Astron. Astrophys. 149, 330–336 (1985)

ASTRONOMY AND ASTROPHYSICS

The visible and infrared extinction law and the gas-to-dust ratio in the Small Magellanic Cloud*

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Received November 23, 1984; accepted February 15, 1985

Summary. We have made photometric observations in the *UBVJHK* bands for 23 O-B3 stars in the Small Magellanic Cloud, for which we have redetermined the MK spectral type and luminosity class. We have derived from these data the extinction curve in the visible and the near-infrared. This curve is very close to the curves in the Galaxy and the Large Magellanic Cloud; we find in particular $R=A_V/E(B-V)=2.7\pm0.2$ in the SMC, only slightly smaller than the galactic value of about 3.1. We have also determined the column density N_H of atomic hydrogen in front of most of these stars from IUE observations of the Lyman alpha interstellar line. We find that the SMC gas-to-dust ratio $N_H/E(B-V)$ is in the range 3.7 to 5.2 10^{22} atoms $\mathrm{cm^{-2}\,mag^{-1}}$, about 8 times the galactic value. This is probably correlated with the large underabundance of the SMC in heavy elements. One star, Sk143, has however a gas-to-dust ratio close to the galactic one.

Key words: Small Magellanic Cloud – interstellar extinction – infrared – visible – gas-to-dust ratio

1. Introduction

There is increasing evidence that the properties of interstellar dust and the gas-to-dust ratio vary from galaxy to galaxy, probably mainly as a function of metallicity. Differences in the far-UV extinction laws of the Galaxy, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) are well established (Nandy et al., 1981; Koornneef and Code, 1981; Prévot et al., 1984): the typical SMC extinction curve, and to a smaller extent the LMC curve, shows little or no feature at 2200Å and [when normalized to $E(B-V)$] rises faster in the far-UV than the galactic curve (Savage and Mathis, 1979). Koornneef (1982) has shown that the gas-to-dust ratio in the LMC, as measured by the ratio of the neutral hydrogen column density to the colour excess $N(\mathrm{H\,I})/E(B-V)$, is higher by a factor of four than the galactic value. However, he shows that the extinction laws in the visible and the near infrared and in particular the ratio $R=A_V/E(B-V)$ of visual extinction to colour excess are very similar in the LMC and the Galaxy. The latter result has also been found by Morgan and Nandy (1982), and confirmed recently by Clayton and Martin (1984).

Given the much smaller metallicity of the SMC, by a factor of about 10 instead of 4 for the LMC, compared to the Galaxy (Lequeux et al., 1979), one expects more extreme differences in the gas-to-dust ratio, and perhaps some differences in the visual and IR extinction curves. We have therefore obtained photometric measurements in the *UBVJH* and *K* wavebands and measurements of the interstellar Lyman alpha line for a number of stars in the SMC for which we also have new spectral classification. This material allows us to determine the extinction curve in the infrared and the visible and the gas-to-dust ratio. Very preliminary results which have been presented by Lequeux et al. (1983) and Prévot et al. (1984) are superseded by the present analysis.

In Sect. 2 we describe the photometric observations, and we discuss the extinction curve. The Lyman alpha observations are presented in Sect. 3 in which the gas-to-dust ratio is determined. Section 4 is the conclusion, where some consequences of our findings are discussed.

2. Infrared photometry

2.1. Observations

The infrared photometry in the bands $J(1.25\,\mu\mathrm{m})$, $H(1.65\,\mu\mathrm{m})$, $K(2.2\,\mu\mathrm{m})$ was carried out with the ESO infrared photometer attached to the 3.60 m telescope at La Silla (Chile), during the nights of October 22nd and 23rd, 1983. Some additional measurements were obtained during the night of December 10th, 1983. An InSb photovoltaic detector cooled with liquid nitrogen at 63 K was used (Kreysa, 1980). A complete description of the system is given in the ESO Users Manual. Stars were centered in a 7.″5 diaphragm, and sky subtraction was achieved by chopping at a frequency of 7 Hz and beam-switching with a 15″ amplitude in the E–W direction. Such a value was chosen in order to avoid any possible contribution of nearby stars. The integration time was set to 15 s and the number of measurements (number of cycles ABBA, as described in the ESO Users Manual) was software-controlled to reach a signal-to-noise ratio higher than 200, with a maximum number of 8 cycles. Usually, such a ratio was obtained for programme stars after 4 cycles, which means a total integration time of about 4 min in each filter.

