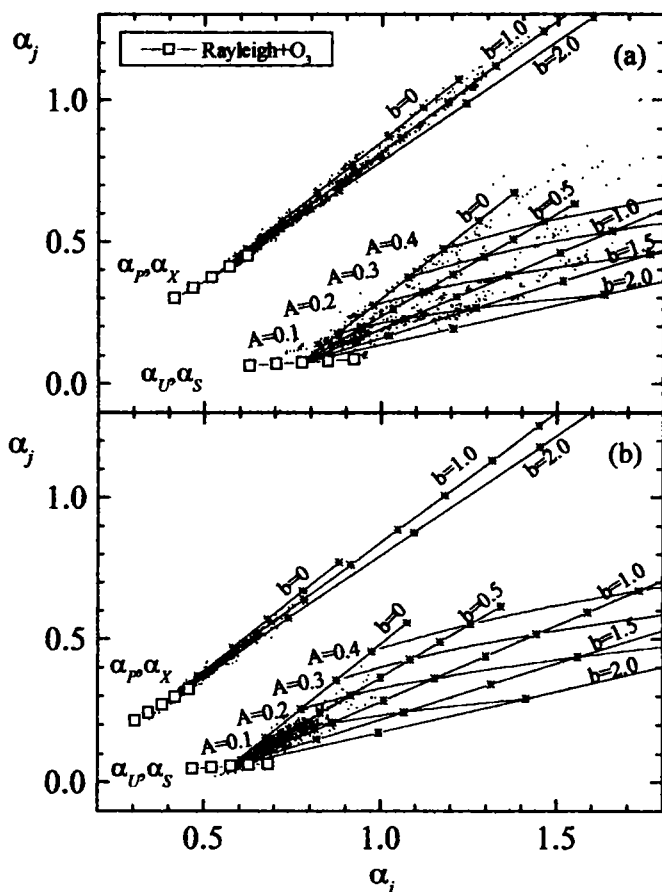


Fig. 3. Correlations between the atmospheric extinction coefficients for magnitudes P and X (one of the best correlations) and U and S (the worst correlation) for Molėtai (a) and Maidanak (b). The lines show model correlations.

In Figs. 3–5, the squares denote the sum of the Rayleigh extinction and the ozone absorption, to which the latter contributes little. The central square in each of the sequences of the $\alpha_R + \alpha_{oz}$ points represents the value calculated with $s=1$, whereas a pair of squares on either side of the central point corresponds to the values of extinction coefficients increased or decreased by 10 and 20 % (i.e., calculated with the multiplier s increased or decreased by 0.1 and 0.2). Other lines in the figures connect the extinction coefficients (in mag) calculated by Eq. (1) with constant values of A_0 and b . The A_0

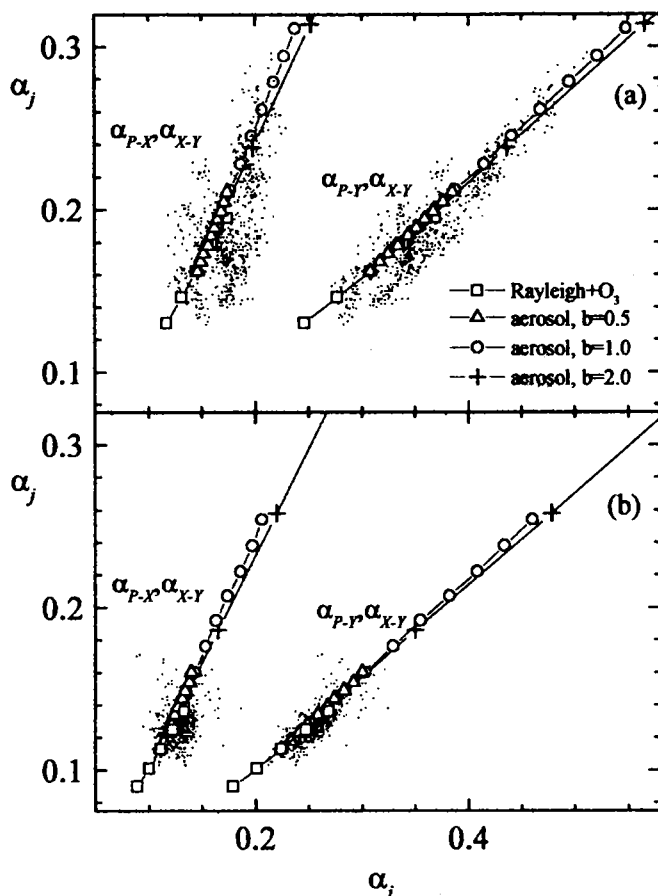


Fig. 4. Correlations between the atmospheric extinction coefficients for $P-X$ and $X-Y$, i.e. the color indices formed from neighboring pass-bands, and $P-Y$ and $X-Y$, i.e. the color indices having the same Y pass-band, for Molétai (a) and Maidanak (b). The lines show model correlations.

