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ON THE HOMOGENEITY OF THE EXTINCTION LAW IN OUR GALAXY *

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ABSTRACT

We analyze the extinction law towards several B1V stars – members of our Galaxy, searching for possible discrepancies from the galactic average extinction curve. Our photometric data allow to build extinction curves in a very broad range: from extreme UV till infrared. Two–colour diagrams, based on the collected photometric data from the *ANS* UV satellite, published UBV measurements and on the infrared 2MASS data of the selected stars, are constructed. Slopes of the fitted straight lines are used to build the average extinction curve and to search for discrepant objects. The selected stars have also been observed spectroscopically from the Terskol and ESO Observatories; these spectra allow to check their Sp/L's. The spectra of only about 30% of the initially selected objects resemble closely that of HD144470, considered as the standard of B1 V type. Other spectra either show some emission features or belong clearly to another spectral types. They are not used to build the extinction curve. Two-colour diagrams, constructed for the selected B1 V stars, showing no emission stellar features, prove that the interstellar extinction law is homogeneous in the Galaxy. Both the shape of the curve and the total–to–selective extinction ratio do not differ from the galactic average and the canonical value (3.1) respectively. The circumstellar emissions usually cause some discrepancies from the average interstellar extinction law; the discrepancies observed in the extraterrestrial ultraviolet, usually follow some misclassifications.

Key words : ISM — clouds — dust: extinction

I. INTRODUCTION

The interstellar extinction curve – the dependence of sum of absorption and scattering on wavelength – is typically determined (and plotted) in the form of ratios of consecutive colour excesses relative to E_{B-V}; *i.e.*, $E_{\lambda-V}/E_{B-V}$ versus $1/\lambda$. It is the continuous absorption spectrum of any HI interstellar cloud. Until now several surveys of the extinction curves, especially in the vacuum–UV spectral range, have been published. They are: Aiello et al. (1988), Fitzpatrick & Massa (1990), Papaj et al. (1991), Cardelli et al. (1989), Valencic et al. (2004). Only the last two surveys include photometric measurements in the infrared, constructing thus extinction curves in a very broad range of wavelengths.

In a typical plot of an extinction curve the value of the total–to–selective extinction ratio ($R = A_V/E_{B-V}$) is represented by the point in which the curve intersects the ordinate axis (i.e., for $1/\lambda = 0$). The extinction for infinite wavelength should be zero by definition. The value of the parameter R is needed to "translate" the curve into absolute extinctions, necessary to deredden real stars; its "canonical" value is believed to be about 3.1. Let's mention, however, a serious difficulty faced in the infrared. When considering the radiative transfer equation in the ultraviolet or visual wavelength ranges we may neglect the re-emission term due to the low temperature of interstellar grains. In the infrared it can easily be a much too simplistic approximation. This makes the determinations of the R value, based on the far–IR photometry, quite uncertain. An extrapolation of the near–IR extinction curve may give better results.

It seems likely that more than one population of dust particles is responsible for the whole extinction curve. The visual and infrared extinction is believed to be caused by relatively big dust particles (of the diameter up to several tenths of a micrometer) while the 2200 Å bump is probably originated in small carbonaceous particles or polycyclic aromatic hydrocarbons (PAHs) while the far–UV growth is most proba-

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*Based on observations obtained on Terskol and ESO Observatories, with ANS UV satellite and infrared 2MASS data.

