THE ROLE OF THE INTERSTELLAR EXTINCTION LAW AND BANDWIDTH EFFECTS IN MULTICOLOR PHOTOMETRY

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Received February 29, 1996.

Abstract. The new mean interstellar extinction law covering the spectral range from 0.15 to 250 μm is derived. This extinction law yields $R_{BV} = A_V / E_{B-V} = 3.17$ for OB stars. The very broad band structure of the extinction law in the visible region of the spectrum is confirmed. It is shown that the new interstellar extinction law is suitable for the investigation of reddening parameters of photometric systems. The dependences of reddening parameters upon MK spectral types of stars in three photometric systems, Vilnius, $UBV$ and $uvby$ are discussed.

Key words: methods: observational – techniques: photometric: Vilnius system, $UBV$, $uvby$ – interstellar medium: interstellar extinction law

1. INTRODUCTION

The interstellar extinction law (ISEL) and response functions define reddening parameters of a photometric system, i. e. color excess ratios and ratios of total to selective extinction. As a rule these ratios are employed in the determination of physical parameters and distances of stars. Therefore, the accuracy of the results obtained depends largely upon the accuracy of the reddening parameters used. The main sources of errors in the reddening parameters are the following: (1) errors of determination of the ISEL; (2) variations of the ISEL in the Galaxy; (3) ignorance or incorrect taking
into consideration the dependence of the reddening parameters on the MK spectral type of a star.

Although in general features the ISEL is uniform throughout the galaxy it shows considerable variations in details. These variations may be large enough to cause considerable errors in the determined physical parameters of stars. Therefore, it is advisable to analyse possible variations of the ISEL in the region of the sky under investigation. However, in many cases there is no possibility to carry out such investigations. Then a certain mean ISEL is used.

It would take a lot of space to give even a brief account of the numerous literature devoted to investigations of the ISEL. Instead, we refer the readers to the monograph of Straizys (1992) where a thorough review of papers dealing with the observational investigations of the ISEL up to 1990 is given. A more recent review of these investigations is presented by Mathis (1993).

Nevertheless, we would like to mention the classical example of Whitford's (1958) mean ISEL which was used as a standard for several decades. For the calibration of the Vilnius photometric system the mean ISEL derived by Sudžius (1974) has been used. During the last two decades the most widely used ISELs were those of Seaton (1979) and Savage & Mathis (1979). However, these ISELs lack many details in the visual and near ultraviolet ranges of the spectrum since this segment of the ISEL is mainly based on data in the $UBV$ system. This imperfection of the ISEL may be the cause of inaccuracies in derived physical parameters of stars and false bandwidth effects in intermediate or narrow band photometry. In particular, these ISELs are of little use in calculating reddening parameters in the Vilnius photometric system or in the $uvby$ system. Cardelli & Clayton (1991) and Mathis (1993) also pointed out the uncertainties of the ISEL in the violet and near ultraviolet regions of the spectrum. Moreover, many investigators using different photometric systems do not verify whether they apply reddening parameters corresponding to the same mean ISEL.

It is well-known that the reddening parameters of a given photometric system vary with the MK spectral type of a star (see, e.g., Straizys 1977, 1992). The amplitude of these variations increases with an increasing width of a passband of a given photometric system. Vilnius astronomers were among the first who investigated thoroughly variations of the reddening parameters in various photometric systems. Reddening parameters in the $UBV$ system have been investigated by Ažusienis & Straizys (1966b, 1969), Kurilienè
& Sūdžius (1974), Straizys et al. (1976), Straizys (1977). The parameters of the Vilnius photometric system have been analysed by Sviderskienė & Straizys (1971), Kurilienė & Sūdžius (1974). These investigations have been extended and well summarized in the monographs of Straizys (1977, 1992).

Theoretical investigation of reddening effects in various photometric systems has been carried out by Golay (1974). The paper of Crawford & Mandwewala (1976) dealing with the reddening parameters in various photometric systems is also worth mentioning.

The aim of the present investigation was twofold. First, we attempted to derive a new detailed mean ISEL that would be applicable for calculation of reddening parameters in intermediate or narrow band photometric systems. Second, we attempted to re-examine the variations of the reddening parameters in three photometric systems, Vilnius, $UBV$ and $uvby$, on the basis of our derived mean ISEL. The review of these photometric systems may be found in Straizys (1977, 1992).

2. BASIC RELATIONS

Heterochromatic color indices are defined by the expression

$$i - j = -2.5 \log \frac{\int F(\lambda) \varphi_i(\lambda) d\lambda}{\int F(\lambda) \varphi_j(\lambda) d\lambda}, \quad (1)$$

where $F(\lambda)$ is the spectral energy distribution (SED) of a star, $\varphi_i(\lambda)$ and $\varphi_j(\lambda)$ are the response functions of the magnitudes $i$ and $j$ respectively.

