Baltic Astronomy, vol. 5, 485–502, 1996.

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

J. Sūdžius, V. Bobinas, S. Raudeliūnas

Vilnius University Observatory,
Čiurlionio 29, Vilnius 2009, Lithuania

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 Straižys (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 Sūdžius (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., Straižys 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 & Straižys (1966b, 1969), Kurilienė

& Sūdžius (1974), Straižys et al. (1976), Straižys (1977). The parameters of the Vilnius photometric system have been analysed by Sviderskienė & Straižys (1971), Kurilienė & Sūdžius (1974). These investigations have been extended and well summarized in the monographs of Straižys (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 Straižys (1977, 1992).

2. BASIC RELATIONS

Heterochromatic color indices are defined by the expression

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

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

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

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

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

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

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:

$$k_{ijl} = \frac{E_{i-l}}{E_{j-l}} \tag{4}$$

and

$$R_{jl} = \frac{A_l}{E_{j-l}}. \tag{5}$$

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

$$\lambda_e = \frac{\int \lambda F(\lambda)\varphi(\lambda)d\lambda}{\int F(\lambda)\varphi(\lambda)d\lambda}. \tag{6}$$

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

$$\lambda_i < \lambda_j < \lambda_l. \tag{7}$$

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., Kurilienė 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., Kurilienė 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 (Straižys 1992).

The ISEL in an absolute form will be obtained by the addition of the ratio of total to selective extinction to the ratios $k_{im_1m_2}$

$$k^0_{im_1m_2} = k_{im_1m_2} + R_{m_1m_2} = \frac{A_i}{E_{m_1-m_2}}. \quad (8)$$

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 *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 Straižys & Kazlauskas (1993). The source of the *UBVRIJHKL* photometry was the catalogue of Morel & Magnenat (1978).

The source of intrinsic color indices in the *UBV* and Arizona systems was the monograph of Straižys (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 $k_{BVi} = E_{V-i}/E_{B-V}$, where i is one of the magnitudes, R, I, J, H, K, L.

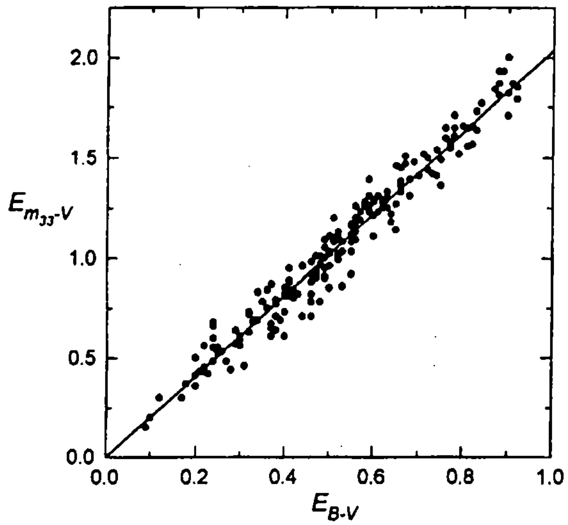

Fig. 1. The two color diagram $E_{m_{33}-V}$ versus E_{B-V}. The continuous line is the least square solution forced through the origin.

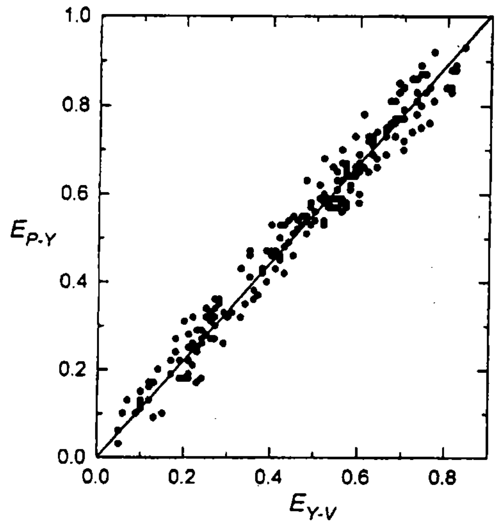

Fig. 2. The two color diagram E_{P-Y} versus E_{Y-V}. The continuous line is the least square solution forced through the origin.

