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Infrared extinction in the Small Magellanic Cloud

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Summary. *JHK* photometry of bright reddened and unreddened early-type SMC members is presented, and the extinction law in those wavebands is studied. *VRI* photometry of several early-type SMC members is also presented and combined with existing observations to study the extinction at R and I also. It is found that, within the errors, the extinction law from V to K is the same for the SMC as for the Galaxy and the LMC, despite differences previously found in the ultraviolet.

1 Introduction

The ultraviolet extinction laws in the Magellanic Clouds are known to be different from the mean extinction law in the Galaxy (see Nandy 1984 and references therein). This difference is particularly strong for the Small Magellanic Cloud where the 2200 Å feature, so dominant in galactic extinction laws is absent and the far ultraviolet extinction is very strong.

It has been shown that the simplest dust model that accurately predicts the normal galactic extinction law also fits the normal SMC law but with a dramatically reduced graphite content (Bromage & Nandy 1983). This model predicts a low value of $R = A_V/E(B-V)$ unless the upper limit of the size of the silicate grains is extended from 0.25 to 0.35 μm. The infrared extinction law and the value of R are crucial to these dust models.

Infrared observations of early-type supergiants in the Large Magellanic Cloud have been made and the infrared interstellar extinction law constructed (Koornneef 1982; Morgan & Nandy 1982). The conclusions of these papers were that there was no significant difference between the value of R for the LMC and the value of 3.1 for the Galaxy.

In this paper we present observations of early-type supergiants in the SMC in the J, H and K wavebands and describe the resulting interstellar extinction law at these wavelengths. We also present some new observations in the $(V-R)$ and $(V-I)$ colours and merge those with existing observations in order to study the extinction law in the visual wavelength range also.

2 Observations

The *JHK* observations were made through a 15-arcsec aperture using the infrared photo-

Table 1. Infrared observations of early-type stars in the SMC.

Star AzzVi	Star Sand	Sp. Type	V	B−V	$J\pm\sigma_J$	$H\pm\sigma_H$	$K\pm\sigma_K$
18	13	B1	12.46	0.03	12.35 ± 0.03	12.33 ± 0.05	12.32 ± 0.15
56	31	B2	11.16	0.00	11.04 ± 0.01	11.02 ± 0.02	10.99 ± 0.04
65	33	B6	11.03	0.12	10.60 ± 0.01	10.53 ± 0.01	10.49 ± 0.02
78	40	B3	11.05	−0.03	11.18 ± 0.02	11.15 ± 0.03	11.14 ± 0.05
	56	B8	10.87	0.04	10.63 ± 0.01	10.59 ± 0.01	10.55 ± 0.02
187	68	B2.5	12.06	−0.10	12.30 ± 0.03	12.47 ± 0.08	12.28 ± 0.09
242	85	B1	12.06	−0.11	12.35 ± 0.03	12.38 ± 0.07	12.33 ± 0.11
362	114	B3	11.36	−0.02	11.28 ± 0.01	11.31 ± 0.02	11.29 ± 0.05
367	117	B7	11.22	0.07	10.97 ± 0.01	10.91 ± 0.02	10.83 ± 0.05
456	143	B0	12.88	0.10	12.75 ± 0.05	12.74 ± 0.07	12.76 ± 0.15
486	157	O9.5	12.17	−0.21	12.79 ± 0.04	12.74 ± 0.09	12.84 ± 0.18
488	159	B0	11.89	−0.13	12.25 ± 0.05	12.37 ± 0.07	12.28 ± 0.14

meter on the ESO 1.0-m telescope at La Silla on 1983 September 15–16. The resulting magnitudes were transformed to the system defined by Koornneef (1983a) using the zero point standards and transformations given by him. The transformations for early-type stars are minimal. Extinction corrections were made using the mean extinction coefficients for La Silla (Engels *et al.* 1981). A bright star monitored throughout each night showed no significant variations in the zero points.

The resulting magnitudes are given in Table 1 along with relevant visual photometry and spectral types. The stars are numbered according to their number in the catalogues of Azzopardi & Vigneau (1975) and Sanduleak (1968). The visual photometry and spectral types vary from author to author. The adopted values shown in Table 1 have been extracted from the catalogue of Azzopardi & Vigneau (1982) and are mainly those given by Ardeberg & Maurice (1977).