The heterochromatic interstellar extinction expressed in magnitudes is defined by the function

$$A_i = -2.5 \log \frac{\int F(\lambda) \varphi_i(\lambda) \tau^z(\lambda) d\lambda}{\int F(\lambda) \varphi_i(\lambda) d\lambda}, \quad (2)$$

where $\tau(\lambda)$ is the transmission coefficient of interstellar dust clouds and $z$ is the relative mass of the intervening dust clouds.

Using relations (1) and (2) we deduce color excesses

$$E_{i-j} = A_i - A_j = (i - j) - (i - j)_0, \quad (3)$$

where $(i - j)$ and $(i - j)_0$ are observed and intrinsic color indices respectively.
Then the reddening parameters, color excess ratios and ratios of total to selective extinction, are expressed by the following relationships:

\[ k_{ijl} = \frac{E_{i-l}}{E_{j-l}} \]  

(4)

and

\[ R_{jl} = \frac{A_l}{E_{j-l}}. \]  

(5)

Effective wavelengths of heterochromatic magnitudes employed in this investigation are defined by the formula

\[ \lambda_e = \frac{\int \lambda F(\lambda) \phi(\lambda) d\lambda}{\int F(\lambda) \phi(\lambda) d\lambda}. \]  

(6)

Usually the effective wavelengths of the magnitudes \( i, j \) and \( l \) satisfy the condition

\[ \lambda_i < \lambda_j < \lambda_l. \]  

(7)

Let us calculate a set of color excess ratios for various magnitudes \( i \) but with one common denominator, \( E_{m_1-m_2} \). Then the set of the ratios \( k_{im_1m_2} \) as a function of inverse effective wavelengths, \( 1/\lambda_i \), is the ISEL in a relative form, and \( m_1 \) and \( m_2 \) are normalizing magnitudes.

It has been a common practice to choose the magnitudes \( B \) and \( V \) of the \( UBV \) system for normalization. However, these magnitudes are not the optimal choice because their passbands are rather wide and embrace a lot of fine structure features of the ISEL. In addition, the effective wavelengths of the magnitudes \( B \) and \( V \) are strongly dependent on the MK spectral type of a star (see, e. g., Kurilienè 1983). These properties of the mentioned passbands may cause discrepancies in the ISEL combined from data in various photometric systems. We intend therefore to use the magnitudes \( Y \) and \( V \) of the Vilnius photometric system for normalization. These passbands are narrower and their effective wavelengths are determined more precisely than those of the \( UBV \) system (cf., e. g., Kurilienè 1983). The transformation of the ISEL expressed in the form of the ratios \( E_{i-V}/E_{Y-V} \) to the ratios \( E_{i-V}/E_{B-V} \) is straightforward since the effective wavelength of the magnitude \( V \) of the Vilnius system approximately coincides with that of the \( UBV \) system (Straizys 1992).

The ISEL in an absolute form will be obtained by the addition of the ratio of total to selective extinction to the ratios \( k_{im_1m_2} \).
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\[ k_{i_{m_1}m_2}^0 = k_{i_1m_2} + R_{m_1m_2} = \frac{A_i}{E_{m_1-m_2}}. \] (8)

3. DATA

For the derivation of the mean ISEL we used stars of normal MK spectral types from O5 to B2. These stars have been selected from the catalogue of Jaschek (1978). Stars located in regions of high density interstellar clouds and in regions of the anomalous ISEL have been excluded.

Photometric data have been compiled from catalogues of three photometric systems, Vilnius system, Arizona system \textit{UBVRIJHKL} and that of Astronomical Netherlands Satellite (ANS).

Observations in the ultraviolet have been selected from the catalogue of the ANS data of Wesselius et al. (1982). Photometric data in the Vilnius system have been compiled from the catalogue of Straizys & Kazlauskas (1993). The source of the \textit{UBVRIJHKL} photometry was the catalogue of Morel & Magnenat (1978).

The source of intrinsic color indices in the \textit{UBV} and Arizona systems was the monograph of Straizys (1992). Intrinsic color indices of O5 – B2 stars in the Vilnius photometric system were taken from the paper of Sūdžius & Bobinas (1994). For the ANS data the intrinsic color indices of Bobinas & Sūdžius (1994) have been used.

