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INTERSTELLAR EXTINCTION LAW IN THE VICINITY OF THE NORTH AMERICA AND PELICAN NEBULAE

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Abstract. The interstellar reddening law is derived for 15 heavily reddened stars in the area which includes the North America and Pelican nebulae and the dark cloud between them. The method is based on photometry of these stars in the Vilnius seven-color system and on their MK spectral types. The mean law in this area is very similar to the law for a much wider area in Cygnus derived earlier by other authors. It differs from the normal law by exhibiting somewhat stronger extinction in the violet and the near ultraviolet spectral region, i.e., it shows a smaller "knee" in the blue part of the spectrum.

Key words: stars: fundamental parameters, classification – interstellar medium: extinction

1. INTRODUCTION

Soon after the implementation of the *UBV* photometric system it was shown that stars in the Great Cygnus Rift exhibit an anomalous interstellar reddening law: the reddening line in the $U-B$,$B-V$ diagram for this area has a somewhat larger slope in comparison with other Milky Way areas for which the normal interstellar reddening law is valid (Johnson & Morgan 1955, Hiltner & Johnson 1956). Later on, Serkowski (1963) has analyzed *UBV* observations of B-type stars compiled from many publications and estimated that the difference in E_{U-B}/E_{B-V} is about 0.05 and that the Cygnus anomaly is present between the galactic longitudes 74 and 85 deg. Despite the critical papers by Divan (1956), Rozis-Saulgeot (1956) and Schalen (1959), the Cygnus Rift anomaly was confirmed by more careful analysis of *UBV* and *RI* observations done by Wampler (1961, 1962, 1964), Borgman & Johnson (1962), Johnson & Borgman (1963), Bogdanovich & Straižys (1966) and Ažusienis, Straižys & Sūdžius (1966) as well as by a new medium-band photometry by Borgman (1961), Köhler (1967), Goy (1972), Sūdžius (1974) and Lucke (1980).

A lower blue "knee" of the interstellar extinction law in Cygnus was confirmed by spectrophotometric observations by Nandy (1964), Whiteoak (1966) and Schild (1977). Ažusienis & Straižys (1966) confirmed the E_{U-B}/E_{B-V} anomaly in Cygnus by synthetic photometry using the Nandy and Whiteoak interstellar extinction laws. The increased extinction in the near ultraviolet has been detected by Meyer & Savage (1981) from photometric measurements by the Astronomical Netherlands Satellite (ANS).

According to Johnson & Borgman (1963) and Johnson (1965, 1968, 1977), the Cygnus stars show no anomaly in the infrared wavelengths. The ratio $R = A_V/E_{B-V}$ also seems to be normal (Johnson & Borgman 1963, Fernie & Marlborough 1963, Gammelgaard 1968, Grubissich 1968, Serkowski 1968, Voelcker & Elsasser 1973, Rieke 1974, Serkowski et al. 1975, Herbst 1975, Turner 1976, Whittet 1977, 1979, McMillan & Tapia 1977, Tapia 1981, Torres et al. 1991).

It is highly improbable, that the Cygnus Rift anomaly is related to intrinsic properties of the individual stars. This question has been raised in many of the cited papers and answered negatively. Most probably, the anomaly is related with the composition of interstellar dust grains or their alignment. Greenberg & Meltzer (1960) and Wilson (1960) have interpreted the anomaly as the result of different orientation of elongated dielectric dust grains, aligned by the magnetic field: in Cygnus our view runs more or less along the galactic magnetic field lines, and we see dust particles along their short axes. According to theoretical calculations, this orientation leads to the enhanced extinction in the ultraviolet. However, Voshchinnikov et al. (1986) have estimated that its size is too small to be detected from observations, since it can be "washed out" by variations of the dust particle size and by variations of the radial component of the galactic magnetic field along the line of sight. The new theoretical calculations of Greenberg & Chlewicki (1987) for the case of $P_{\max}/A_V = 0.03$ also exhibit the orientation effect to be of much smaller size in comparison with the case of perfect alignment.

The boundaries of the anomaly are very uncertain due to the uneven distribution of the observed stars. Therefore, it would be important to determine a more exact location of the anomaly to help its interpretation. Close to the northern boundary of the anomaly given by Serkowski, a number of heavily reddened stars have been found by Straižys et al. (1989a,b, 1993) in the course of an investigation of interstellar extinction in the vicinity of the North America and Pelican nebulae using the Vilnius photometric system. These stars are located between ℓ = 84 deg and 87 deg. Most of them are of spectral class B. For some of them the interstellar extinction A_V is as large as 4–5 mag. These stars are well suited to the determination of the interstellar extinction law, provided their MK spectral types are known.