The new *VRI* observations are presented in Table 2: they were made through a 14-arcsec aperture using the two-channel chopping photometer on the Mt Stromlo and Siding Spring Observatories 1.0-m telescope on the night of 1983 August 16. The photomultiplier tube was an RCA 31034A tube (see Bessell 1979) and was used with filters designed to give measurements in the Cousins *VRI* system. Accordingly, the observations were transformed to the Cousins *VRI* system using colour equations constructed from observations of standard stars (Landolt 1983) with extinction corrections made using mean coefficients for the site. One SMC star, AzzVi 56, was observed several times during the night, showed no significant variation, and gave results in good agreement with the values given by Vigneau & Azzopardi (1982). The photometric errors as derived from the observed scatter in the individual observations are ~ 2 per cent. The spectral types, V magnitudes and $(B-V)$ colours are taken from the literature as in Table 1, except for BBB 280 (Basinski, Bok & Bok 1967) for which the photometry was obtained by ourselves (unpublished). The spectral type for this star is given as B1 and is based on the strengths of the C IV and Si IV resonance lines as seen in *IUE* images of this star.

In addition to these data, *VRI* photometry of bright stars in the SMC has been published by Mendoza (1970) and Vigneau & Azzopardi (1982). The latter is also in the Cousins *VRI* system, but the former is in the Johnson (1966) system. We have used the transformations derived by Bessell (1979) to transform Mendoza's data to the Cousins system. However, since the transformations are found to be rather uncertain for late B – early A stars (Fernie

Table 2. *VRI* photometry of early-type stars in the SMC.

Star AzzVi	Star Sand	Sp. Type	V	B-V	V-R	V-I	Source
16	11	B1e	13.11	0.12	0.39	0.45	1
18	13	B1	12.46	0.03	0.05	0.08	1
20	14	B9	12.08	0.29	0.20	0.43	2
26	18	O7	12.51	-0.18	-0.09	-0.22	1
48	27	B3	11.03	-0.03	0.04	0.05	3
56	31	B2	11.16	0.00	0.05	0.08	2
56	31	B2	11.16	0.00	0.03	0.05	1
65	33	B6	11.03	0.12	0.06	0.16	3
71	36	B0e	13.57	-0.01	0.10	0.19	1
78	40	B3	11.05	-0.03	0.01	0.02	3
	56	B8	10.87	0.04	0.03	0.11	3
85	191	B1.5	11.86	-0.04	0.04	0.04	3
171	61	B6	13.28	0.00	0.06	0.17	2
186		O9	14.00	-0.20	-0.08	-0.15	2
215	76	B3	12.77	-0.11	-0.03	-0.09	2
216		B0	14.20	-0.16	-0.04	-0.06	2
242	85	B1	12.06	-0.11	-0.03	-0.10	1
258		O9e	13.75	0.02	0.17	0.47	1
362	114	B3	11.36	-0.02	0.04	0.05	3
367	117	B7	11.22	0.07	0.12	0.18	3
393	124	B1.5	11.43	-0.02	0.03	0.04	3
443	137	B2.5	10.97	-0.06	0.01	0.00	3
(BBB 280)		B1	14.88	0.18	0.12	0.29	1

Source of VRI data:
1. This paper.
2. Vigneau & Azzopardi 1982.
3. Mendoza (1970) – transformed to Cousins system – see text.

1983), we have applied them to stars of type B8 and earlier. Altogether, we have 22 stars for which colour excesses can be computed. Table 2 also gives the *VRI* photometry from Vigneau & Azzopardi (1982), and from Mendoza (1970) transformed to the Cousins system, with the visual data adopted as described earlier.

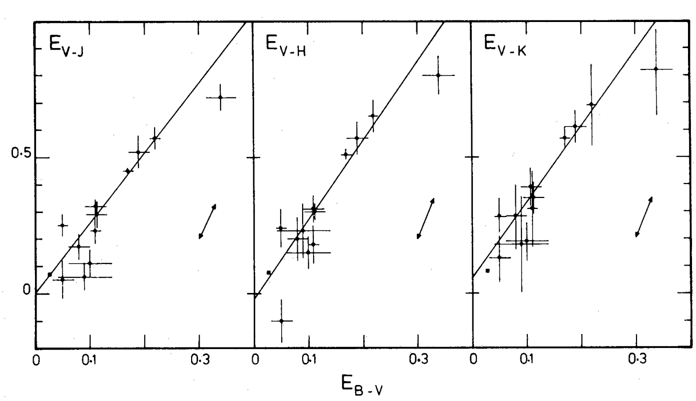


Figure 1 (a)–(c). Colour excesses $E(V-J)$, $E(V-H)$ and $E(V-K)$ plotted against visual colour excess $E(B-V)$. The straight line is a weighted, least-squares fit. The double-arrowed bar shows the displacement due to an error of one subclass in spectral type near B1. The filled square shows the foreground reddening.