The standard stars used were: HR 512; HR 1294; HR 8658; HR 8700; HR 8701. They were taken in the list of Wamsteker (1981) with some changes in the standard values according to the

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* Based on observations with the International Ultraviolet Explorer (IUE) at the Villafranca Satellite Tracking Station of the European Space Agency, and on observations at the European Southern Observatory, La Silla, Chile

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Table 1. Spectral types and *UBVJHK observed magnitudes for* SMC stars

Star No.	Spectral type	*V*	*B–V*	*U–B*	*n*	*J*	*H*	*K*	*n*
Sk 7	B3Ia	12.65	−0.05	−0.74	3	12.68	12.73:	12.65	2
13	B2.5Ia	12.40	+0.01	−0.76	3	12.37	12.35	12.32	3
18	07+Neb	12.47	−0.20	−0.96	3	12.93	13.03	13.04	1
32	04III−V	13.55	−0.19	−1.04	3	13.91:	13.93	13.84	2
65	B3Ia−Ib	13.07	+0.01	−0.70	3	13.03	13.07	13.03	1
73	B2Ia	12.66	−0.03	−0.80	3	12.72	12.69	12.68	1
76	B1I	12.77	−0.10	−0.93	3	12.96	13.05	13.07	1
82	B0.2Ia	12.13	−0.14	−0.93	3	12.29	12.27	12.20	3
85	B1−1.5Ia	12.05	−0.12	−0.91	6	12.29	12.32	12.32	3
94	B1.5−2Iab	12.38	−0.16	−0.90	3	12.61	12.70	12.72	3
103	B0I	12.37	−0.15	−0.94	3	12.61	12.66	12.71	2
107	09−9.5III	12.90	−0.19	−1.01	3	13.37	13.42	13.52	1
119	B2Ia	12.18	−0.08	−0.83	6	12.39	12.42	12.43	2
120	(B0.5:)	13.50	−0.11	−0.89	3	13.77	13.79	13.87	1
124	B2Ia	11.50	−0.04	−0.85	3	11.51	11.46	11.41	2
142	07:V	13.55	−0.12	−0.98	3	13.79	13.78	13.58	2
143	09.7Ib	12.90	+0.07	−0.76	3	12.82	12.81	12.81	2
145	B2.5Ia	12.54	−0.14	−0.90	3	12.89	12.94	12.95	2
159	B0.2Ia	11.88	−0.17	−0.94	3	12.17:	12.24:	12.25:	2
191	B1.5Ia	11.84	−0.04	−0.85	6	12.00	12.03	12.00	2
197	08−9Ve	13.38	−0.05	−0.97	3	13.30	13.20	13.03	1
AV 214	B1Ia−Iab	13.35	+0.05	−0.77	3	13.37	13.35	13.32	1
398	09.7Ia	13.86	+0.08	−0.78	6	13.64	13.61	13.60	2

homogenized set of Koornneef (1983a). Reductions of the observations were made in the manner described by Engels et al. (1981), and the mean extinction coefficients of these authors were used. For the standard stars, the maximum deviation between observed and standard magnitudes never exceeds ± 0.02 mag. The results of the measurements are presented in Table 1. Nearly all the stars used in the determination of the far ultraviolet extinction curve of the SMC (Prévot et al., 1984) have been observed at least twice. The average standard deviations for one measurement and for each infrared magnitude are the following:

$$\bar{\sigma}(J)=0.020 \qquad \bar{\sigma}(H)=0.025 \qquad \bar{\sigma}(K)=0.019\,.$$

These values have been obtained after an iterative process which consisted in eliminating measurements differing by more than 2σ from the average magnitude, in the cases where stars were measured more than twice. However, when stars were observed only twice, there remained a few pairs of values which differed by more than 2σ: the suspected lower quality of these measurements is indicated by a colon in Table 1. A colon should be implicitly added after *JHK* magnitudes determined by single observations. Table 1 gives also the MK spectral types we derived from plate material obtained by us between 1981 and 1983 with the ESO 1.5 m and 3.6 m telescopes and the result of a new *UBV* photometry we carried out during the same period with the ESO 1 m telescope. Further details on *UBV* photometry and spectroscopic observations will be published in a separate paper. The stars are designated in the present paper by their number in the catalogues of Sanduleak (1968, 1969) or Azzopardi and Vigneau (1975).

2.2. Two-colour diagrams

We will now determine the slopes of the reddening lines in several selected two-colour diagrams obtained by plotting infrared colours as a function of the *B–V* index. These colours must first be corrected for differences in spectral types, in order to isolate the colour variations due to interstellar extinction. This correction is made possible by using a set of homogeneous intrinsic colours. What is important for our purpose is to use a coherent set of colours with spectral type: actual values of colours are relatively unimportant, as underlined by Koornneef (1982) in his study of the LMC infrared extinction. Unfortunately we do not have a complete set of intrinsic colours for the SMC supergiants and we have been led to adopt the *UBV* intrinsic values derived by Johnson (1966) for galactic supergiants together with the *JHK* intrinsic colours from Koornneef (1983b) which refer also to galactic supergiants.

The only way to avoid the use of intrinsic colours is the so-called "pair-method". We used it with some success for determining the *UV* extinction in the SMC, and we tried to apply it to this study. However, due to small differential reddenings of stars pairs, we obtained appreciably scattered results which justified the process that was adopted.

Following the method used by Koornneef (1982) we normalized the observed colours to the spectral type B0.5Ia which represents the average spectral type of our sample. The normalized colours are given in Table 2 and the corresponding colour-colour diagrams are presented in Fig. 1. A common feature to all three diagrams is the behaviour of several stars: Sk 32, Sk 82, Sk 124, Sk142 and Sk197 are located systematically below the reddening lines. These positions correspond to infrared excesses which are even more clearly visible when plotting the observed infrared magnitudes as a function of $1/\lambda$.

