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Determination of R_V towards galactic O stars

P. Patriarchi[⋆,1], L. Morbidelli[1], M. Perinotto[2], and G. Barbaro[3]

[1] CAISMI/CNR, Largo E. Fermi 5, 50125 Firenze, Italy
[2] Dipartimento di Astronomia e Scienza dello Spazio, Universitá di Firenze, Largo E. Fermi 5, 50125 Firenze, Italy
[3] Dipartimento di Astronomia, Universitá di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy

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Abstract. We present new measurements of the interstellar reddening parameter $R_V = A_V/E(B-V)$ towards 35 O stars. The results are combined with measurements from the literature for 60 stars to study the behaviour of R_V with heliocentric distance. R_V is the single basic parameter which characterizes the interstellar extinction from the near-infrared to the far-UV spectral region. The absolute extinction A_V, from which R_V is derived, is best determined by optical and near-infrared photometry (Cardelli et al. 1989). We consider important the derivation of R_V with the same technique in the direction of as many as possible galactic O stars.

Key words. interstellar medium: dust, extinction

1. Introduction

The interstellar extinction curve is an important diagnostic tool to determine the physical and chemical nature of the particulate matter in the space. It is known that this curve is rather homogeneous in the galactic disk from the near-infrared to the space UV wavelengths reached by the Copernicus and IUE satellites (Savage et al. 1977; Mathis 1990). Indeed a single mean interstellar extinction curve (MIEC) is representative of the dust behaviour in several directions in the galactic disk. Significant deviations from MIEC have been noted (cf. Mathis 1990; Papaj et al. 1991; Megier et al. 1997), particularly towards regions of high mass concentration and/or intense radiation field, as in the outstanding case of θ^1 Ori C (Johnson 1968; Patriarchi & Perinotto 1980; Bohlin & Savage 1981). These deviations affect mostly the region of the bump at λ 0.22 μm and the rising branch towards the far UV.

On the other hand it has been suggested that such homogeneity is more the result of the superposition of various individual clouds than the effect of an interstellar medium with uniform extinction properties. This has been sufficiently well established by Krełowski and collaborators with observations able to separate the contribution from different clouds along the line of sight (Krełowski & Papaj 1992, 1993). In order to better understand the role of dust in the interstellar medium it is also fundamental to examine the relationship with the environment (optical dark clouds, diffuse clouds, etc.) of the individual lines of sight with R_V deviating from the 3.1 value of the MIEC. So it is important to classify the lines of sight according to their extinction behaviour, preferably using photometric parameters, in order to reach larger distances than using spectrophotometric data.

The possibility of clearly classifying the extinction in different lines of sight is indeed offered by the parameter $R_V = A_V/E(B-V)$, the so-called "total-to-selective" extinction ratio, which can be derived from photometric data. It has been found in fact by Cardelli et al. (1989, CCM89) that the extinction A_λ/A_V in the range 0.125–3.5 μm depends in practice only on R_V. The same authors also showed that the absolute extinction A_V, and consequently R_V, are best determined from optical and near-infrared photometry. CCM89 also found an empirical relationship between R_V and the observed extinction in UV. This is evidently related to the mentioned property of R_V as the single parameter able to characterize the interstellar extinction curve from far-UV to near-infrared wavelengths.

The determination of R_V is performed towards O, B, and also A-type stars, since, contrary to late type stars, they have a continuum sufficiently free of stellar atmospheric absorption lines. It has been reported that R_V derived from O stars tend to be higher than from B stars in the same cluster (Thè & Groot 1985). On the other hand, from the extended and accurate study of R_V in southern

Send offprint requests to: P. Patriarchi,
e-mail: `pat@arcetri.astro.it`

⋆ Visiting Astronomer, German-Spanish Astronomical Centre, Calar Alto, operated by the Max-Planck-Institute for Astronomy, Heidelberg, jointly with the Spanish National Commission for Astronomy.