and b values used are, whenever possible, displayed in the figures. If not displayed, the marks (asterisks) on the lines are for the following A_0 values: 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45.

The correlations between the extinction coefficients for magnitudes and those for color indices are given in Tables 3 and 4, respectively, in which we present the correlation coefficients (r), parameters of the linear regression (k_0 and k_1) and rms scatter around the regression line. By way of example, we displayed in Fig. 3 the cor-

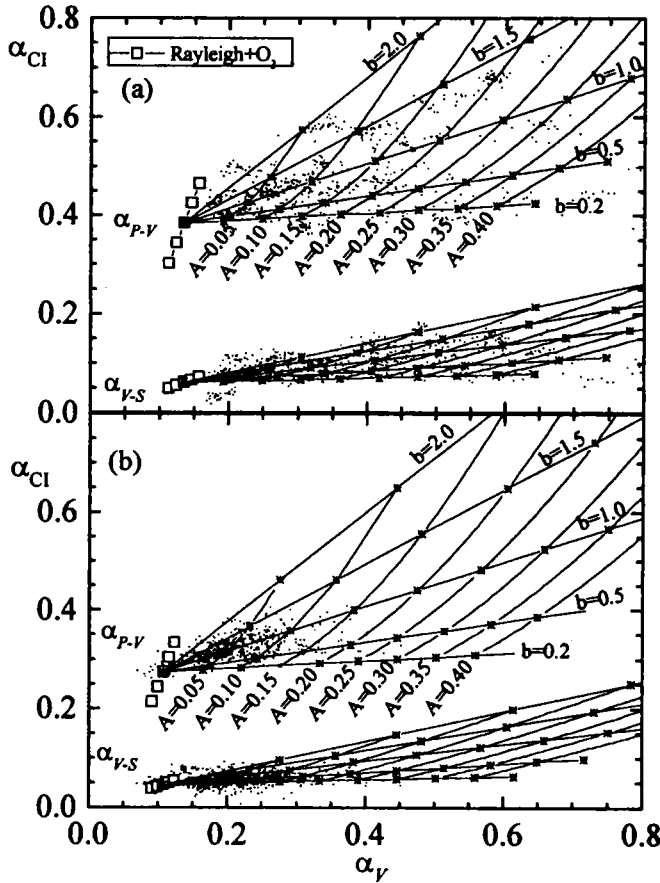


Fig. 5. Correlations between the atmospheric extinction coefficients for magnitude V and color indices $P-V$ and $V-S$ for Molėtai (a) and Maidanak (b). The lines show model correlations.

relations between the extinction coefficients for the neighboring (as regards wavelength) magnitudes P and X , which show the least scatter, and the same correlations for the remote magnitudes U and S , which show the largest scatter. For both observatories, Molėtai and Maidanak, the large majority of data points form a wedge-shaped area between the two lines drawn for aerosols with $b = 0$ (neutral, or gray, extinction) and $b = 1.5$. The correlation coefficients for different magnitudes (Table 3) vary from 0.85 to 1.00 for Molėtai and from 0.93 to 0.99 for Maidanak. It is apparent that, when the difference between the wavelengths of the passbands used is larger, the

Table 3. Correlation coefficients (r), parameters of the linear regression (k_0 and k_1) and rms scatter about the regression line ($\alpha_i = k_0 + k_1 * \alpha_j$) for the magnitudes of the *Vilnius* system.