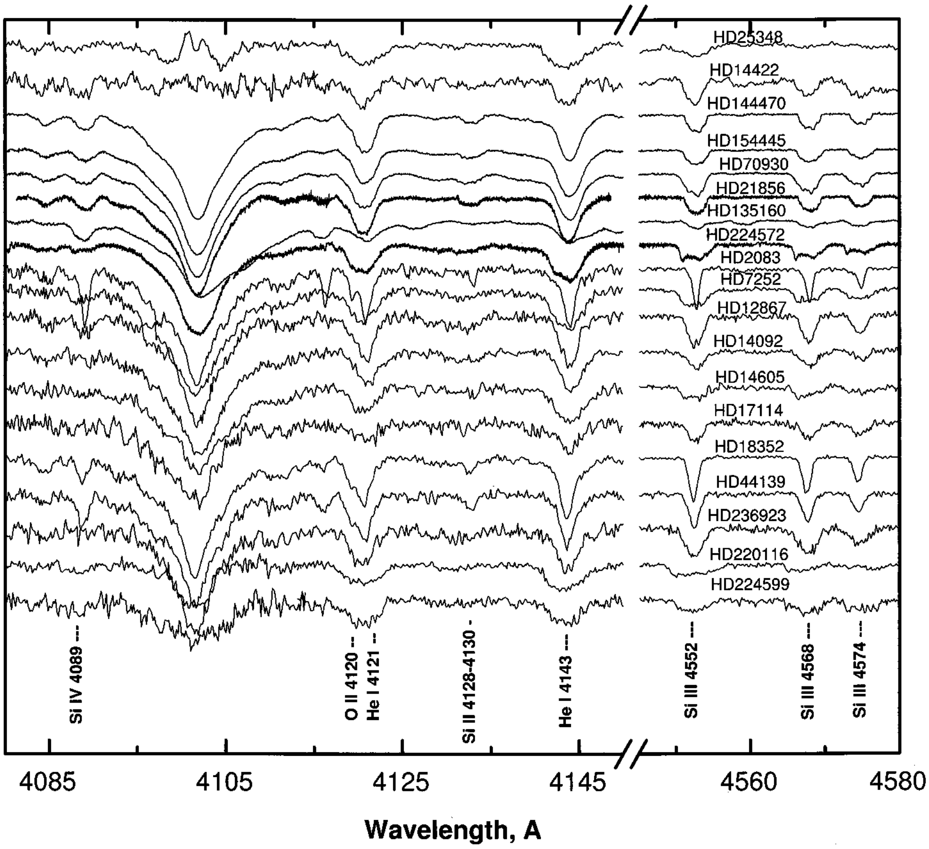

Fig. 1.— The spectra of the selected B1 V stars with the classification criteria, proposed by Walborn & Fitzpatrick indicated (1990). Two object in the top of the plot show evident emissions in the Balmer line.

bly due to small silicate grains, although a contribution from PAHs is also considered possible. A final shape of the extinction curve depends on the size distribution as well as on the chemical composition and crystalline structure of the grains populating the cloud under consideration.

Any realistic model must aim at reproducing the curve from far–IR to far–UV. Only in such a case one can determine the proportions between large and small dust particles and check whether their abundance ratios are constant from cloud to cloud. However, as recently emphasized by Fitzpatrick and Massa (2005), the far–UV segment of extinction curve is very sensitive to Sp/L uncertainties. This makes difficult to answer the especially interesting question: whether the observed peculiarities of extinction in the vacuum–UV are accompanied by those in the infrared.

Our recent paper (Megier et al. 2005) demonstrated that carriers of different interstellar absorptions may not be spatially correlated. It seems likely that ionized calcium, represented by the H and K lines, fills quite evenly the interstellar space while molecules, dust grains and DIB carriers (very likely some complex, carbon–bearing species, perhaps PAHs) appear to be concentrated in relatively small but dense clumps. This makes investigations of mutual correlations between different interstellar absorptions important; only features originating in spatially correlated species may be considered as spectra formed in environments characterized by the same physical parameters.

In many cases the "interstellar" phenomena are in fact caused by some matter closely related to the observed stars. The latter, typically young, early type objects, have recently been formed out of interstellar clouds and are likely embedded in the remnants of their parent clouds. Such clouds have being right after the