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Milky Way stars by He et al. (1995), it results that individual measurements average out: $< R_V > = 3.05 \pm 0.30$ in their 30 O stars and $< R_V > = 3.05 \pm 0.28$ in their 124 B stars. At least in a statistical sense one is then justified to consider R_V measured towards O-type stars to be as reliable as that towards B-type stars, as generally done in the literature. Moreover O stars allow the exploration of larger distances in the Galaxy and are numerous enough to constitute a conspicuous data base within the reach of moderate size telescopes. The catalogue of O stars by Garmany et al. (1982) contains in fact more than 750 entries. It is probably complete to a distance of about 2.5 kpc and to a limiting magnitude V between 9 and 10. We consider then useful to first concentrate on the O-type stars.

A search of the literature since 1975 has shown that individual measurements of R_V have been reported so far only for 60 O stars. We considered important to increase this number, with the final goal to possibly cover all the entries in the Garmany et al. catalogue. In the present work we contribute with observations of 35 stars not yet observed in the near-infrared (cf. Gezari et al. 1999). In Sect. 2 we present optical and infrared photometry of our stars. In Sect. 3.1 A_V and R_V are derived, while in Sect. 3.2 similar data from the literature are presented. The discussion follows in Sect. 4.

2. Observations and data reduction

Using the German 1.23 m telescope of Calar Alto Observatory (Spain) equipped with a NICMOS 256×256 near-infrared camera (MAGIC) and a 1024×1024 CCD camera, we observed 35 O type stars with magnitudes from $m_V = 7.2$ to $m_V = 10.1$. The photometric filters V, R, I, J, H, K (Johnson 1966; Bessell & Brett 1988) were used.

Using MAGIC we took a mosaic of five images for each star. The first with the star at the center of the detector and the other four with the star moved to the center of each quadrant. This technique works well, allowing the combination on the same frame of star and sky measurements with no penalty in observing time. Flat-field frames were produced with exposures in the filters J, H, K of a uniformly illuminated part of the dome. The data reduction was performed as follows. We first eliminated bad pixels and then constructed a sky frame by calculating the median of the five exposures. On each of the five images of the mosaic, we applied sky subtraction and flat fielding and, over the resulting frames, we performed aperture photometry of our target. Finally, the calibration with a standard star was applied. The five derived values were then averaged. When the standard deviation of the individual measurements was larger than 0.03 mag, the data were discarded.

For the CCD observations, flat-field images were obtained taking exposures of an illuminated part of the dome. The standard starswere taken from Landolt (1983) in the case of V, R, I filters and Elias et al. (1982) for J, H, K filters.

Table 1. Photometric results in our program stars.

Star	V	R	I	J	H	K
HD 15137	7.87	7.82	7.75	7.83	7.85	7.86
HD 186980	7.48			7.35	7.33	7.35
HD 189957	7.79	8.02	8.01	7.99	8.10	8.00
HD 190864	7.83	7.75	7.65	7.36	7.35	7.29
HD 191201	7.26	7.20		6.94	6.87	6.93
HD 193117	8.67	8.35	8.02	7.30	7.09	7.04
HD 193794	9.01	8.60	8.30	7.50	7.30	7.19
HD 195213	8.74	8.30	7.70	6.81	6.44	6.28
HD 207538	7.31	7.10	6.95	6.80	6.74	6.77
HD 213023	8.52	7.97	7.42	6.67	6.52	6.34
HD 218195	8.39	8.25	8.05	7.80	7.79	7.72
HD 227018	9.03			8.27	8.08	8.05
HD 227245	9.74	9.59	9.03	8.25	8.13	8.18
HD 227757	9.30			8.70	8.57	8.62
HD 228368	8.37	8.16	7.90	7.30	7.15	7.12
HD 228534	9.25			8.59	8.55	8.55
HD 228841	8.98	8.71	8.59	7.87	7.76	7.72
HD 235673	9.14	9.10		8.69	8.62	8.57
HD 235825	9.29	9.05	8.80	8.69	8.68	8.63
HD 240165	10.13	9.90	9.65	9.04	8.91	8.86
HD 240464	9.62	9.40	9.20	8.87	8.81	8.80
HD 332755	8.73			8.38	8.26	8.25
BD +24 3881	9.07			7.58	7.32	7.30
BD +40 4179	9.65	9.30	9.00	8.53	8.35	8.29
BD +45 3216	9.07	8.90	8.65	8.20	8.13	8.08
BD +45 3260	9.06	8.75	8.40	8.00	7.82	7.76
BD +49 3591	9.67	9.45	9.10	8.50	8.30	8.22
BD +53 2843	9.50	9.43		9.01	8.98	9.02
BD +55 2840	10.01	9.79	9.52	8.95	8.87	8.81
BD +57 2513	9.53	9.20	8.80	8.19	8.02	7.95
BD +59 191	9.26	8.98	8.50	8.32	8.20	8.14
BD +61 105	9.40	9.23	8.85	8.70	8.64	8.64
BD +61 2550	9.31	9.12	8.85	8.53	8.55	8.51
BD +61 2559	9.73	9.60	9.30	9.06	9.01	9.02
BD +62 79	9.33	9.07	8.60	8.38	8.28	8.27