4. THE MEAN INTERSTELLAR EXTINCTION LAW

The initial data for derivation of the ISEL were color excesses defined by the expression (3). Color excesses have been deduced for all the selected stars in three previously mentioned photometric systems and have been plotted on various two color diagrams. Two examples of these diagrams are shown in Figs. 1 and 2.

Stars, not fitting the general trend of the reddening line on any of plotted diagrams, were excluded from further calculations. From these diagrams we computed color excess ratios by linear least-square fits forced through the origin. In the Vilnius photometric system we computed color excess ratios \( k_{iYV} = E_{i-Y}/E_{Y-V} \), where \( i \) stands for one of the magnitudes of Vilnius system excluding magnitudes \( Y \) and \( V \). The results are presented in Table 1.

In the Arizona system we computed color excess ratios \( k_{BV_i} = E_{V-i}/E_{B-V} \), where \( i \) is one of the magnitudes, \( R, I, J, H, K, L \).
Fig. 1. The two color diagram $E_{m3r-V}$ versus $E_{B-V}$. The continuous line is the least square solution forced through the origin.

Fig. 2. The two color diagram $E_{P-Y}$ versus $E_{Y-V}$. The continuous line is the least square solution forced through the origin.
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Table 1. Color excess ratios in the Vilnius photometric system

<table>
<thead>
<tr>
<th>$E_u - y$</th>
<th>$E_b - y$</th>
<th>$E_x - y$</th>
<th>$E_y - z$</th>
<th>$E_v - s$</th>
<th>$n$</th>
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<td>1.600</td>
<td>1.120</td>
<td>0.753</td>
<td>0.651</td>
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Table 2. Color excess ratios in the Arizona system $BVRIJHKL$

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<th>$E_v - i$</th>
<th>$E_v - j$</th>
<th>$E_v - h$</th>
<th>$E_v - k$</th>
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<td>±0.030</td>
<td>±0.035</td>
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Table 3. Color excess ratios for the ANS data

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<th>$E_{18} - V$</th>
<th>$E_{22} - V$</th>
<th>$E_{25} - V$</th>
<th>$E_{33} - V$</th>
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<td>4.903</td>
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The results are given in Table 2. From the ratio $E_{v - k}/E_{v - v}$ we immediately obtain the ratio $R_{BV} = 1.1E_{v - k}/E_{v - v} = 3.14$. Color excesses in the photometric system of the ANS combined with $E_{v - v}$ enable us to compute ratios $k_iBV = E_i - V/E_{v - v}$, where $i$ denotes one of the magnitudes of the ANS system, $m_{15}, m_{18}, m_{22}, m_{25}$ and $m_{33}$. However, we did not apply the previously described method in this case because we could use color excess ratios deduced by Bobinas & Sudžiūs (1994). Their results are given in Table 3.

Following the discussion of Chapter 2 we used the magnitudes $Y$ and $V$ of the Vilnius photometric system for normalization. The
initial version of the mean ISEL was deduced in the form of the ratios $k_{\lambda Y V} = E_{\lambda - V}/E_{Y - V}$. The transformation of ratios of the series of $E/E_{B - V}$ to the ratios $E/E_{Y - V}$ has been carried out using the ratio $k_{BY V} = E_{B - V}/E_{Y - V} = 1.35$ (Kurilienè & Sūdžius 1974).

In the near ultraviolet and visual spectral ranges we adopted the extinction curve of Sūdžius (1974) for Cep-Per-Mon since we did not find significant differences between the color excess ratios of Sūdžius (1974) and those obtained in the present paper. In the ultraviolet we interpolated between the points of the ANS magnitudes using the parameterizing function of Fitzpatrick & Massa (1988). The coefficients of this function were calculated using our color excess ratios from Table 3. In the infrared the point of the magnitude $I$ does not fit the general trend of the extinction curve which was interpolated using the second order polynomial. Apparently, this is due to the ambiguously defined response function of the magnitude $I$ (Straizys 1992). It was excluded from further treatment. The extension of the ISEL to the far infrared beyond the magnitude $L$ was made using data of Mathis (1990). According to the relationship (8), the final absolute mean ISEL is expressed in the form of the ratios

$$
\frac{A_{\lambda}}{E_{B - V}} = \frac{k_{\lambda Y V}}{k_{BY V}} + R_{BV},
$$

where $R_{BV} = A_{V}/E_{B - V} = 3.1$ (Mathis 1990).