TABLE 1.
PHOTOMETRIC DATA OF THE SELECTED B1 V STARS

STAR	$15W-V$	$18-V$	$22-V$	$25-V$	$33-V$	$U-V$	$B-V$	$J-V$	$H-V$	$K-V$	V
HD2083	−2.42	−2.21	−1.20	−1.46	−1.10	−0.80	0.03	0.02	0.15	0.16	6.89
HD7252	−1.85	−1.74	−0.56	−1.08	−0.91	−0.65	0.09	−0.15	−0.10	−0.09	7.12
HD12867	−1.27	−1.30	−0.13	−0.82	−0.79	−0.52	0.15	−0.32	−0.28	−0.28	9.41
HD14092	−0.72	−0.81	0.54	−0.39	−0.57	−0.36	0.23	−0.52	−0.57	−0.56	9.23
HD14422	0.39	0.25	1.86	0.47	−0.12	−0.13	0.49	−0.72	−0.87	−1.00	9.08
HD14605	−1.04	−1.03	0.27	−0.54	−0.59	−0.48	0.27	0.06	0.07	0.06	9.34
HD17114	0.48	0.40	2.25	0.65	−0.04	0.05	0.50	−1.10	−1.21	−1.26	9.16
HD18352	−1.23	−1.09	0.42	−0.49	−0.63	−0.42	0.21	−0.48	−0.38	−0.46	6.83
HD21856	–	–	–	–	–	−0.92	−0.06	0.11	0.18	0.22	5.90
HD25348	−0.99	−0.98	0.15	−0.58	−0.72	–	0.19	−1.09	−1.27	−1.49	8.43
HD44139	−0.36	−0.52	0.72	−0.29	−0.53	−0.29	0.29	−0.64	−0.63	−0.65	8.79
HD46660	−1.06	−0.86	0.81	−0.22	−0.51	−0.30	0.31	−0.65	−0.66	−0.77	8.04
HD49787	−2.68	−2.47	−1.64	−1.71	−1.14	−0.95	−0.11	0.22	0.36	0.35	7.48
HD70930	−2.98	−2.80	−2.40	−2.12	−1.35	−0.99	−0.15	0.31	0.37	0.34	4.82
HD135160	−3.23	−2.92	−1.99	−2.01	−1.34	−0.95	−0.08	0.13	0.20	0.21	5.73
HD144470	−2.83	−2.56	−1.57	−1.70	−1.19	−0.87	−0.05	0.19	0.22	0.04	3.97
HD154445	–	–	–	–	–	−0.50	0.16	−0.32	−0.28	−0.34	5.63
HD161056	−0.67	−0.48	1.08	0.09	−0.28	−0.11	0.37	−0.83	−0.91	−0.94	6.32
HD220116	0.65	0.60	2.42	0.84	−0.07	0.16	0.59	−1.10	−1.19	−1.33	8.69
HD224572	−2.61	−2.42	−1.69	−1.69	−1.16	−0.89	−0.06	0.31	0.29	0.27	4.88
HD224599	0.25	0.11	1.56	0.33	−0.12	−0.09	0.42	−0.96	−1.15	−1.29	9.59
HD236923	0.40	0.34	1.74	0.23	−0.39	−0.05	0.40	−0.87	−0.92	−0.97	9.68

phase of the gravitational collapse are currently irradiated by the newly born stars. Thus the extinction, originated in circumstellar matter may be characterized by different parameters, especially different extinction law. Our paper aims at finding possible discrepancies from the average extinction law and to check whether they originate in circumstellar matter or in the general interstellar medium. For this purposes we select a sample of B1V ((B-V)$_0$ = -0.23) stars because of the possibility to find both slightly and heavily reddened objects of this spectral/luminousity class.

(a) Determining Extinction Law

Let us consider a set of stars of the same spectrum and luminosity class (Sp/L). In the absence of extinction a plot of a given colour $(\lambda - V)$ vs. $(B-V)$ should reduce to a single point. If extinction is present, the relation becomes linear and can be expressed in the form:

$$\lambda - V = a_\lambda * (B-V) + b_\lambda.$$

By introducing the reddening explicitly into the equation we can rewrite the formula as:

$$\lambda - V = a_\lambda * [(B-V)_0 + E_{B-V}] + b_\lambda = (\lambda - V)_0 + a_\lambda * E_{B-V},$$

which reduces to:

$$E_{\lambda - V} = a_\lambda * E_{B-V}.$$

Therefore, we can derive the mean extinction curve of a sample from the slopes of its two-colour relations. The only assumption here is that all targets share **the same spectral type and luminosity class**, i.e. they are intrinsically identical. This method was applied in the already published papers (Papaj, Krełowski & Wegner (1993); Wegner (1994)) In this paper we decided to check, as far as possible, whether the published spectral types and luminosity classes allow such the analysis of any selected sample. We also aim at collecting stars for which photometric data cover the whole available spectral range, i.e. from far–UV till infrared.

II. THE OBSERVATIONAL MATERIAL

(a) Photometric Data

We have selected from the ANS catalogue the set of B1 V stars. We have also included objects classified as B0.5 V and B1.5 V, as half of a subtype is considered as the typical accuracy of spectral classification. Table 1. contains ANS (Wesselius et al. (1982)), U, B, V data for our targets as well as infrared 2MASS (Kleinmann et al. (1994)) magnitudes.