Table 3. Near-infrared colour excess ratios.

Colour excess ratio	SMC	Galaxy	LMC
E(V-J)/E(B-V)	2.58 ± 0.28	2.38 ± 0.04	2.21 ± 0.10
E(V-H)/E(B-V)	2.94 ± 0.31	2.62 ± 0.04	2.59 ± 0.09
E(V-K)/E(B-V)	2.79 ± 0.18	2.82 ± 0.04	2.92 ± 0.12

3 Discussion

3.1 *JHK* PHOTOMETRY

Fig. 1(a)–(c) shows the colour excesses $E(V\text{–}J)$, $E(V\text{–}H)$ and $E(V\text{–}K)$ plotted against the visual colour excess $E(B-V)$. The error bars are the observational errors for the *JHK* photometry as given in Table 1 combined with estimates of the uncertainty of the V magnitude and the $(B-V)$ colours as revealed by the variations of V and $(B-V)$ reported in the literature.

The colour excesses were calculated from the photometry of Table 1 and intrinsic colours as given by Koornneef (1983b) and Fitzgerald (1970) for galactic class Ia supergiants. Errors of spectral type will cause displacements in the colour excess diagrams. Each diagram shows the average displacement due to errors of one spectral subclass near B1. Since this displacement is almost parallel to the reddening lines, spectral type errors will introduce very little error in the reddening lines.

The reddening lines shown in Fig. 1(a)–(c) are weighted, least-squares fitted straight lines; their slopes are given in Table 3. Also given in Table 3 are the colour excess ratios for the Galaxy as adopted by Koornneef (1983b) and those for the LMC (Morgan & Nandy 1982). The quoted errors for the galactic values are estimates typical of both the spread between the results of different authors and the errors quoted by individual authors. Within the errors, these three sets of colour excess ratios are the same. It must be remembered that some of the reddening is due to foreground galactic dust which presumably obeys the normal galactic reddening law. For these SMC stars a foreground reddening of $E(B-V)=0.03$ is expected. This is about 10 per cent of the reddening of the more heavily reddened stars in the sample, and is indicated in Fig. 1.

Since the lines showing the best fit pass reasonably close to the origin the adopted intrinsic colours are seen to be a reasonable representation of the SMC supergiant colours. The poorest fit is for $E(V\text{–}K)$ for which the best fitting line passes 3σ from the origin. The intrinsic infrared colours of galactic and LMC stars were also found to be well matched (Morgan & Nandy 1982; Koornneef 1982).

The ratio R can be obtained by extrapolating the near-infrared extinction law to $1/\lambda=0$ using the theoretical van de Hulst curve no. 15. Using the observed value of $E(V\text{–}K)/E(B-V)$, this gives $R = 3.1 \pm 0.2$. A similar result ($R = 3.11 \pm 0.11$) has been obtained by Feast & Whitelock (1984) from *JHK* photometry of A supergiants in the SMC. These results are in contrast to the low value of $R \sim 2.0$ obtained by Isserstedt (1980) from a statistical analysis of *UBV* measurements of SMC stars.

The errors in the colour excess ratio estimates are quite large due to the relatively small sample and the low reddenings involved. To obtain estimates of the SMC reddening comparable in accuracy with the galactic estimates it is necessary to have a much larger sample of more heavily reddened stars. Nevertheless, the results do show that the near-infrared colour excess ratios are not widely discrepant from the galactic and LMC values.

The similarity in the near-infrared extinction laws of the three galaxies is in marked contrast with the dissimilarities of their ultraviolet extinction laws. There is clearly no correlation between R and the 2200 Å feature or the far-ultraviolet extinction. This lack of correlation also exists for certain stars in the Galaxy (see e.g. Whittet *et al.* 1981).