2. MK CLASSIFICATION

For the present investigation we selected from Straižys et al. (1989a and 1993) 33 stars with A_V = (1–5) mag, listed in Table 1. Their V magnitudes are between 8.4 and 12.8, and their photometric classes are distributed as follows: 23 are B-stars, 7 are A-stars and the remaining 3 are F- and G-stars. All these stars were classified by Vilnius photometry applying some methods based on the interstellar reddening-free Q-parameters, calculated for the normal interstellar reddening law. Almost all these stars have also one-dimensional spectral classes determined from low-dispersion objective prism spectra. Only for three stars MK spectral types are available.

Grating spectra with 2.8 Å resolution and a signal-to-noise ratio of 100 or more were obtained by one of us (C.C.) by the Boller and Chivens spectrograph on the 2.3 m (90") telescope of Steward Observatory at Kitt Peak. The CCD spectra were processed and extracted using standard IRAF routines *, but they were not flux calibrated, just normalized.

* IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Heavily reddened stars in the area of the North America and Pelican nebulae. The strength of the interstellar 4430 band is indicated in last column. Notes for the stars denoted by an asterisk are given below table. Star numbers 112–249 are from Straižys et al. (1989a), star numbers 1044–1209 are from Straižys et al. (1993, Table 2). Identification charts are given in these catalogs.

No.	BD	RA(1950) Sp (Viln.)	DEC(1950) Sp (other)	V Sp (Corbally)	A_V 4430 Å band
112.	42.3880	20 48 06	+42 39.0	9.79	1.04
		A2 V	A2	A6 III	–
131.		20 49 53	+43 48.2	10.78	2.07
		B6: Vp?	B8	B2 V	mod.
140.		20 50 21	+43 52.4	10.52	2.74
		B5 V	B5	B3 V	mod.
141.	43.3747	20 50 24	+44 14.7	8.66	2.70
		Be	B1 Ve	B1 Ve *	mod.
148.	43.3751	20 50 46	+44 00.3	9.66	2.16
		B3 V	B8	B2 Vp *	mod.
1044.		20 51 00	+43 44.4	11.02	2.47
		B6: V	A0	B7 V	mod.
153.	42.3894	20 51 04	+42 25.1	8.39	2.74
		B1.5 IV	B3	B1 IV	mod.
1052.		20 51 18	+43 25.9	11.18	3.82
		B2 V	G0	B2 Vn	mod.
1057.		20 51 28	+43 36.6	12.49	4.95
		B2 V		B1 V	v.str.
163.		20 51 47	+43 57.7	11.45	3.96
		B5 V	B5	B3 V	mod.
176.	44.3627	20 53 01	+44 39.2	9.85	3.02
		B3 III	B8	B2 III	str.
177.	44.3629	20 53 18	+44 34.0	10.06	1.53
		B8 III	B8	B8 V	wk.
1130.		20 54 12	+42 30.3	11.61	1.04
		F0 V	F5	F3 V *	v.wk.
190.		20 54 18	+45 10.0	11.27	1.98
		B3 V	B5	B5 IV *	wk.

Table 1 (continued)

No.	BD	RA(1950) Sp (Viln.)	DEC(1950) Sp (other)	V Sp (Corbally)	A_V 4430 Å band
195.	42.3914	20 54 35	+42 56.2	8.43	4.05
		B2 IV	B0 III	B0.5 IV	mod.
197.		20 54 37	+44 27.8	11.13	1.80
		B6 V	A2	B5 V	wk.
1174.		20 56 07	+43 15.3	10.92	3.22
		A8 II	A0	A3 III	wk.
1178.		20 56 09	+43 02.6	12.28	2.29
		A0 V		A0.5 III-IV	wk.
218.	44.3655	20 56 39	+44 57.3	9.19	1.62
		B3 III	B1 IV	B1 IV	mod.
1190.		20 56 46	+43 36.5	12.81	1.15
		A6 V		F0 V	–
1191.		20 56 48	+43 00.0	10.04	1.08
		B9 IV	A0	A0 IV	v.wk.
1196.		20 57 00	+42 51.8	11.31	1.22
		A2 V	A2	A2 V	v.wk.
1198.		20 57 12	+42 44.0	11.34	2.79
		B9 III	A0	B9.5 IV-V *	mod.
1205.		20 57 24	+43 33.5	11.90	1.08
		A7 V		F0 V	–
226.		20 57 27	+44 35.2	10.33	2.07
		B7 Vp?	A2	B4 III(n)	mod.
1207.		20 57 34	+43 40.8	12.42	1.76
		F5 III?		G4 V	–
230.		20 57 44	+45 05.6	11.08	1.84
		B6 V	B5	B4 III	wk.
1209.		20 57 46	+43 02.4	12.02	1.13
		A5 V	A0	A5 Vm *	–
236.	44.3664	20 58 10	+45 08.4	10.19	2.43
		B2.5 V	B9	B1 Vn	mod.
238.	42.3935	20 58 16	+42 24.2	9.83	3.06
		G9 II?	cG0:	G1 Ib	mod.
239.	44.3666	20 58 19	+44 51.0	10.18	2.25
		B2 V	B5	B1 Ve *	mod.