The errors are of the order of 0.03–0.04 mag for the J, H, K photometry and of 0.02–0.03 mag for the V, R, I photometry. The photometric data are reported in Table 1.

3. Determination of A_V and R_V

3.1. Our program stars

From the observed fluxes, colour excesses $E(\lambda - V)$ were derived using the intrinsic colours of OB stars given by Wegner (1994). This work was preferred due to the accurate dereddening procedure used in determining the intrinsic colours. While the standard stars for J, H, K photometry in Elias et al. (1982) belongs to the CIT system (see Bessell & Brett 1988), Wegner's intrinsic colours are

Table 2. Extinction parameters of the program stars.

Star	Sp type	$E(B-V)$	A_V	R_V	Assoc.	Dist. (kpc)
HD 15137	O9.5III	0.34	0.84 ± 0.05	2.46 ± 0.29		3.2
HD 186980	O8III	0.35	1.03 ± 0.09	2.93 ± 0.42	Vul OB1	2.4
HD 189957	O9.5III	0.28	0.46 ± 0.29	1.63 ± 1.16		3.6
HD 190864	O6.5III	0.59	1.45 ± 0.27	2.45 ± 0.54	Cyg OB3	2.4
HD 191201	O9.5IV	0.42	1.24 ± 0.15	2.94 ± 0.49	Cyg OB3	1.4
HD 193117	O9.5II	0.85	2.47 ± 0.40	2.90 ± 0.54	Cyg OB8	2.9
HD 193794	O9.5IV	0.86	2.79 ± 0.40	3.24 ± 0.54		1.6
HD 195213	O7II	1.15	3.54 ± 0.52	3.08 ± 0.50	Cyg OB9	1.6
HD 207538	O9V	0.61	1.13 ± 0.06	2.47 ± 0.17	Cep OB2	1.0
HD 213023	O9V	1.03	3.26 ± 0.25	3.17 ± 0.31		0.8
HD 218195	O9III	0.60	1.53 ± 0.20	2.54 ± 0.42		2.9
HD 227018	O6.5III	0.64	2.02 ± 0.23	3.15 ± 0.45	Cyg OB3	3.1
HD 227245	O7	0.91	2.73 ± 0.52	2.99 ± 0.64	Cyg OB3	3.1
HD 227757	O9.5V	0.41	1.66 ± 0.33	4.04 ± 1.00	Cyg OB3	2.3
HD 228368	O9V	0.77	2.21 ± 0.35	2.86 ± 0.53		1.2
HD 228534	O9.5II	0.51	1.54 ± 0.42	3.01 ± 0.95		5.7
HD 228841	O6.5V	0.81	2.30 ± 0.44	2.83 ± 0.61	Cyg OB1	2.1
HD 235673	O6.5V	0.50	1.56 ± 0.23	3.11 ± 0.58		3.3
HD 235825	O9V	0.51	1.63 ± 0.08	3.19 ± 0.28	Cep OB1	2.4
HD 240165	O9.5V	0.74	2.21 ± 0.35	2.98 ± 0.55	Cep OB5	2.6
HD 240464	O9V	0.61	1.79 ± 0.15	2.93 ± 0.34	Cas OB5	2.6
HD 332755	O8II	0.57	1.43 ± 0.33	2.50 ± 0.67		4.5
BD +24 3881	O6.5III	0.98	2.97 ± 0.32	3.03 ± 0.39	Vul OB1	2.0
BD +40 4179	O8V	0.86	2.41 ± 0.23	2.81 ± 0.33	Cyg OB9	2.2
BD +45 3216	O8	0.68	1.99 ± 0.29	2.94 ± 0.52		3.3
BD +45 3260	O9V	0.79	2.28 ± 0.18	2.89 ± 0.30	Cyg OB7	1.6
BD +49 3591	O7.5	0.81	2.48 ± 0.40	3.06 ± 0.57		3.4
BD +53 2843	O8	0.50	1.51 ± 0.22	3.04 ± 0.56	Cep OB1	4.9
BD +55 2840	O7.5	0.74	2.25 ± 0.34	3.03 ± 0.55	Cep OB1	2.9
BD +57 2513	O9.5V	0.87	2.57 ± 0.29	2.95 ± 0.40		1.7
BD +59 191	O9.5II	0.54	1.98 ± 0.11	3.66 ± 0.35		4.7
BD +61 105	O9V	0.48	1.75 ± 0.14	3.64 ± 0.44	Cas OB4	2.4
BD +61 2550	O9.5II	0.56	1.62 ± 0.17	2.88 ± 0.41		5.7
BD +61 2559	O9V	0.57	1.68 ± 0.16	2.94 ± 0.39	Cas OB5	2.9
BD +62 79	O9.5IV	0.60	2.08 ± 0.14	3.46 ± 0.35	Cas OB4	2.5