Table 1. Color excess ratios in the Vilnius photometric system

$\frac{E_{U-Y}}{E_{Y-V}}$	$\frac{E_{P-Y}}{E_{Y-V}}$	$\frac{E_{X-Y}}{E_{Y-V}}$	$\frac{E_{Y-Z}}{E_{Y-V}}$	$\frac{E_{V-S}}{E_{Y-V}}$	n
1.600	1.120	0.753	0.651	0.835	220
±.003	±.002	±.002	±.002	±.002	

Table 2. Color excess ratios in the Arizona system *BVRIJHKL*

$\frac{E_{V-R}}{E_{B-V}}$	$\frac{E_{V-I}}{E_{B-V}}$	$\frac{E_{V-J}}{E_{B-V}}$	$\frac{E_{V-H}}{E_{B-V}}$	$\frac{E_{V-K}}{E_{B-V}}$	$\frac{E_{V-L}}{E_{B-V}}$	n
0.816	1.599	2.311	2.675	2.856	2.986	64
±.012	±.013	±.030	±.035	±.029	±.033	

Table 3. Color excess ratios for the ANS data

$\frac{E_{15-V}}{E_{B-V}}$	$\frac{E_{18-V}}{E_{B-V}}$	$\frac{E_{22-V}}{E_{B-V}}$	$\frac{E_{25-V}}{E_{B-V}}$	$\frac{E_{33-V}}{E_{B-V}}$	n
5.170	4.903	6.615	4.209	2.065	197
±.003	±.002	±.002	±.002	±.002	

The results are given in Table 2. From the ratio E_{V-K}/E_{B-V} we immediately obtain the ratio $R_{BV} = 1.1E_{V-K}/E_{B-V} = 3.14$. Color excesses in the photometric system of the ANS combined with E_{B-V} enable us to compute ratios $k_{iBV} = E_{i-V}/E_{B-V}$, 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 & Sūdžius (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 $k_{\lambda YV} = E_{\lambda-V}/E_{Y-V}$. 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 $k_{BYV} = E_{B-V}/E_{Y-V} = 1.35$ (Kurilienė & 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 (Straižys 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

$$\frac{A_\lambda}{E_{B-V}} = \frac{k_{\lambda YV}}{k_{BYV}} + R_{BV}, \tag{9}$$

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 Krełowski & 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 Krełowski & Papaj (1992). The ultraviolet extinction bump at 220 nm is wider than that of Savage & Mathis (1979) and Krełowski & 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