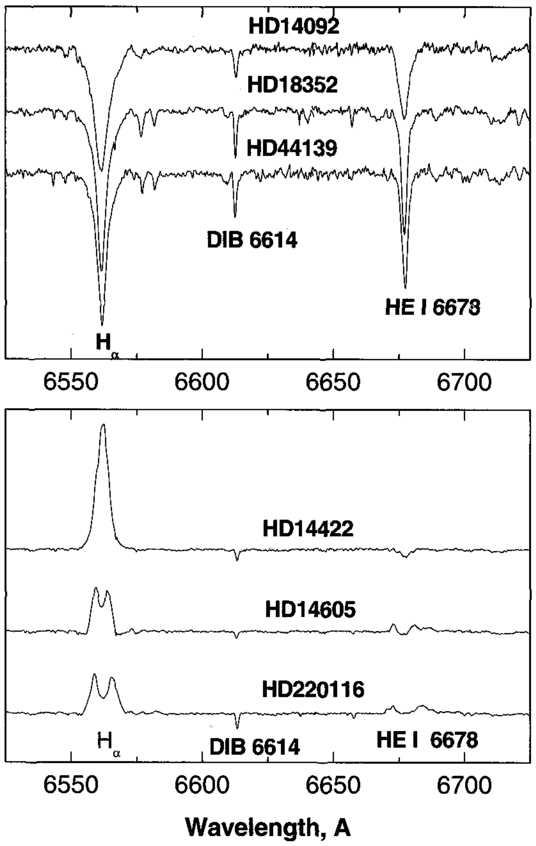

Fig. 2.— The examples of the spectra of normal stars (top panel) and those with circumstellar emissions (bottom panel). The latter are marked with open symbols in Fig. 3.

The fact that the vacuum–UV segments of extinction curves already exist motivated us to extend them into the infrared region. Such an extension can help us answering the question of whether the behaviour of an extinction curve in the infrared is related to that in the far–UV as already postulated by Cardelli et al. (1989).

(b) Spectral Observations

The observations have been conducted at the Observatory on top of the peak Terskol (Northern Caucasia), equipped with the Cassegrain echelle spectrometer fed by the 2m telescope. The spectral range, covered in one exposure is ~ 3700 – 7280 Å divided into 31 orders. The resolution of the recorded spectra ($R = \lambda/\delta\lambda$) is close to 14,000. While using such a resolution one can easily acquire spectra of relatively faint stars, some of them – because of high reddening. The S/N ratio of our spectra varies between 250 and 350, allowing reasonably precise measurements of the strengths of interstellar absorption features. All spectral observations have been conducted by the end of 2004 and beginning of 2005 by one of us (AB).

We have also included several stellar spectra acquired at ESO using the Feros spectrograph, fed with the 2.2m telescope. In this case the resolution was R=48,000 and the spectral range: ~ 3700 – 9000 Å.

III. RESULTS

The collected spectra allowed us to check the spectral types and luminosity classes of the selected stars. We aimed especially at picking from the original sample the objects whose spectra resemble as closely as possible that of HD144470 which is considered as the standard B1 V star (Walborn and Fitzpatrick (1990)). Only about 30% of the originally selected (i.e. according to literature data) objects clearly belong to this spectral type. Spectral types of other objects are either uncertain (e.g. because of very rapid rotation) or show evident circumstellar emissions. Fig. 1 presents the Sp/L criteria used according to Walborn and Fitzpatrick to select our final sample. The spectra of two objects showing evident emissions are plotted as well on top of the plot.

Using the sample of Fig. 1 we have constructed two–colour diagrams, ($\lambda - V$) vs. $(B - V)$ involving objects which are of (nearly) the same Sp/L as HD144470. The result is shown in Fig. 3. The plots show very tight correlations while only the objects, classified as B1 V stars, without emission features are used. The only discrepant points represent the emission line objects (in the infrared bands). As demonstrated above the slopes of the resultant relations allow to compose the extinction curve, average for the selected sample of intrinsically identical stars. We observe no evident discrepancies from the average in the extraterrestrial ultraviolet. The plot presenting the "15" ANS band shows a bit larger scatter but this spectral range is extremely sensitive to even very small differences of the stellar effective temperature.