given in the SAAO system. To eliminate the small but not negligible systematic errors introduced by the different systems, we transformed Wegner's colours to the CIT system. The quantity A_V was then determined with a least square solution, by fitting (CCM89) the relationship

$$E(\lambda - V) = A_V[R_{\rm L}(\lambda) - 1] \tag{1}$$

where $\lambda = R, I, J, H, K$ and $R_{\rm L}$ is the extinction curve A_λ/A_V by Rieke & Lebofsky (1985). From the derived A_V and the known $E(B-V)$ we obtain R_V. Since the fitting expression (1) is a homogeneous equation, the uncertainty of each A_V has been calculated considering that we have N–1 degrees of freedom (N is the number of the photometric bands used). From the mentioned uncertainty of A_V only a lower limit to the accuracy of R_V could be derived. This because of the uncertainties introduced by inaccuracy in the spectral types and consequently in the adopted intrinsic colour. Anyhow an estimate of the accuracy of the deduced R_V has been done. Our final A_V and R_V are reported, with their errors, in Table 2. The spectral types in this table are from Garmany et al. (1982). They are discussed in detail in the next section. Membership in associations is also from Garmany et al. (1982). From A_V in Table 2 and V in Table 1 we have derived the distances making use of the calibration M_V vs. spectral type from Panagia (1973).

3.2. R_V from previous works

We present in Table 3 the other O-type stars which we have found in the literature to have R_V determined using a technique similar to ours, together with their spectral types taken from the original sources. These are: Thè et al. (1980), Thè & Groot (1985), CCM89, He et al. (1995), and

Table 3. Extinction parameters of O stars with R_V from the literature.