λ, nm	$\frac{A_\lambda}{E_{B-V}}$	λ, nm	$\frac{A_\lambda}{E_{B-V}}$	λ, nm	$\frac{A_\lambda}{E_{B-V}}$	λ, nm	$\frac{A_\lambda}{E_{B-V}}$
150	8.310	232	8.820	405	4.426	610	2.730
155	8.189	233	8.722	410	4.384	615	2.705
160	8.094	234	8.625	415	4.342	620	2.679
165	8.028	235	8.529	420	4.297	625	2.650
170	7.993	236	8.435	425	4.249	630	2.625
175	7.996	237	8.342	430	4.201	635	2.599
180	8.044	238	8.251	435	4.150	640	2.573
185	8.147	239	8.162	440	4.102	645	2.548
190	8.318	240	8.076	445	4.057	650	2.522
195	8.568	245	7.681	450	4.009	655	2.495
200	8.896	250	7.349	455	3.958	660	2.466
202	9.044	255	7.071	460	3.916	665	2.437
203	9.120	260	6.819	465	3.881	670	2.410
204	9.196	265	6.604	470	3.849	675	2.381
205	9.272	270	6.417	475	3.813	680	2.354
206	9.346	275	6.252	480	3.769	685	2.323
207	9.419	280	6.107	485	3.721	690	2.292
208	9.489	285	5.979	490	3.663	695	2.262
209	9.555	290	5.863	495	3.608	700	2.232
210	9.616	295	5.759	500	3.557	800	1.748
211	9.671	300	5.663	505	3.509	900	1.410
212	9.718	305	5.581	510	3.458	1000	1.164
213	9.758	310	5.502	515	3.406	1100	0.979
214	9.788	315	5.427	520	3.352	1205	0.828
215	9.809	320	5.353	525	3.307	1650	0.465
216	9.820	325	5.280	530	3.256	2140	0.280
217	9.820	330	5.209	535	3.208	3410	0.154
218	9.809	335	5.151	540	3.166	5000	0.083
219	9.787	340	5.095	545	3.121	7000	0.061
220	9.755	345	5.041	550	3.076	9000	0.137
221	9.713	350	4.986	555	3.048	9700	0.182
222	9.662	355	4.932	560	3.009	10000	0.168
223	9.602	360	4.868	565	2.974	12000	0.086
224	9.533	365	4.807	570	2.942	15000	0.046
225	9.458	370	4.749	575	2.913	18000	0.072
226	9.378	375	4.695	580	2.887	20000	0.065
227	9.292	380	4.643	585	2.858	25000	0.042
228	9.202	385	4.595	590	2.836	35000	0.011
229	9.109	390	4.557	595	2.810	60000	0.006
230	9.013	395	4.518	600	2.785	100000	0.004
231	8.917	400	4.470	605	2.759	250000	0.001

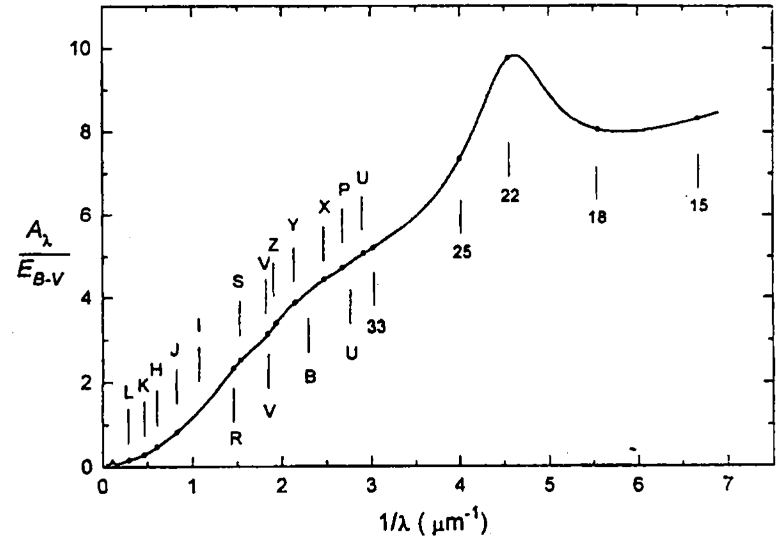

Fig. 3. The mean interstellar extinction law. Dots are original data derived from the color excess ratios computed in the present paper. The continuous line is the interpolated extinction curve. The positions of the magnitudes used are shown.