The examples of discrepant (in the IR) objects are shown in Fig. 2. Apparently such stars are embedded in some circumstellar envelopes revealed by both H_α and HeI 6682 Å lines.(The star HD25348 cannot be shown in the presented scale because of extremely strong emission in H_α.) The circumstellar shells apparently emit, most evidently in the infrared; in the vacuum–UV the discrepancies (if any) are most likely due to misclassification of the selected targets.

Fig. 5 represents a comparison between the extinction curve constructed from our sample (without the objects having discrepant points) with the galactic average one published by Krełowski and Papaj (1992). Both curves are quite similar; that already published is based on a much larger sample but Sp/L's are directly taken from literature. Both curves are also compared in Table 2.

Our spectra allowed also to measure the equivalent widths of the CaII H and K lines; using the relations of them to parallaxes Megier et al. (2005) we have calculated distances to our sample stars (see Table 3.). Removing the extinction we used the curve shown in

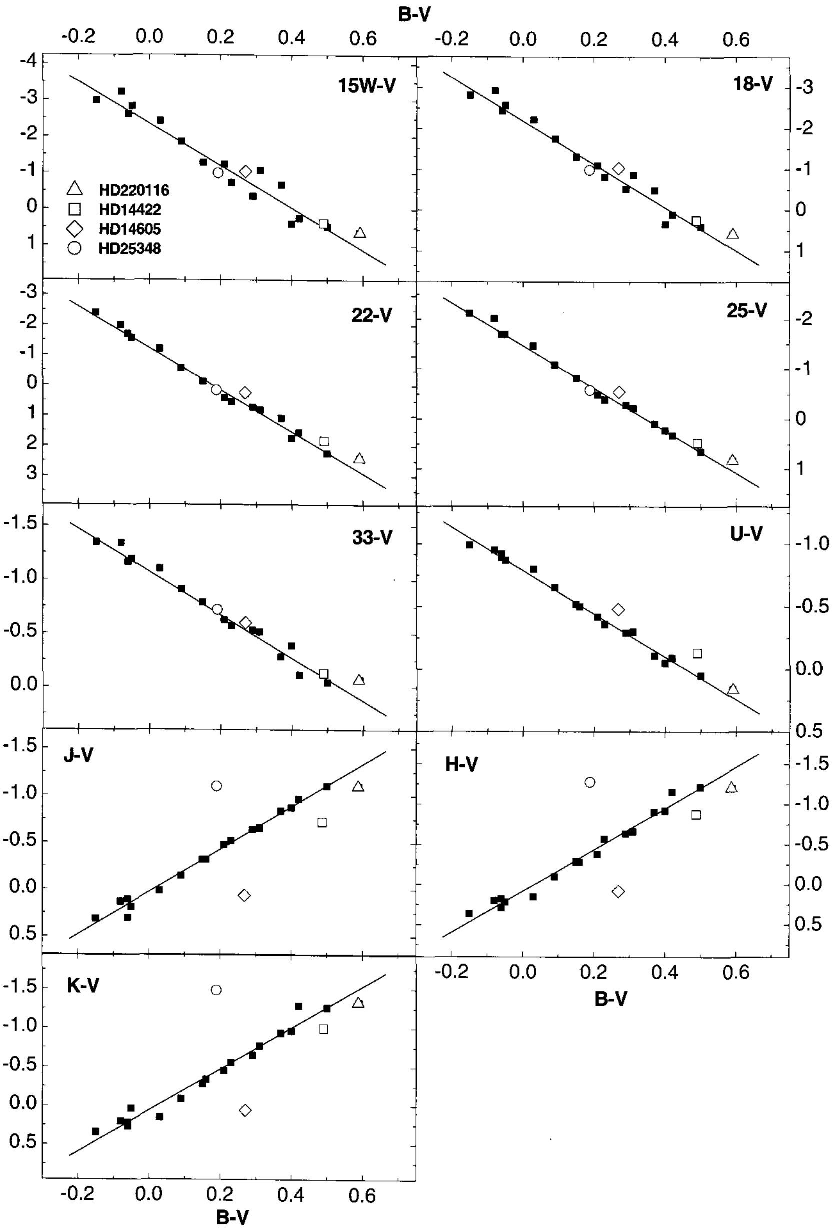

Fig. 3.— Two-colour diagrams (note the very tight correlations!) and the resultant extinction curve (solid line) compared to the galactic average of Krełowski & Papaj (1992) – dotted line. Open symbols – stars with emission lines.