α_i, α_j	Molėtai				Maidanak			
	r	k_0	k_1	σ	r	k_0	k_1	σ
α_U, α_P	0.99	0.196	1.059	0.018	0.99	0.184	1.017	0.008
α_U, α_X	0.98	0.351	1.101	0.027	0.99	0.281	1.094	0.008
α_U, α_Y	0.96	0.522	1.180	0.037	0.97	0.396	1.190	0.011
α_U, α_Z	0.93	0.604	1.226	0.048	0.96	0.445	1.241	0.012
α_U, α_V	0.91	0.643	1.227	0.053	0.95	0.457	1.268	0.014
α_U, α_S	0.85	0.771	1.200	0.063	0.93	0.533	1.242	0.016
α_P, α_X	1.00	0.142	1.046	0.014	0.99	0.099	1.067	0.007
α_P, α_Y	0.98	0.302	1.125	0.027	0.98	0.209	1.169	0.009
α_P, α_Z	0.96	0.376	1.178	0.039	0.97	0.258	1.217	0.011
α_P, α_V	0.94	0.412	1.185	0.045	0.97	0.268	1.251	0.011
α_P, α_S	0.88	0.534	1.168	0.056	0.94	0.344	1.221	0.015
α_X, α_Y	0.99	0.150	1.081	0.019	0.99	0.103	1.095	0.007
α_X, α_Z	0.97	0.217	1.142	0.030	0.98	0.148	1.143	0.008
α_X, α_V	0.96	0.251	1.152	0.037	0.98	0.158	1.172	0.010
α_X, α_S	0.91	0.366	1.145	0.050	0.95	0.228	1.151	0.013
α_Y, α_Z	0.99	0.059	1.064	0.018	0.99	0.041	1.045	0.005
α_Y, α_V	0.98	0.086	1.085	0.022	0.99	0.049	1.077	0.005
α_Y, α_S	0.95	0.189	1.098	0.038	0.97	0.113	1.059	0.010
α_Z, α_V	0.99	0.025	1.020	0.013	0.99	0.009	1.024	0.005
α_Z, α_S	0.97	0.118	1.048	0.027	0.98	0.068	1.021	0.008
α_V, α_S	0.99	0.089	1.036	0.019	0.98	0.059	0.985	0.009

correlations get worse and the angle between the above mentioned aerosol lines becomes larger. The best correlation is for the extinction coefficients of neighboring magnitudes (e.g., U and P , P and X , etc.).

Much of the scatter in the diagrams representing correlations between the magnitude-extinction coefficients (α_i vs. α_j) is due to variations of the parameter b . When the aerosol extinction and the range of values of b get larger, the scatter of points also becomes larger. The largest scatter is observed for the Molėtai data, which varies, for different diagrams, from 0.013 to 0.063 mag. The same diagrams for the Maidanak data give the rms scatter from 0.005 to only 0.016 mag, i.e. both the largest and the smallest deviations are nearly equal.

Table 4. Correlation coefficients (r), parameters of the linear regression (k_0 and k_1) and rms scatter about the regression line ($\alpha_i = k_0 + k_1 * \alpha_j$) for the color indices of the *Vilnius* system.

α_i, α_j	Molėtai				Maidanak			
	r	k_0	k_1	σ	r	k_0	k_1	σ
$\alpha_{U-P}, \alpha_{P-X}$	0.61	0.107	0.803	0.011	-0.26	0.227	-0.276	0.006
$\alpha_{P-X}, \alpha_{X-Y}$	0.53	0.104	0.367	0.013	0.26	0.094	0.250	0.006
$\alpha_{X-Y}, \alpha_{Y-Z}$	0.50	0.142	0.561	0.015	0.31	0.105	0.465	0.004
$\alpha_{Y-Z}, \alpha_{Z-V}$	0.10	0.080	0.151	0.012	-0.29	0.055	-0.302	0.004
$\alpha_{Z-V}, \alpha_{V-S}$	0.45	0.003	0.300	0.011	-0.39	0.027	-0.228	0.005
$\alpha_{U-Y}, \alpha_{P-Y}$	0.93	0.124	1.336	0.014	0.84	0.184	1.031	0.007
$\alpha_{P-Y}, \alpha_{X-Y}$	0.92	0.105	1.364	0.010	0.80	0.094	1.250	0.005
$\alpha_{P-Y}, \alpha_{Y-V}$	0.85	0.233	1.114	0.014	0.53	0.186	1.066	0.006
$\alpha_{Y-Z}, \alpha_{Y-V}$	0.85	0.005	0.683	0.011	0.62	0.017	0.526	0.004
$\alpha_{Y-V}, \alpha_{Y-S}$	0.95	-0.003	0.555	0.009	0.65	0.022	0.354	0.005
$\alpha_{U-V}, \alpha_{P-V}$	0.97	0.138	1.223	0.015	0.91	0.171	1.066	0.007
$\alpha_{P-V}, \alpha_{X-V}$	0.98	0.103	1.230	0.010	0.89	0.093	1.175	0.006
$\alpha_{P-V}, \alpha_{Y-V}$	0.95	0.233	2.114	0.010	0.77	0.186	2.066	0.005
$\alpha_{P-V}, \alpha_{Z-V}$	0.64	0.394	2.682	0.014	0.40	0.303	1.293	0.005
$\alpha_{P-V}, \alpha_{V-S}$	0.77	0.274	2.096	0.016	0.22	0.297	0.423	0.008