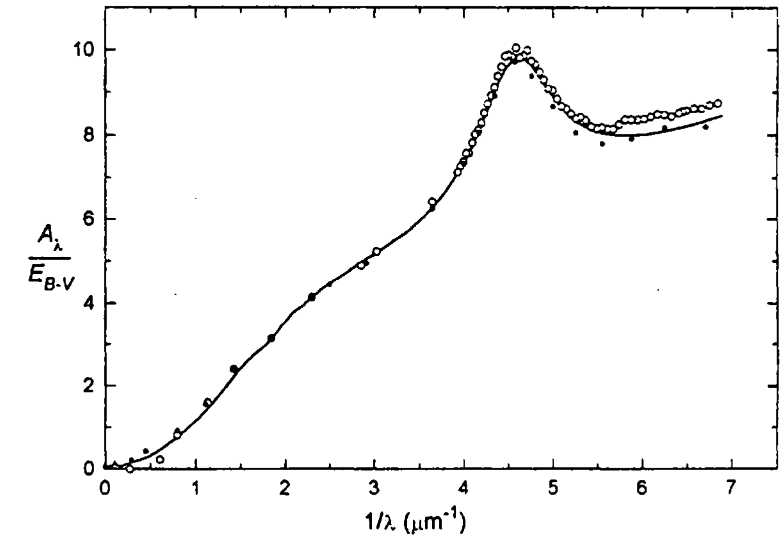

Fig. 4. The comparison of the mean ISEL (*continuous line*) with that of Savage & Mathis (1979) (*dots*) and that of Krełowski & Papaj (1992) (*circles*).

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 Sviderskienė (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 & Straižys (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., Straižys 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 (Straižys 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., Kurilienė & Sūdžius 1974; Straižys et al. 1976; Straižys 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 Straižys (1992).

The reddening parameters in the Vilnius photometric system for various MK spectral types and luminosity classes have been

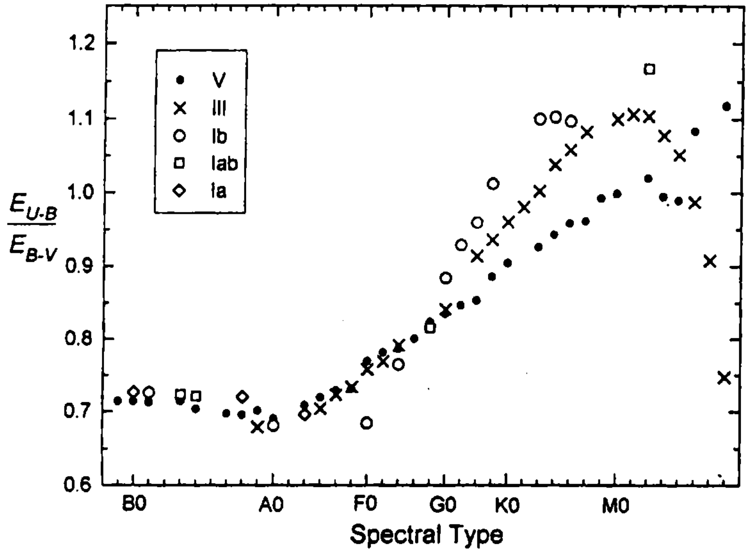

Fig. 5. Color excess ratios E_{U-B}/E_{B-V} versus MK spectral type for different luminosity classes.

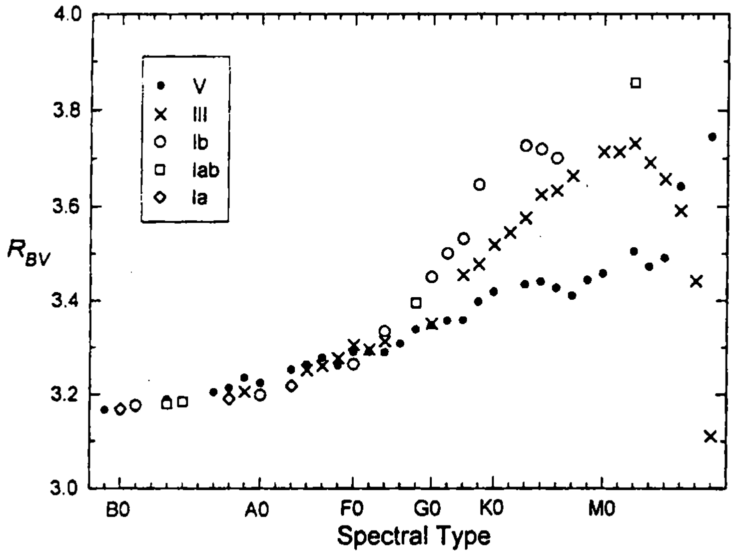

Fig. 6. Ratios of total to selective extinction $R_{BV}=A_V/E_{B-V}$ versus MK spectral type for different luminosity classes.