Star	Sp type	$E(B-V)$	V	R_V	Assoc.	Dist. (kpc)
HD 93205	O3V	0.30	7.8	4.0	Tr 14-16	3.4
HD 93250	O3V((f))	0.60	7.38	3.7	Tr 14-16	1.8
HD 303308	O3V	0.46	8.15	3.8	Tr 14-16	3.2
HD 93160	O6III(f)	2.2	6.8	3.4	Tr 14-16	2.5
HD 93204	O5V	0.4	8.4	3.7	Tr 14-16	3.5
Tr 16 100	O6V((f))	0.53	8.60	4.1	Tr 14-16	2.2
HD 93130	O6III(f)	0.53	8.09	3.6	Cr 228	2.2
HD 93146	O6.5V((f))	0.30	8.41	4.4	Cr 228	2.6
HD 93222	O7III((f))	0.34	8.10	4.3	Cr 228	2.7
HD 93027	O9.5V	0.23	8.72	3.8	Cr 228	2.6
HD 93208	O9V	0.26	8.73	3.9	Cr 228	2.5
HD 305523	O9II	0.43	8.50	4.0	Cr 228	3.8
Tr 15 18	O9.5I-II	1.42	12.72	4.0	Tr 15	2.9
HDE 305518	O9.5IV	0.70	9.71	3.9	Cr 228	2.3
HDE 305532	O5V	0.67	10.20	4.4	Cr 228	4.1
Cr 228 97	O5V	0.86	10.36	3.7	Cr 228	3.9
HDE 305525	O6V	1.00	10.00	3.5	Cr 228	2.3
HD 34078	O9.5V	0.53	5.95	3.42	Ori OB1	0.4
HD 37022	O7V	0.34	5.13	5.50	Ori OB1	0.4
HD 46202	O9V	0.47	8.19	3.12	Mon OB2	1.6
HD 48099	O7V	0.27	6.37	3.52	Mon OB1	1.1
HD 73882	O8.5V	0.72	7.21	3.39	Vel OB1	0.7
HD 93028	O9V	0.24	8.37	3.92	Cr 228	2.2
HD 93222	O7III	0.40	8.10	4.98	Cr 228	2.1
HD 149757	O9V	0.32	2.57	3.09		0.1
HD 167771	O8I	0.44	6.54	3.48	Sgr OB4	2.0
HD 193322	O8.5III	0.41	5.83	3.05		1.1
HD 229196	O6III	1.22	8.50	3.12		1.2
CPD –59 2600	O6V	0.53	8.62	4.17	Tr 16	2.2
LSS 441	O9IV	0.75	10.54	2.88		4.9
LSS 773	O9III	0.89	10.63	1.73		1.8
LSS 1216	O8III	0.89	8.40	3.03		1.8
LSS 1238	O9V	1.24	11.20	2.87		2.5
LSS 1242	O8Iab	1.39	8.99	2.91		1.9
LSS 1262	O9V	1.16	11.17	2.76		2.6
LSS 1448	O9V	1.65	11.14	2.78		1.5
LSS 2025	O6V	0.57	9.82	3.15		5.3
LSS 2826	O9V	1.09	9.89	2.99		3.2
LSS 3386	O9III	1.92	10.98	2.83		1.6
LSS 3553	O9V	0.95	9.94	2.88		2.2
LSS 3675	O9IV	0.86	9.45	3.44		2.0
LSS 3769	O9III	0.98	9.85	3.83		5.1
LSS 3776	O8IV	0.68	9.13	3.56		2.7
LSS 3874	O9.5IV	1.20	10.14	3.53		1.3
LSS 3906	O9V	0.99	10.6	3.26		3.3
LSS 3997	O9III	1.64	10.15	2.95		1.6
LSS 4157	O9IV	1.26	9.80	2.93		1.8
LSS 4258	O9Ib	1.02	8.37	3.22		2.5
LSS 4342	O9III	0.95	9.87	3.68		2.5
LSS 4389	O9IV	1.20	10.23	2.81		2.7
LSS 4453	O9V	1.23	11.72	2.89		3.9
LSS 4551	O9Ib	1.45	10.41	2.86		3.1
LSS 4816	O9II	1.41	10.72	3.12		2.8
LSS 4854	O9V	1.07	10.6	3.49		1.7
LSS 4883	O9Iab	1.30	8.78	3.20		1.6
LSS 4923	O6V	1.74	10.45	2.91		3.2
LSS 4960	O9V	0.89	9.73	3.60		1.7
LSS 4962	O9Ia	1.39	11.77	2.56		13.
LSS 4981	O9.5V	0.92	10.47	2.57		3.5
HD 206267	O6.5V	0.52	1.49	2.86	Tr 37	0.7
HD 204827	O9.5V	1.10	3.03	2.75	Tr 37	0.7