The extinction coefficients for color indices are independent of neutral extinction. Therefore, the scatter of points in the diagrams of correlations between the extinctions in color indices (Fig. 4) is much smaller when compared with that for magnitudes, but still remains the largest for Molėtai (see Table 4). Here, the wavelength exponent b becomes no longer valid, and we have to use instead the exponent b_s from the equation

$$\alpha_{aei} = \alpha_n + A_{0s} \lambda_i^{-b_s}, \quad (5)$$

where α_n is the neutral extinction, A_{0s} and b_s are the parameters of the selective extinction. In this case, the scatter of points is primarily due to errors in the extinction coefficients, and, secondly, it depends on the values of b_s and the aerosol extinction. The decrease in the amount of scatter is partly due to the relation which exists between A_{0s} and b_s (see Fig. 7). The smallest correlation coefficients are found for the extinctions in color indices formed from neighboring magnitudes. Practically, these coefficients do not correlate. This fact confirms our proposition that the scatter seen in the diagrams for

color indices is due mainly to observational errors. In the case of color indices adjacent to each other, the error of a common magnitude affects both color indices, but each in the opposite sense.

Our previous suggestion (Paper I) that the scatter in the α_i , α_j diagrams is smallest when the color indices are calculated with respect to the magnitude Y is confirmed by the present analysis; although the differences in the scatter appear to be very small (see Table 4).

The largest scatter is seen in the diagrams which show the correlations between the extinction coefficients for a color index and a magnitude. As an example, Fig. 5 exhibits the diagrams α_{P-V} , α_V and α_{V-S} , α_V . We see that most of the observed extinction is due to scattering by aerosol particles, which shows the wavelength dependence by λ^{-b} , with b (for the total aerosol extinction) changing from 0 to about 1.5. Certain groups of the deviating points can be explained by observational errors.

It should be noted that the α_i , α_j diagrams shown in Figs. 3–5 can be used to indirectly estimate the mean thickness of the ozone layer for a given period of observations, because the pointed edge of the scatter of the observed extinction coefficients (in mag) start at the same s value. Since the coefficients not affected by the ozone absorption give $s \cong 1$, the ozone layer thickness has to be taken such as to give $s \cong 1$ for the ozone influenced extinction coefficients as well. This leads to the conclusion that the Rayleigh constant 0.0095 (see Eq. 4) is good to within the accuracy of our data, and this value will be used further in our investigation.

3.3. Analysis of the aerosol extinction

Using some of the calibrated relationships (wedge-like plots) between the extinction coefficients for two magnitudes or, better, between the extinction coefficients for a color index and a magnitude, approximate values of the parameters A_0 and b for the total aerosol extinction (Eq. 2) can be determined. More exact values of A_0 and b can be calculated from the system of Eqs. (2), written for all magnitudes of the *Vilnius* system. Solving a system of Eqs. (5), written for all color indices, gives us the parameters of selective aerosol extinction, A_{0s} and b_s . Thus, the neutral aerosol extinction can be determined as a difference between the observed coefficients α_i and

Table 5. Selective aerosol extinction, Rayleigh scattering and ozone absorption in the passbands of the *Vilnius* system for Molėtai and Maidanak. For the aerosol extinction, the mean and maximal values are from nightly averages; the minimal values are accepted equal to zero. The ozone absorption is calculated for a certain type star, assuming the total ozone thickness over Molėtai and Maidanak to be 3 mm and 2.8 mm, respectively.