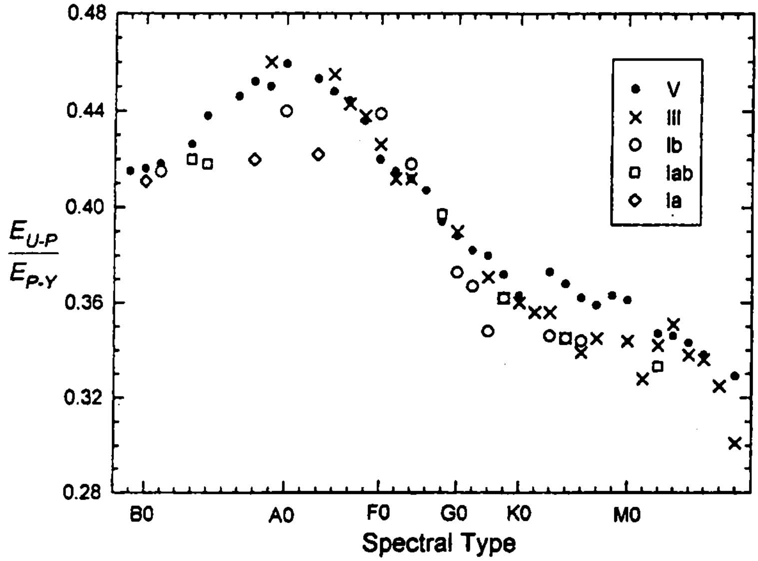

Fig. 7. Color excess ratios E_{U-P}/E_{P-Y} versus MK spectral type for various luminosity classes.

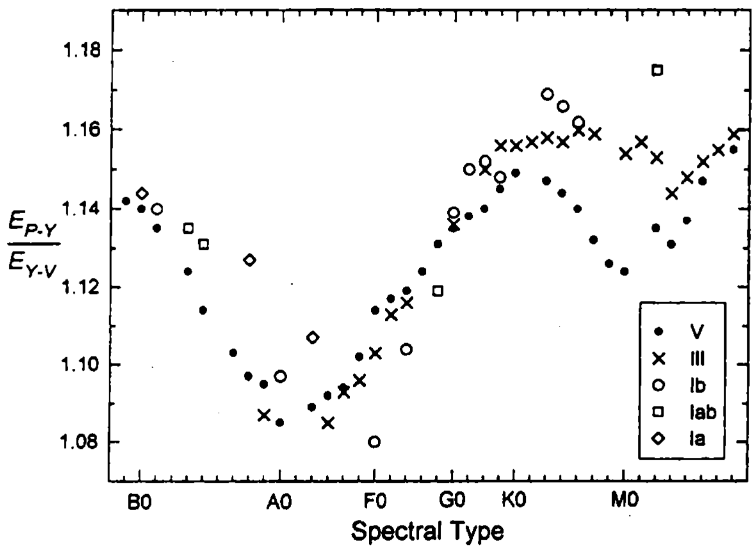

Fig. 8. Color excess ratios E_{P-Y}/E_{Y-V} versus MK spectral type for various luminosity classes.