Table 1 (continued)

No.	BD	RA(1950) Sp (Viln.)	DEC(1950) Sp (other)	V Sp (Corbally)	A_V 4430 Å band
245.	42.3937	20 59 10	+42 34.8	9.34	1.76
		B8 III	A0	B8 III-IV	mod.
249.		20 59 36	+43 58.2	11.18	2.56
		B6.5 V	B8	B5 III	mod.
Two stars of low reddening as a check:					
242.	42.3936	20 58 40	+43 21.9	8.36	0.40
		B9 V	A0, A2	B9 V	–
246.	42.3939	20 59 21	+43 20.2	8.57	0.14
		F0 V	F0	F0 V	–

Notes to MK classifications:

140. Fill-in by emission of Balmer-line cores and the Fe II (42) nebular lines;
148. Helium (=B3 strength) is slightly too weak;
1130. Fe I 4046 slightly weak;
190. Luminosity is a compromise: He I 4121 = V; H-wings = III–IV;
1198. Mild shell star;
1209. A2 according to K-line, A5 according to H lines and A7 according to metallic lines;
239. Emission fill-in in same lines as 140, but a little stronger.

MK spectral classification has been done by the same author using a grid of standard star spectra established for this spectrograph. The results are given in Table 1 together with other estimates of spectral types collected from the literature. A comparison of the present results with the three MK types from the literature suggests the usual accuracy of better than a luminosity class and a temperature subclass.

3. EXTINCTION LAW DETERMINATION

For the extinction law determination 15 early B-type stars were selected. We have limited ourselves to B0–B5 stars since these stars give the highest accuracy of the extinction law. For cooler stars the ultraviolet color indices vary with the temperature so rapidly that any error of spectral class determination leads to large errors of color excesses and their ratios. We have also rejected two stars of early B subclasses: the star 131 shows contradiction between its spectroscopic and photometric spectral classes, and its Q-parameters seem to be peculiar. A similar situation holds with the star 190 which photometrically is B3 V and spectroscopically is about B5 IV. Two Be stars (141 and 239) have Hβ in emission, and so presumably Hα should be also in emission; for them the ratio E_{V-S}/E_{Y-V} was not calculated.

For deriving the interstellar reddening law we used the following sequence of calculations.

• Intrinsic color indices $(U-V)_0$, $(P-V)_0$, $(X-V)_0$, $(Y-V)_0$, $(Z-V)_0$ and $(V-S)_0$ for each star were taken from the Straižys (1992) monograph according to their MK spectral types;

• Color excesses E_{U-V}, E_{P-V}, E_{X-V}, E_{Y-V}, E_{Z-V} and E_{V-S} were calculated as differences of the observed and the intrinsic color indices:

$$E_{U-V} = (U-V)_{\rm obs} - (U-V)_0,$$
$$E_{P-V} = (P-V)_{\rm obs} - (P-V)_0,$$
$$E_{X-V} = (X-V)_{\rm obs} - (X-V)_0,$$
$$E_{Y-V} = (Y-V)_{\rm obs} - (Y-V)_0,$$
$$E_{Z-V} = (Z-V)_{\rm obs} - (Z-V)_0,$$
$$E_{V-S} = (V-S)_{\rm obs} - (V-S)_0.$$

Observed color indices were taken from Straižys et al. (1989a, 1993).

• Ratios of color excesses with respect to E_{Y-V}, i.e. E_{m-V}/E_{Y-V}, were calculated.