α_i	Molėtai				Maidanak			
	α_{aes}		α_{R}	α_{Oz}	α_{aes}		α_{R}	α_{Oz}
	mean	max		O V	mean	max		G0 V
α_U	0.210	0.613	0.746	0.048	0.085	0.259	0.534	0.045
α_P	0.212	0.578	0.519	0	0.086	0.248	0.381	0
α_X	0.178	0.524	0.373	0	0.070	0.206	0.270	0
α_Y	0.148	0.413	0.208	0.003	0.053	0.161	0.154	0.003
α_Z	0.118	0.340	0.137	0.015	0.043	0.132	0.101	0.014
α_V	0.102	0.279	0.110	0.025	0.037	0.118	0.082	0.023
α_S	0.060	0.190	0.053	0.021	0.032	0.091	0.040	0.020

the selective aerosol extinction coefficients $\alpha_{\text{aes}i}$ calculated using the known values of A_{0s} and b_s :

$$\alpha_{\text{aes}i} = A_{0s} \lambda_i^{-b_s}, \quad (6)$$

where i denotes V or other passband of the *Vilnius* system.

Therefore, the parameters b and b_s for the blue spectral region can be calculated by using only the magnitudes U , P , X , and Y . In the red, b and b_s can be obtained by using the magnitudes Y , Z , V and S . To estimate the extinction model parameters α_n , A_{0s} and b_s , extinction coefficients for at least three magnitudes are needed, whereas for the estimation of the mean values of the parameters of total aerosol extinction, A_0 and b , extinction coefficients for only two magnitudes are necessary.

The mean and maximal nightly values of the selective aerosol extinction α_{aes} in the passbands of the *Vilnius* system, observed at Molėtai and Maidanak, are given in Table 5. Here, the minimal aerosol extinction is taken to be equal to zero, i.e. as if no aerosol in the atmosphere. In such a case, we have only Rayleigh scattering by atmospheric molecules, α_{R} (Columns 4,8), and absorption by ozone gas, α_{Oz} (Columns 5,9). The ozone extinction values are given

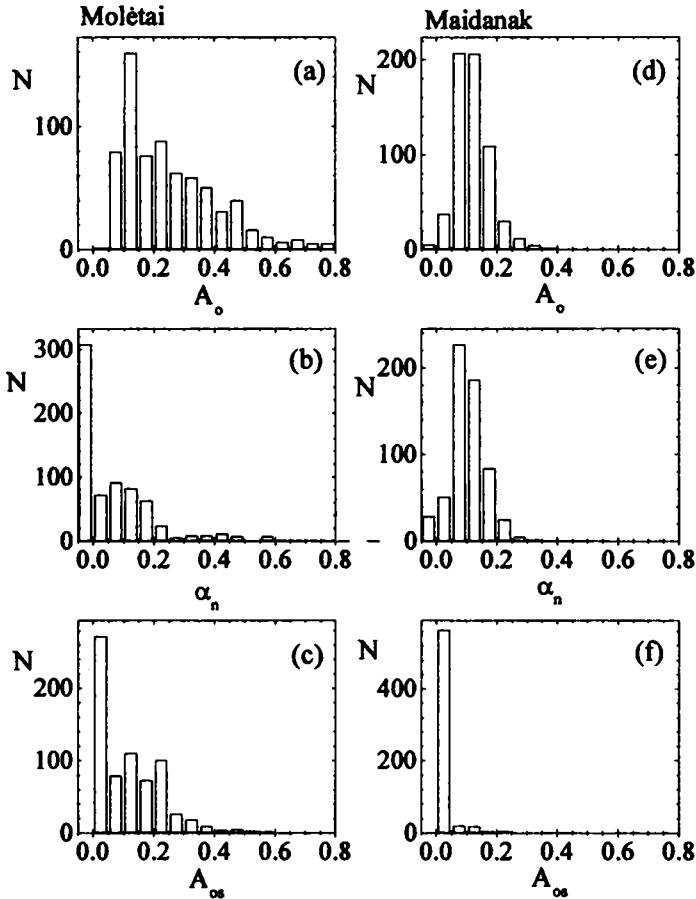


Fig. 6. Distributions of the total aerosol extinction (a,d), neutral aerosol extinction (b,e) and selective aerosol extinction (c,f) at Molėtai (left-hand panels) and Maidanak (right-hand panels). N is the number of nights.

for stars of spectral types O V and G0 V, which were calculated by assuming the total ozone thickness over Molėtai and Maidanak to be 3 mm and 2.8 mm, respectively.