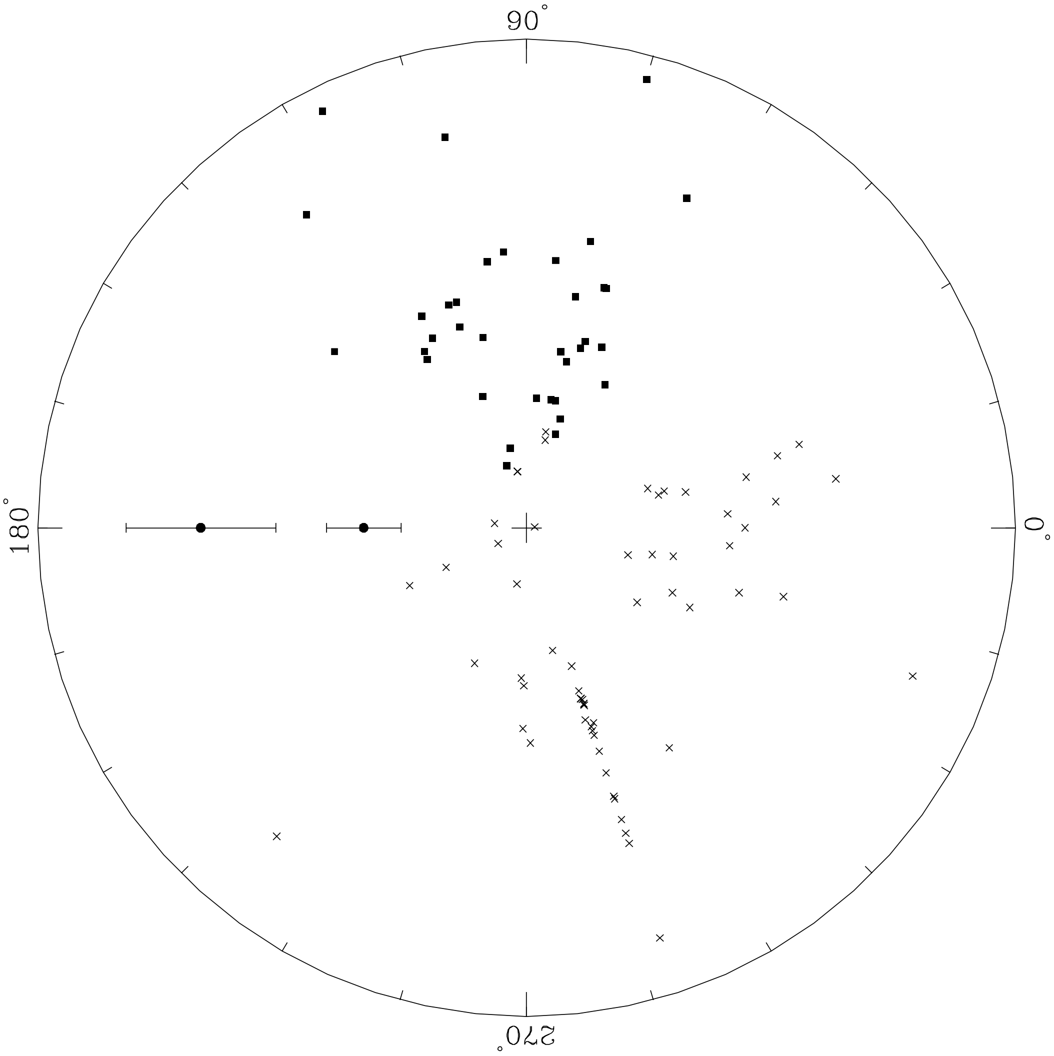

Fig. 1. All the O type stars with R_V so far measured photometrically are plotted in the galactic plane centered on the Sun. Full squares denote the program stars, while crosses refer to O stars with R_V from the literature. The circle has a radius of 6 kpc. Most stars belong to OB associations (see Tables 2 and 3). Error bars for $d = 2$ and $d = 4$ kpc, corresponding to a dispersion in M_V of ± 0.5, are also plotted.

Morbidelli et al. (1997). Entries in Table 3 are divided in blocks of 12, 5, 12, 30 and 2 stars, referring to the above papers, respectively.

Thè et al. (1980) consider 14 stars in the Trumpler 14–16 and Collinder 228 open clusters in the area of the Carina nebula. Thirteen are classified as O stars, while one is without spectral classification. One of the thirteen stars is a spectroscopic binary (a supergiant plus a dwarf) and has been discarded in Table 3. Thè & Groot (1985) consider the extinction law towards other 14 stars belonging to the same clusters as in the Thè et al. paper. Five of them are O stars, while the others are B and A. The CCM89 paper contains 12 O stars. He et al. (1995) consider 154 OB stars in the southern Milky Way; among them 30 are O-type