The detailed ISEL covering the spectral range from 0.15 to 250 μm is presented in Table 4 and in Fig. 3. It is compared with the widely used ISEL of Savage & Mathis (1979) and the recently derived ISEL of Krelowski & Papaj (1992) in Fig. 4. The general features of the obtained ISEL are similar to those of Savage & Mathis (1979). However, we also notice slight differences between our mean ISEL and that of Savage & Mathis (1979) and Krelowski & Papaj (1992). The ultraviolet extinction bump at 220 nm is wider than that of Savage & Mathis (1979) and Krelowski & Papaj (1992). Our results confirm the very broad band structure in the visual region of the spectrum. We note the smooth transition of the extinction curve from the $R$ to $S$ and from the magnitude $U$ to $m_{33}$ and do not find any displacements of segments of the extinction curve in the ultraviolet mentioned by Mathis (1993). This quality of the ISEL confirms the self-consistency of the set of intrinsic color indices used.
### Table 4. The mean interstellar extinction law

<table>
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<tr>
<th>( \lambda ), nm</th>
<th>( \frac{A_{\lambda}}{E_{B-V}} ), 10^{-17}</th>
<th>( \lambda ), nm</th>
<th>( \frac{A_{\lambda}}{E_{B-V}} ), 10^{-17}</th>
<th>( \lambda ), nm</th>
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<td>395</td>
<td>4.518</td>
<td>600</td>
<td>2.785</td>
<td>100000</td>
<td>0.004</td>
</tr>
<tr>
<td>231</td>
<td>8.917</td>
<td>400</td>
<td>4.470</td>
<td>605</td>
<td>2.759</td>
<td>250000</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Fig. 3. The mean interstellar extinction law. Dots are original data derived from the color excess ratios computed in the present paper. The continuous line is the interpolated extinction curve. The positions of the magnitudes used are shown.

Fig. 4. The comparison of the mean ISEL (continuous line) with that of Savage & Mathis (1979) (dots) and that of Krelowski & Papaj (1992) (circles).
5. REDDENING PARAMETERS

In order to prove the usability of the obtained ISEL for multicolor photometry and to reveal the dependence of reddening parameters upon MK spectral type, we carried out calculations of reddening parameters in three photometric systems Vilnius, $UBV$ and $uvby$. The basic formula for these calculations are expressions (2)-(5) given in Chapter 2 of the present paper. The spectral energy distribution curves for various MK spectral types were taken from Sviderskiene (1988). The transmission function of interstellar matter $\tau(\lambda)$ was derived from data of Table 4. The relative mass of interstellar matter adopted in all our calculations yields the color excess $E_{B-V} = 0.25$ or $E_{Y-V} = 0.18$ for OB stars.

Color excess ratios $E_{U-B}/E_{B-V}$ and ratios of total to selective extinction $R_{BV}$ for various MK spectral types and luminosity classes have been computed using response functions of Ažusienis & Straizys (1966). The results are shown in Figs. 5 and 6.

The computed color excess ratio $E_{U-B}/E_{B-V} = 0.72$ for O-type stars coincides with that derived from observations (cf., e.g., Straizys 1977, 1992). However, the variations of the ratio $E_{U-B}/E_{B-V}$ over the entire MK spectral range are rather large. It decreases down to 0.68 for A0 supergiants and increases over 1.1 for M1 - M2 giants and supergiants.

From Fig. 6 we derive the ratio $R_{BV} = 3.17$ for OB stars. It is in good agreement with our value deduced from the ratio $E_{V-K}/E_{B-V}$ and with the most probable mean value adopted on the basis of various observational data of present time (Straizys 1992, Mathis 1993). From Fig. 6 we see that the ratio $R_{BV}$ continuously increases with the run of MK spectral sequence up to 3.7 for M1 - M2 giants and over 3.8 for M2 supergiants. The large amplitudes of variations of the ratios $R_{BV}$ and $E_{U-B}/E_{B-V}$ lead us to the conclusion that we must take into account the dependence of the reddening parameters upon spectral energy distribution of a star when dealing with photometric data in the $UBV$ system. It should be noted that variations of ratios $E_{U-B}/E_{B-V}$ and $R_{BV}$ with MK spectral type in general features resemble those determined in earlier papers (see, e.g., Kurilienè & Sudžius 1974; Straizys et al. 1976; Straizys 1977, 1992). For the practical application therefore it is convenient to use the empirical expressions of $R_{BV}$ and $E_{U-B}/E_{B-V}$ derived by Straizys (1992).

The reddening parameters in the Vilnius photometric system for various MK spectral types and luminosity classes have been
Fig. 5. Color excess ratios $E_{U-B}/E_{B-V}$ versus MK spectral type for different luminosity classes.

Fig. 6. Ratios of total to selective extinction $R_{BV} = A_V/E_{B-V}$ versus MK spectral type for different luminosity classes.
The interstellar extinction law and bandwidth effects

Fig. 7. Color excess ratios $E_{U-P}/E_{P-Y}$ versus MK spectral type for various luminosity classes.