For both observatories, the distributions of the aerosol extinction in magnitude V , observed over the entire periods of observations, are shown in Fig. 6. The histograms are given separately for the total (panels a, d), neutral (panels b, e) and selective (panels c, f) extinctions. It should be noted that the presence of negative values of the

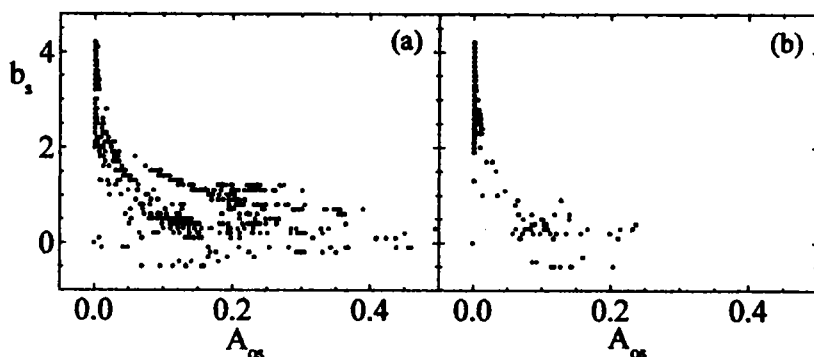


Fig. 7. Relation between the parameters A_{0s} and b_s of the selective aerosol extinction at Molėtai (a) and Maidanak (b).

neutral extinction is due entirely to errors in the calculated values of the selective extinction which, in the absence of neutral extinction, can be slightly larger than the observed values. We see that, for Maidanak, the distributions of both the total and the neutral extinctions are very close. This means that at this site the aerosol extinction is mostly neutral. For Molėtai, however, this is not the case. Here the selective aerosol extinction appears to be much more pronounced (panel c). Therefore, it is necessary to pay attention to the behavior of the parameters of the selective aerosol extinction, A_{0s} and b_s . The parameter A_{0s} grows with growing selective aerosol extinction. However, the relation between A_{0s} and b_s is more complicated (Fig. 7). In the case of small selective aerosol extinction, its increase is accompanied by decrease in b_s . When the selective aerosol extinction becomes large, b_s does not practically depend on A_{0s} and varies in a narrow interval, keeping its values small. This minimizes the range of selective extinction variations. It should be noted that, differently from the parameter b which reflects variations in the number and size distributions of all aerosol particles, b_s is related to only those particles which are responsible for selective scattering in the spectral range considered (in our case, from 350 to 640 nm).

Fig. 8 displays the rms differences between the observed extinction coefficients for all (except U) passbands of the *Vilnius* system and those calculated from Eq. (2) for the total aerosol extinction (top panels) and from Eq. (5) for the selective aerosol extinction (bottom