These ratios are given in Table 2 and their arithmetic mean values (circles) are plotted in Fig. 1 as a function of the reciprocal effective wavelengths of the passbands taken from Kuriliene (1983). The y-axis gets normalized to 1.0 at λ_e^{-1} of the Y passband, and to 0.0 at λ_e^{-1} of the V passband. The crosses for each passband represent the normal interstellar extinction law from Straižys (1992). A systematic displacement of the circles upwards for the X, P and U passbands is evident. The scatter of the ratios for individual stars can be explained either by real differences of the extinction

Table 2. Color-excess ratios E_{m-V}/E_{Y-V} for 15 B0–B5 stars used to derive the mean interstellar reddening law for the North America and Pelican nebulae area. The m passbands are $U,P,X,Y,Z,$ V and S.

m	λ^{-1}	140	141	148	153	1052	1057	163	176
U	2.925	2.91	2.76	2.84	2.76	2.54	2.74	2.74	2.83
P	2.683	2.36	2.23	2.33	2.18	2.14	2.18	2.26	2.23
X	2.479	1.83	1.83	1.88	1.84	1.81	1.80	1.74	1.80
Y	2.152	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Z	1.943	0.33	0.35	0.35	0.34	0.35	0.33	0.32	0.38
V	1.843	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S	1.541	0.91	–	0.92	0.82	0.92	0.89	0.87	0.94

m	λ^{-1}	195	197	218	226	230	236	239	Mean
U	2.925	2.94	2.68	3.05	3.00	3.00	3.00	2.88	2.83
P	2.683	2.30	2.22	2.32	2.35	2.35	2.35	2.35	2.27
X	2.479	1.86	1.80	1.83	1.86	1.79	1.82	1.88	1.82
Y	2.152	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Z	1.943	0.33	0.32	0.36	0.37	0.28	0.33	0.36	0.34
V	1.843	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S	1.541	0.87	0.95	0.93	0.96	0.88	0.95	–	0.91

law or by the limitation in the accuracy of inferring intrinsic colors from spectral classification. This limitation comes both from the "cosmic scatter" within a spectral subclass and from any errors in the spectral classification itself. For an estimate of such errors we took the intrinsic colors of stars differing from our MK spectral class by ± 1 subclass. In this case, for the B0–B5 stars the E_{m-V}/E_{Y-V} errors are listed in Table 3.

The errors show that the observed scatter of color-excess ratios can be explained exclusively by spectral class errors and the impossibility of giving spectral classes to tenths of a subclass.

To obtain the average extinction law for the North America and Pelican area we took the arithmetic mean of points of all 15 stars.

Table 3. Errors of color-excess ratios for B0–B5 stars, including U, P, X and S passbands. For $\Delta(E_{V-S}/E_{Y-V})$ errors are negligible.

	$\Delta\frac{E_{U-V}}{E_{Y-V}}$	$\Delta\frac{E_{P-V}}{E_{Y-V}}$	$\Delta\frac{E_{X-V}}{E_{Y-V}}$	$\Delta\frac{E_{V-S}}{E_{Y-V}}$
Absolute error	±0.23	±0.13	±0.02	±0.01

Table 4. The North America and Pelican (NA+P) interstellar extinction law compared to the Cygnus law and the normal law.

	$\frac{E_{U-V}}{E_{Y-V}}$	$\frac{E_{P-V}}{E_{Y-V}}$	$\frac{E_{X-V}}{E_{Y-V}}$	$\frac{E_{Z-V}}{E_{Y-V}}$	$\frac{E_{V-S}}{E_{Y-V}}$
NA+P	2.83±0.20	2.27±0.10	1.82±0.02	0.34±0.01	0.91±0.01
Sūdžius (1974) law for O-stars	2.75	2.24	1.81	0.36	0.91
Sūdžius (1974) synthetic	2.76	2.25	1.81	0.36	0.90
Sūdžius (1974) normal law	2.62	2.14	1.76	0.36	0.84

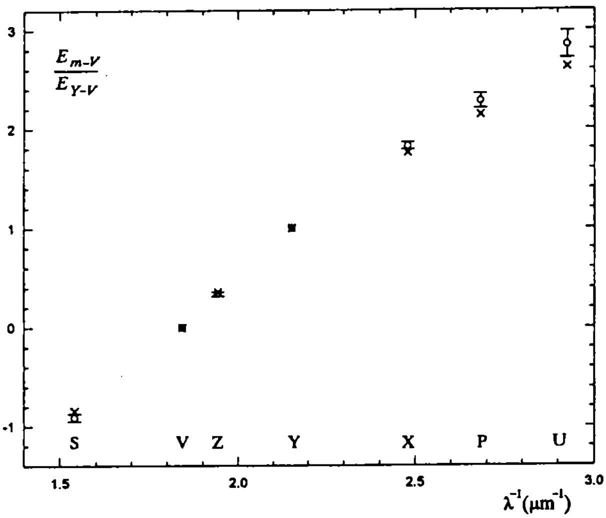

Fig. 1. Interstellar reddening law in the North America and Pelican nebulae area. The circles with the error bars are for the North America and Pelican area and the crosses are for the normal extinction law.