Fig. 8. Color excess ratios $E_{P-Y}/E_{Y-V}$ versus MK spectral type for various luminosity classes.
Fig. 9. Color excess ratios $E_{X-Y}/E_{Y-Z}$ versus MK spectral type for various luminosity classes.

Fig. 10. Color excess ratios $E_{X-Z}/E_{Z-S}$ versus MK spectral type for various luminosity classes.
The interstellar extinction law and bandwidth effects

4.35
4.30
4.25
RYV
4.20
4.15
4.10

Fig. 11. Ratios of total to selective extinction, $R_{YV} = A_Y/E_{Y-V}$, versus MK spectral type for various luminosity classes.

computed using the response functions from Straizys & Zdanavičius (1970). Some of these results are shown in Figs. 7 – 11. The differences between computed color excess ratios and those deduced from observations for O stars are insignificant and do not exceed 0.01. The amplitudes of variations of the color excess ratios in the Vilnius photometric system are considerably smaller than those in the $UBV$ system. This property is easily explained by the smaller widths of the passbands of the Vilnius system in comparison with those of the $UBV$ system. However, there is a common practice to take into account the dependence of color excess ratios of the Vilnius system upon MK spectral type in practical applications of this system.

Detailed relationships between color excess ratios in the Vilnius photometric system and MK spectral types may be found in earlier papers of Kurilienė & Südzius (1974) and Straizys (1977, 1992).

We note that the ratio $R_{YV}$ is almost constant in the spectral range O – K0. From our computations we obtain the mean $R_{YV} = 4.20$ for OB stars. For spectral types O – K0 of all luminosity classes we derive the mean $R_{YV} = 4.206 \pm 0.008$. Therefore, for this spectral range we can adopt the constant $R_{YV} = 4.21$ with high accuracy.
**Fig. 12.** Color excess ratios $E_{u-b}/E_{b-y}$ versus MK spectral type for various luminosity classes.

**Fig. 13.** Color excess ratios $E_{c1}/E_{b-y}$ versus MK spectral type for various luminosity classes.
The interstellar extinction law and bandwidth effects

The largest variations of the ratios \( R_{YV} \) are characteristic for late type stars. The lowest value \( R_{YV} = 4.15 \) is obtained for K7 - M0 main sequence stars. The highest ratio \( R_{YV} = 4.32 \) is derived for M6 - M7 giants. The amplitude of variations of the ratios \( R_{YV} \) is of the order of 0.08 while that of the ratios \( R_{BV} \) is about 0.34. Small variations of the ratio \( R_{YV} \) with spectral type support our viewpoint that the application of this ratio must be preferred to \( R_{BV} \).

The reddening parameters in the \textit{uvby} system for various MK spectral type and luminosity classes have been computed using the response functions of Matsushima (1969). The results are shown in Figs. 12 - 13. The computed ratios \( E_{c_1}/E_{b-y} \) and \( E_{m_1}/E_{b-y} \) for O stars coincides with those derived from observations. However, the computed ratio \( E_{u-b}/E_{b-y} \) differs from that deduced from observations (cf. 1.554 and 1.5 respectively). The amplitudes of variations of color excess ratios in the \textit{uvby} system are of the same order as those of the Vilnius system.

Since we do not find significant differences between computed and observed values of reddening parameters in various photometric systems we arrive at the conclusion that the derived ISEL is a good representation of the galactic mean ISEL and that the response functions of three above discussed photometric systems are defined reasonably well.

6. CONCLUSIONS

We have derived the mean ISEL covering the spectral range from 0.15 to 250 \( \mu \text{m} \). The general features of the derived ISEL are similar to those of Savage & Mathis (1979). Our ISEL has the very broad band structure in the visible region of the spectrum. It is shown that our ISEL is suitable for computations of reddening parameters in various photometric systems.

Our computations confirm large variations of reddening parameters of the \textit{UBV} system with MK spectral types and luminosities of stars. These variations must be taken into account in investigations of physical properties of stars based on \textit{UBV} photometry. The variations of reddening parameters of the Vilnius and \textit{uvby} systems with MK spectral types and luminosities are much smaller in comparison with those of the \textit{UBV} system. It is shown that the ratio of total to selective extinction, \( R_{YV} = A_V/E_{Y-V} \), is almost constant over the spectral range O - K0. For this spectral range we have deduced \( R_{YV} = 4.21 \).
ACKNOWLEDGMENTS. J. S. gratefully acknowledges the individual grant from the American Astronomical Society.

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