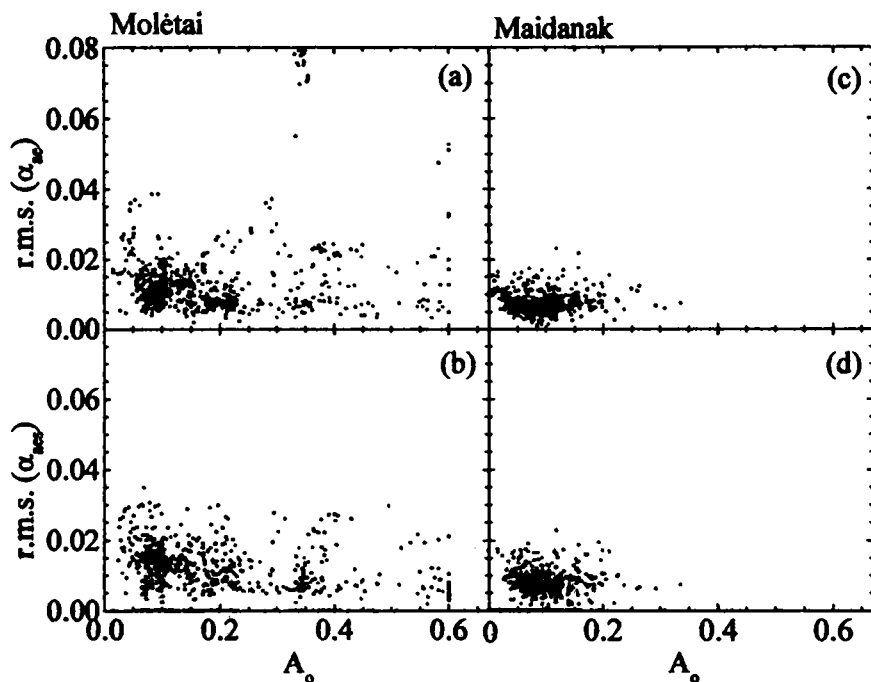


Fig. 8. The rms differences between the observed extinction coefficients for the *PXYZVS* passbands of the *Vilnius* system and those calculated from Eq.(2) (the total aerosol extinction; panels a, c) and from Eq. (5) (the selective aerosol extinction; panels b, d). Left-hand panels are for Molėtai and right-hand panels are for Maidanak.

panels). The scatter of points seen is due to both the observational errors and the suitability of the equations used. The differences between the observed values and those calculated by Eq.(2) and Eq.(5) are nearly the same. This shows that both equations are equally good for the determination of extinction coefficients, except for nights with very high extinction. But, again, the scatter is larger for Molėtai, and we think that this is primarily due to larger errors in the observed extinction coefficients. It is worth mentioning, however, that the errors of approximation by Eq. (2) increase suddenly at large extinction values, while in the case of using Eq. (5) they remain the same. For U , the observed extinction coefficients appear to be less than the calculated values. This may be conditioned by the fact that, in determining α_U , the Forbes effect was not taken into

account and, perhaps, by possible error in the effective wavelength assumed for the U magnitude.

4. SUMMARY AND CONCLUSIONS

Large atmospheric extinction variations, especially in the ultraviolet, which, for example, at Molėtai reach for $U-V$ almost 0.4 mag during the whole period of observations (7 years) and 0.1 mag during the night, can by themselves fully explain why mean extinction coefficients cannot be used when high-precision photometry is the goal. The use of mean nightly extinction coefficients for color indices can be justified only for nights with a stable selective or varying neutral extinction. The neutral extinction variations have no influence on observed color indices.

Multicolor photometry performed with photometers, measuring starlight in several passbands simultaneously or having permanently rotating filter wheels, permit one to find reliable values of the instantaneous extinction coefficients even in the case of extinction variations with periods of a few seconds or minutes.

At Maidanak, the neutral extinction component is the main contributor to the aerosol extinction during the majority of nights. At Molėtai, however, both aerosol extinction components, selective and neutral, are usually present. At both sites, some nights with negligible aerosol scattering were observed, i.e., the extinction values were nearly identical to the theoretical limit of Rayleigh scattering. Seasonal extinction variations are more pronounced at Molėtai than at Maidanak.

When the extinctions in a few of the system's passbands are known, the extinction coefficients for the remaining passbands can be determined in two ways: (1) by using a model for extinction with known instantaneous parameters or (2) from adjacent extinction coefficients by means of the established relationships. The first way is more accurate. In both cases, it is preferable to know the extinction coefficients for the magnitudes P , Y and V . Knowing of the extinction coefficients for two magnitudes allows us, in principle, to estimate the parameter b of the total aerosol extinction and then the unknown extinction coefficients for other magnitudes.

The use of a model for extinction in the Earth's atmosphere and the mean relationships established between the extinction coefficients

for different magnitudes and colors can help us make rough values of extinction coefficients more accurate. A small scatter in the best correlations between the extinctions at different wavelengths shows that a good photometric precision can be achieved even in the case of variable atmospheric transparency. However, a high stability of instrumental sensitivity should be guaranteed in such a case. Accurate extinction determinations and stable apparatus are especially required in preparing fundamental photometric catalogues.

Using photometric observations at the Molėtai and Maidanak observatories over a prolonged period, the highest and the lowest values of the observed extinction coefficients for color indices have been found and appropriate parameters of an extinction model have been determined. They will be used in the future for studying the second-order extinction coefficients, i.e. the dependence of extinction on the color of an extinction star. The knowledge of the limiting values of the selective extinction will allow us to investigate, by means of synthetic photometry, the variations of the second-order extinction coefficient and their influence on the precision of photometry in broad and medium band systems.

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