The results are given in Table 4. The other lines in Table 4 give color-excess ratios from Sūdžius (1974): the 2nd line gives the values for Cygnus from observations of O-type stars at ℓ = 72–81 deg, the 3rd line gives the synthetic color-excess ratios calculated for the Cygnus extinction law and the 4th line gives the values obtained from observations of O-stars elsewhere except Cygnus. It is seen that the values of E_{m-V}/E_{Y-V} for the North America and Pelican nebulae are very close to the values obtained for O-type stars in Cygnus at smaller galactic longitudes. This means that the Cygnus Rift anomaly also includes the area of the North America and Pelican nebulae, extending the galactic longitude range up to 87 deg.

The overall majority of the stars used for the extinction law determination (14 from 15) are situated at distances 450–900 pc (Straižys et al. 1989a, 1993), i.e., most of them should belong to the North America and Pelican nebulae complex. Consequently, they should be reddened predominantly by the dark cloud at the distance of the nebulae, at 580±100 pc (Straižys et al. 1993).

4. DISCUSSION AND CONCLUSIONS

To our knowledge, the Cygnus Rift anomaly is the largest region of the Milky Way to show a well confirmed, uniform peculiarity of the interstellar extinction law. If the anomaly extends from ℓ = 74 deg to ℓ = 87 deg, i.e. by 13 deg, at a distance of 580 pc it should be about 134 pc wide. If it has a similar depth, the size of the anomaly would be comparable to large stellar associations, such as the Orion OB1 association. However, the size of the anomaly probably is considerably larger, which follows from the following considerations.

It is considered that the dark clouds of the Great Cygnus Rift extend from 500 pc to 2000 pc (Bochkarev & Sitnik 1985). This oblong structure should be about 290 pc across in the middle (at 1250 pc distance), i.e., the ratio of axes of the structure is 1:5. The dust cloud separating the North America and Pelican nebulae probably belongs to the same Rift system, being in the front side of it, at a distance of 580 pc from the Sun. A similar distance for another dark cloud at the galactic longitude 90 deg has been found (Straižys, Kalytis & Sūdžius 1979). In the volume of the Great Cygnus Rift Cash et al. (1980) have identified a giant superbubble of gas, dust and luminous stars, emitting soft X-rays.

Our investigation shows that the same type of anomaly of the extinction law is valid for the stars both near the front edge of the structure (in the North America and Pelican area) and in all its volume, including the far edge at 2 kpc (O-type stars investigated by Sūdžius 1974). Somewhere in the middle of this structure the associations Cyg OB1, Cyg OB2 and Cyg OB9 are situated, their distances being 1.8, 1.8 and 1.2 kpc, respectively (Bochkarev & Sitnik 1985).

It is highly improbable that dust particles in the whole of the structure are modified by the radiation of hot luminous stars. Most of them are too far from the front edge of the structure. Probably, the region of the North America and Pelican nebulae is not even seen from these OB-associations, being covered by dark clouds of the Rift.

On the other hand, hot luminous stars usually modify the interstellar extinction law in the opposite direction: they remove small dust particles from their vicinity, making the extinction law similar to that observed in the Orion OB1 association. This law has a larger break of slope near the blue "knee" and shows lower extinction in the ultraviolet, opposite to what is observed in Cygnus.

Therefore, it is more acceptable that the anomaly of the extinction law in Cygnus is the intrinsic property of dust particles within all this huge volume of space due to their alignment by the galactic magnetic field. Another global agent, which could affect the dust chemistry, is the X-ray radiation within the Cygnus superbubble, described by Cash et al. (1980).

The anomalous interstellar extinction law in Cygnus should be taken into account when classifying reddened stars by their multicolor photometric Q-parameters. The methods of stellar classification in the presence of anomalous interstellar reddening are described by one of the authors (Straižys 1992, 1999).

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