TABLE 2.
COMPARED AVERAGE $E_{(\lambda-V)}/E_{(B-V)}$ FOR OUR SAMPLE AND THAT OF KREŁOWSKI & PAPAJ (1992)

Colour Index	$15W-V$	$18-V$	$22-V$	$25-V$	$33-V$	$U-V$	$J-V$	$H-V$	$K-V$
old	5.48±0.15	5.03±0.04	6.70±0.04	4.23±0.03	2.08±0.02	1.74	-2.34±0.05	-2.70±0.05	-2.93±0.07
new	5.67±0.33	5.17±0.23	6.74±0.20	4.19±0.11	1.97±0.08	1.72	-2.03±0.25	-2.31±0.28	-2.44±0.32

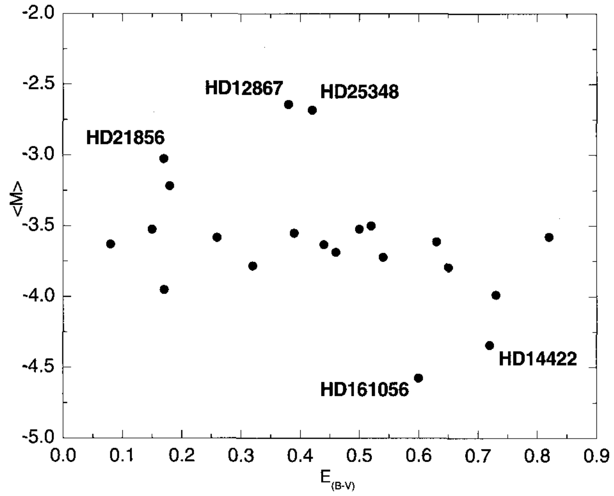

Fig. 4.— Absolute magnitudes of the sample stars plotted vs. E_{B-V}; emission line stars apparently deviate from the average as well as the very fast rotator – HD161056 which may be intrinsically hotter.

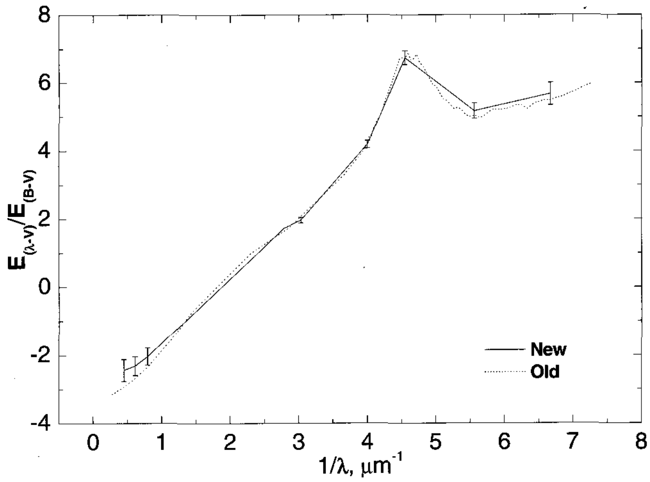

Fig. 5.— Comparison of extinction curves.

Fig. 3 (also – Table 2.) and the "canonical" value for the total–to–selective extinction ratio, i.e. 3.1. Fig. 5 demonstrates the calculated M_V's of B1 V stars vs. the colour excess E_{B-V}. The plot proves clearly that both distances and total extinctions were calculated properly. In the case of wrong distances one should expect a much broader scatter; wrong R value should result in a slope of the demonstrated relation. The average M_V of B1 V stars is -3.64 ± 0.19 a bit larger than that, estimated by Schmidt–Kaler (Aller et al. 1982), i.e. -3.2 magnitude. Let's also mention another determinations of the B1 V absolute visual magnitudes: Kulikovski (1985) estimated it to be -3.5 mag while Wegner (2006) – as small as -3.14 mag. Our estimate is well inside the scatter of the previously determined values.

The reasonably large scatter among the slightly reddened stars in Fig. 5 follows most likely the fact that distance estimates, based on equivalent widths of the CaII H and K lines, may be error–prone in cases of nearby objects, i.e. where the interstellar space cannot be considered as relatively homogeneous. It is to be emphasized that the resultant M_V's are very similar even in cases of CaII lines differing in intensities by a factor of 8 (HD14092 vs. HD154445). Some of our targets seem to be intrinsically much fainter than the average. This can either be due to some stellar peculiarities, to locally larger ratios of total–to–selective extinction or to the presence of a grey (neutral) extinction in some localized regions of the interstellar medium. The first possibility looks rather unlikely as the stellar spectra are really similar; the second indicates for circumstellar effects, the third requires much more abundant observational material.