stars. The paper of Morbidelli et al. (1997) contains two O stars. The star HD 93222 has been observed both by Thè et al. (1980) and by CCM89. We attribute to it $R_V = 4.64$, the mean of the two determinations. Its distance turned out to be 2.4 kpc.

We have thus found in the literature individual R_V determinations for 60 O stars.

4. Discussion

Tables 2 and 3 contain in total 95 stars. As far as we know all O-type stars with individual determinations of R_V published so far are included. Some considerations are in order regarding the spectral types reported in these tables. The spectral types of the 35 stars of the present work come, as said, from the catalogue of O stars of Garmany et al. (1982). These authors, however, do not report "suffixes" to the basic MKK types, such as "e" (emission lines), "n" (narrow features) etc., (cf. Walborn 1971, 1972 and 1973, who discusses the meaning of these "suffixes").

In the present context we consider particularly relevant the suffix "e", because it suggests the existence of circumstellar matter which may be associated with hot dust and a relatively extended ionized envelope. Continuum as well

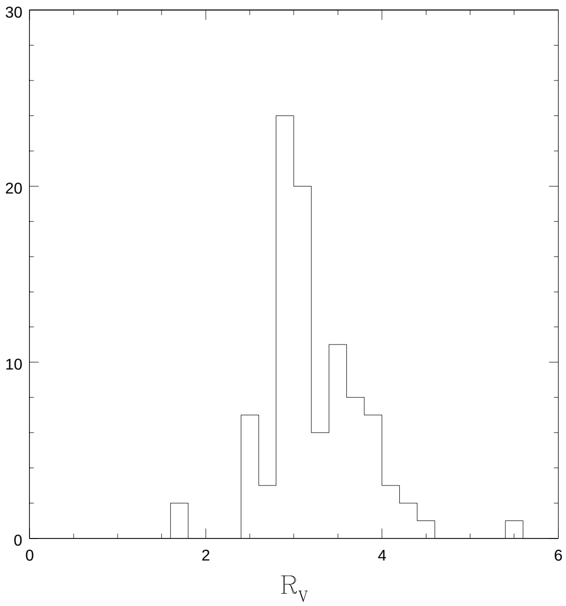

Fig. 2. Histogram of all the 95 stars (bin = 0.2).