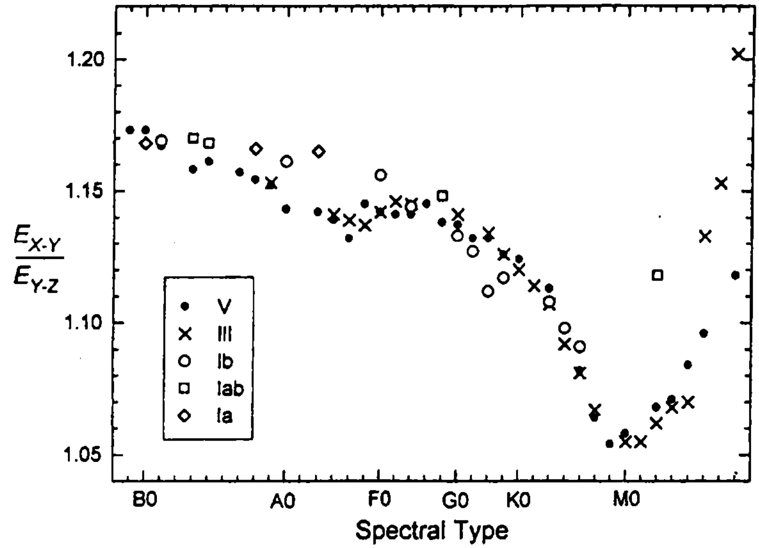

Fig. 9. Color excess ratios E_{X-Y}/E_{Y-Z} versus MK spectral type for various luminosity classes.

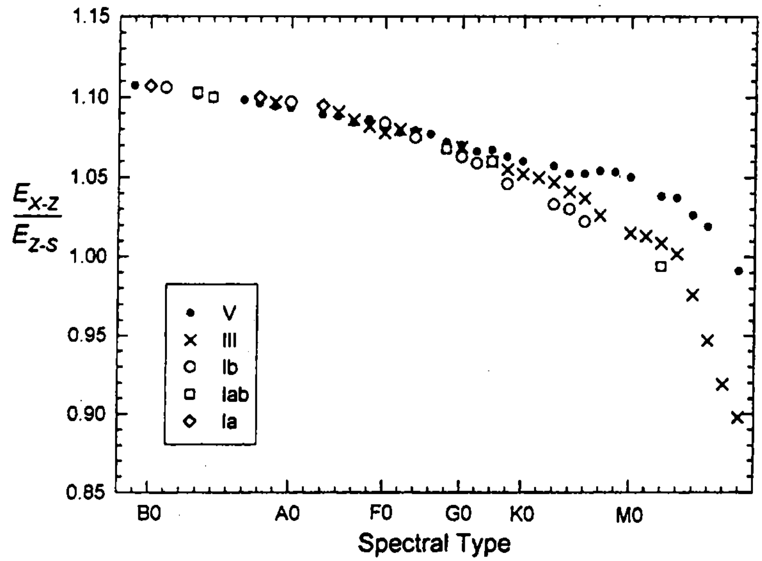

Fig. 10. Color excess ratios E_{X-Z}/E_{Z-S} versus MK spectral type for various luminosity classes.

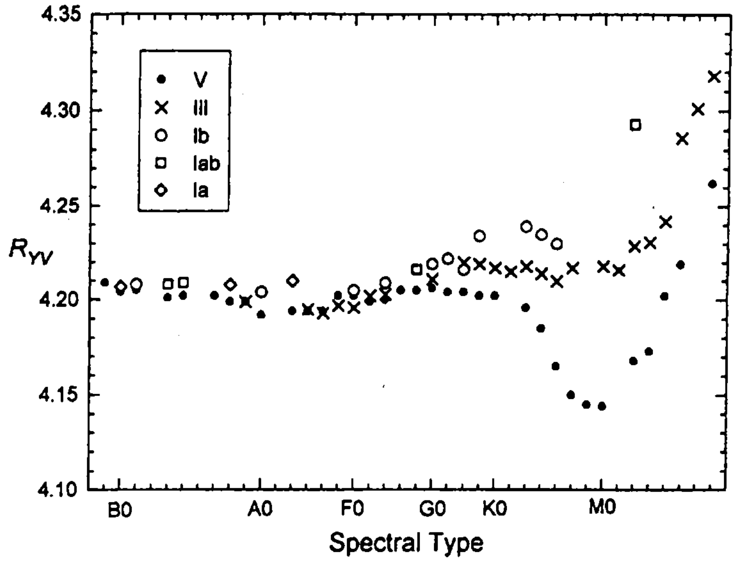

Fig. 11. Ratios of total to selective extinction, $R_{YV}=A_V/E_{Y-V}$, versus MK spectral type for various luminosity classes.