IV. DISCUSSION

Our results suggest that the general interstellar medium is populated with grains which are surprisingly similar in every place. Our sample contains nearby, slightly reddened stars as well as heavily reddened, distant objects. Anyway – the small scatter seen in our two–colour diagrams reveals that the extinction law does nor change at least in the radius of about 2kpc. The only documented discrepancies (i.e. being not caused by uncertainties of spectral types and luminosity classes) are those which originate in circumstellar envelopes (disks). The lack of evidently discrepant points in our two–colour diagrams motivates the application of the "canonical" value of the total–to–selective extinction ratio, i.e. 3.1

TABLE 3.
EQUIVALENT WIDTHS OF INTERSTELLAR H AND K LINES IN MÅ CALCULATED DISTANCES IN PC, ABSOLUTE MAGNITUDES AND COLOR EXCESSES OF THE SELECTED STARS. WE USED (B-V)$_0$ EQUAL TO -0.23 AND "CANONICAL" R VALUE – 3.1.

STAR	EW_H	EW_K	d_H	d_K	M_H	M_K	$< M >$	$E_{(B-V)}$
HD 2083	168	239	918	803	−3.73	−3.44	−3.58	0.26
HD 7252	186	278	1005	917	−3.88	−3.68	−3.78	0.32
HD 12867	274	499	1429	1567	−2.54	−2.74	−2.64	0.38
HD 14092	423	592	2147	1840	−3.86	−3.52	−3.69	0.46
HD 14422	281	466	1462	1470	−4.34	−4.35	−4.34	0.72
HD 14605	363	580	1858	1805	−3.55	−3.49	−3.52	0.50
HD 17114	307	450	1588	1423	−4.11	−3.87	−3.99	0.73
HD 18352	111	199	643	685	−3.57	−3.70	−3.63	0.44
HD 21856	80	124	494	465	−3.09	−2.96	−3.03	0.17
HD 25348	170	250	927	835	−2.80	−2.57	−2.68	0.42
HD 44139	260	433	1361	1373	−3.49	−3.51	−3.50	0.52
HD 46660	204	304	1091	994	−3.82	−3.62	−3.72	0.54
HD 49787	120	190	686	659	−2.07	−1.99	−2.03	0.12
HD 70930	64	122	416	459	−3.53	−3.74	−3.63	0.08
HD135160	97	160	576	570	−3.54	−3.52	−3.53	0.15
HD144470	21	39	209	215	−3.19	−3.25	−3.22	0.18
HD154445	59	100	392	394	−3.55	−3.56	−3.55	0.39
HD161056	120	170	686	600	−4.72	−4.43	−4.58	0.60
HD220116	183	233	990	785	−3.83	−3.33	−3.58	0.82
HD224572	72	123	455	462	−3.94	−3.97	−3.95	0.17
HD224599	379	586	1935	1823	−3.86	−3.73	−3.79	0.65
HD236923	363	595	1858	1849	−3.62	−3.61	−3.61	0.63

The CaII "telemeter" proposed by Megier et al. (2005) apparently allows quite precise distance determinations to early type stars. The location of all our objects in the narrow, horizontal band in Fig. 5 proves that their distances are correct – otherwise we should expect a cloud of points instead. Among the discrepant points one can mention HD25348 – clearly embedded in circumstellar shell; the R value for this object is uncertain, very likely different from the canonical value. In the case of HD161056, the very fast rotator, trigonometric parallax (2.34) leads to the M value 3.6 – which coincides with the average for B1 V stars. For other discrepant points trigonometric parallaxes are either negative or do not exist at all.

Our sample does not allow to conclude that discrepancies from the average extinction law do not take place in our Galaxy as a whole. "Peculiar" extinction may be present in some localized regions; according to Megier et al. (2005) dust grains do not fill evenly the interstellar space. However, if some localized clumps of matter, containing very specific grains, exist – they are very likely quite small and thus we may expect to find them most easily in nearby OB associations.

The photometric data, analyzed in this paper, were collected in different epochs; in cases of any stellar variability this may cause some differences in the determined extinction curves, revealed by the scatter in our two–colour diagrams.

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