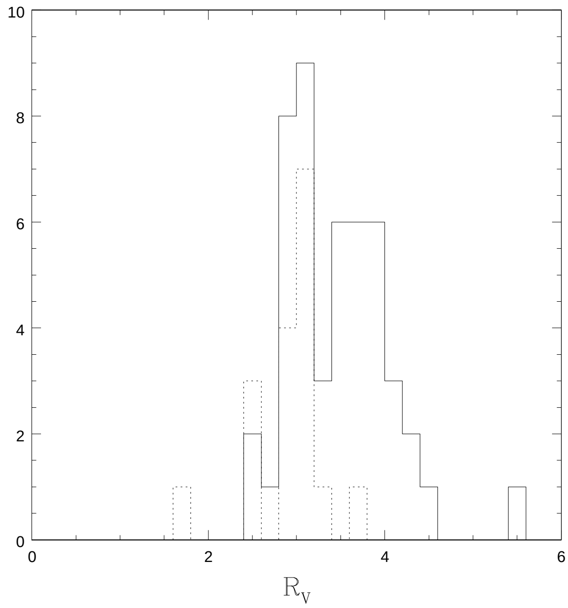

Fig. 3. Histograms of the stars belonging to clusters or associations (full line) and of field stars (dashed line). LSS stars are not included. (bin = 0.2).

as line emission from this matter might then alter the K photometry, thus affecting the determination of R_V. For this reason we have examined the spectral types of our program stars as reported in the Catalogue of O stars by Cruz-González et al. (1974), which is the most important source for the Garmany et al. catalogue itself. They are indeed those adopted by Garmany et al. (1982), except for the "suffixes", ignored by Garmany et al. Actually we have found no indication of "e" in the spectra of our program stars. For the sake of completeness we have also inspected the primary sources of spectral types referred to by Cruz-González et al. (1974). Again we have not found any record of the property "e" in our program stars.

The spectral types of the stars in Table 3 are reported as given by the authors, who indeed report the mentioned "suffixes".

The distances in Table 3 have been derived using the relevant data contained in the table. The distances reported in Tables 2 and 3 are plotted, after projection on the galactic plane, in Fig. 1. They span from the Sun neighborhood to 6 kpc. Even though with some dispersion, the local and Perseus arms are visible.

Note the peculiar alignment of the objects in the Carina region at the galactic longitude of about 235° (corresponding to the clusters Trumpler 14/16/37 and Collinder 228). This effect is related to the errors associated with the relationship M_V–spectral type. Panagia (1973) reports $M_V = \pm 0.5$ as an estimate of the intrisic dispersion of the absolute magnitude for each spectral type and luminosity class. In Fig. 1 typical error bars are plotted assuming that the M_V dispersion is the prevailing source of error in deriving the distances.

Although the data have a relatively high dispersion, R_V does not appear anyhow to depend on the heliocentric distance. The R_V values span from 1.7 (HD 189957; LSS 773) up to 5.5 (HD 37022 in Orion OB1).

The distribution of R_V for all 95 stars of Tables 2 and 3 is shown in Fig. 2. Two stars in Fig. 2 have very low R_V and two have R_V quite high. About the first, HD 189957 ($R_V = 1.70$) is a field star, while we do not have information on cluster membership for LSS 773 ($R_V = 1.73$). As with the two stars with the highest R_V, HD 93222 ($R_V = 4.6$) and HD 37022 ($R_V = 5.5$), both belong to OB associations: Collinder 228 and Orion 1, respectively.

Two peaks look significant in Fig. 2: one at $R_V = 3.0$ with 44 stars, the other at $R_V = 3.7$ with 26 stars. A second histogram in Fig. 3 compares stars belonging to OB associations with field stars (the LSS stars have been excluded because information about their cluster membership is not available). In spite of the small numbers of field stars, Fig. 3 tends to indicate that members of associations exhibit a higher mean R_V. This is consistent with the fact that the secondary peak of the distribution in Fig. 2 is mainly due to stars belonging to associations.

With the present sample, we have shown that stars within OB associations have on average an R_V larger than field stars. Further work will allow a more comprehensive understanding of the behaviour of R_V across the Galaxy and of its implications, including the possibility of a more precise correction for the reddening of astronomical sources near the galactic plane according to their location in the Galaxy.

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