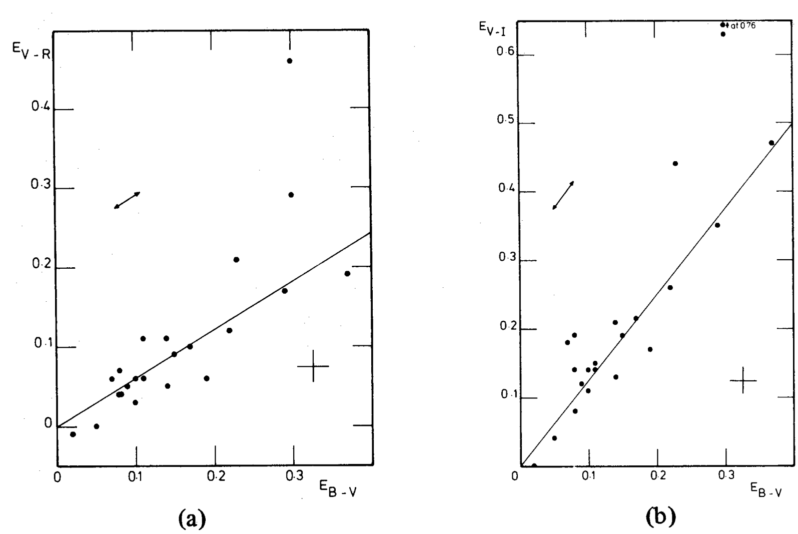
Although the errors for the SMC infrared colour excess ratios are relatively large, they still place constraints on dust models. For example, the low value of R predicted by Bromage & Nandy (1983) is 3σ below the mean observed value. Since the observed extinction at J and H is also 'normal', their model requires modification. A possible modification is to increase the maximum size of the silicate grains from 0.25 to 0.35 μm.

3.2 *VRI* PHOTOMETRY

The colour excesses $E(V{-}R)$ and $E(V{-}I)$ were calculated for the 22 stars of Table 2. The intrinsic $(V{-}I)$ versus $(B{-}V)$ colours of supergiants (Cousins 1978a) calibrated using Fitzgerald's (1970) calibration were used in the computation of $E(V{-}I)$. The intrinsic $(V{-}R)$ colours used in the computation of $E(V{-}R)$ were obtained from the above $(V{-}I)$ versus $(B{-}V)$ sequence and the $(V{-}I)$ versus $(R{-}I)$ colours computed by Cousins (1981): certainly, the analogous computed intrinsic $(V{-}R)$ colours for class V stars give a good representation of the intrinsic colours of class V stars as constructed directly from $(V{-}R)$ observations by Cousins (1978b).

The colour excesses $E(V{-}R)$ and $E(V{-}I)$ are shown plotted against $E(B{-}V)$ in Fig. 2(a) and (b) respectively. Again the result of a spectral type error of one subclass near type B1 is shown and it can be seen that this too has little effect on the resulting reddening lines.

The straight lines shown in Fig. 2 are the colour excess ratios for the galactic extinction law. The galactic value for $E(V{-}I)/E(B{-}V) = 1.25$ was taken from Dean, Warren & Cousins (1978); $E(V{-}R)/E(B{-}V) = 0.61$ was calculated from that value assuming a $1/\lambda$ extinction law and adopting the effective wavelengths of the passbands given by Bessell (1979) for an unreddened A0 star. Although an A0 star has colours fairly close to those of the reddened B stars used here, it is for the R-waveband that the effective wavelength is most sensitive to colour. The figures show that the SMC extinction is well represented by the galactic extinction law. Three stars. AzzVi16, AzzVi71 and AzzVi258 exhibit large red excesses [*cf.* Fig. 2(a)–(b)]: these may be due to red companions. In addition, the flux in the R waveband for AzzVi 16 is affected by the very strong Hα emission from this star. In fact, the



(a) (b)

Figure 2 (a)–(b). As Fig. 1 for $E(V{-}R)$ and $E(V{-}I)$. The error bars are typical errors for the photometry. The straight lines show the galactic extinction law (see text).

slopes of the least-squares fitted straight lines through the data of Fig. 2(a) and (b), but excluding the three stars with large red excesses, are $E(V-R)/E(B-V) = 0.53 \pm 0.04$ and $E(V-I)/E(B-V) = 1.19 \pm 0.06$. Both these lines pass through the origin within 1σ.

4 Conclusions

Within the observational errors, the extinction law in the SMC from 5500 Å to 2.2 μm is the same as that in the Galaxy. This is in marked contrast with the ultraviolet extinction law. Extrapolation of the infrared extinction law to $1/\lambda = 0$ using the standard van de Hulst curve no. 15 and the observed value of $E(V-K)/E(B-V)$ gives a value of $R = 3.1 \pm 0.2$.

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