computed using the response functions from Straižys & 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 & Sūdžius (1974) and Straižys (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.

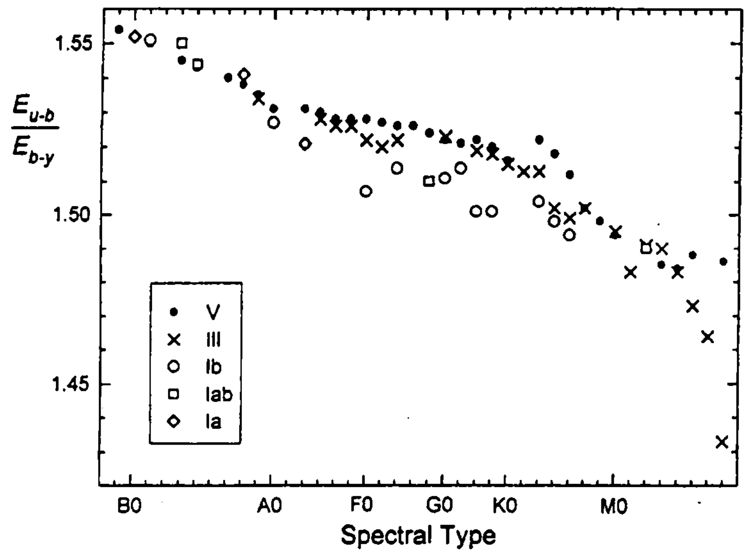

Fig. 12. Color excess ratios E_{u-b}/E_{b-y} versus MK spectral type for various luminosity classes.

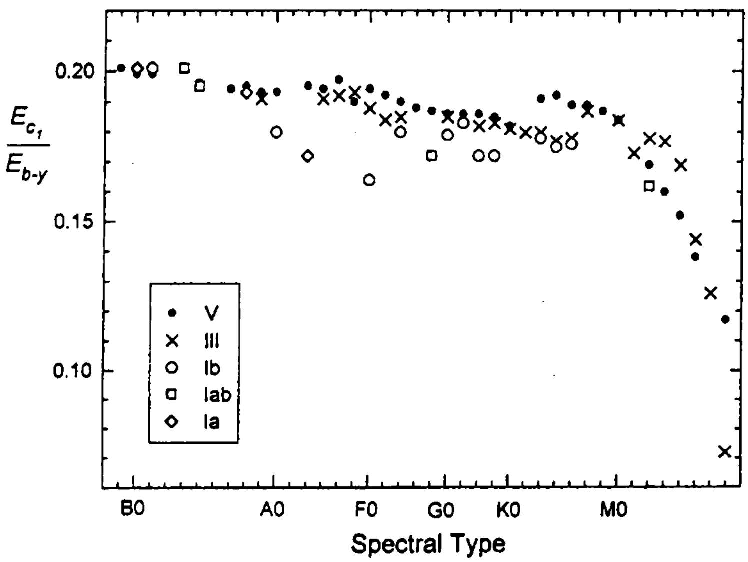

Fig. 13. Color excess ratios E_{c_1}/E_{b-y} versus MK spectral type for various luminosity classes.

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 *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 *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 μm. 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 *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 *UBV* photometry. The variations of reddening parameters of the Vilnius and *uvby* systems with MK spectral types and luminosities are much smaller in comparison with those of the *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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