Sk 32 and Sk 142 are early O stars [located respectively in the nebular regions DEM 66 and DEM140, Davies et al. (1976)]. When dereddened by the *E*(*B–V*) given in Table 3 using the SMC

Table 2. Observed colours of SMC stars normalized to the spectral type B 0.5 Ia

Star No.		*U–V*	*B–V*	*V–J*	*V–H*	*V–K*
Sk	7	−1.08	−0.16	−0.30	−0.40	−0.33
	13	−0.98	−0.08	−0.19	−0.21	−0.19
	18	−1.02	−0.14	−0.26	−0.31	−0.31
	32	−1.09	−0.12	−0.16	−0.13	−0.03
	65	−0.98	−0.10	−0.23	−0.32	−0.29
	73	−1.00	−0.10	−0.24	−0.23	−0.23
	76	−1.10	−0.13	−0.24	−0.33	−0.36
	82	−1.04	−0.13	−0.12	−0.09	−0.02
	85	−1.12	−0.16	−0.33	−0.36	−0.37
	94	−1.20	−0.22	−0.37	−0.48	−0.51
	103	−1.04	−0.13	−0.16	−0.20	−0.25
	107	−1.08	−0.15	−0.36	−0.31	−0.40
	119	−1.08	−0.15	−0.39	−0.44	−0.46
	120	−1.00	−0.11	−0.27	−0.29	−0.37
	124	−1.06	−0.11	−0.19	−0.16	−0.12
	142	−0.96	−0.05	−0.03	+0.08	+0.29
	143	−0.60	+0.11	+0.19	+0.21	+0.21
	145	−1.27	−0.23	−0.57	−0.66	−0.68
	159	−1.08	−0.16	−0.25	−0.31	−0.32
	191	−1.01	−0.09	−0.27	−0.31	−0.29
	197	−0.90	+0.01	+0.28	+0.47	+0.65
AV	214	−0.78	+0.02	−0.07	−0.05	−0.03
	398	−0.61	+0.12	+0.33	+0.37	+0.38

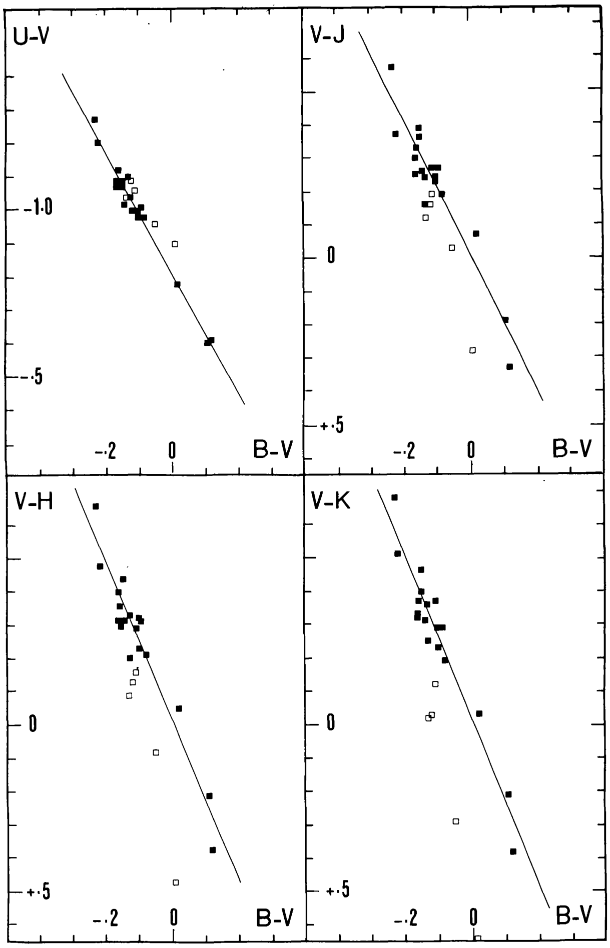

Fig 1. Colour-colour plots for stars in the SMC. The colours have been normalized to the spectral type B 0.5 Ia as explained in the text. Five stars deviate systematically from the mean trends in the diagrams which involve infrared magnitudes, indicating infrared excesses. They are symbolized by open squares and are not used in the determination of the slopes of the reddening lines

Table 3. IUE observations, atomic hydrogen column densities and colour excesses for the programme stars

Star No.		SWP IUE image No.	N_H (10^{21} cm^{-2})	*E(B–V)*
Sk	7	10317[a]	5±1	0.09
	13	8295,[a] 10321	11±2	0.17
	18	8294	9±2	0.12
	32	16253[a]	1±0.5	0.13
	73	22365[a]	8±1	0.15
	76	10322, 18910[a]	11±2	0.12
	82	8293, 8346	4±1	0.12
	85	8296	3±1	0.09
	94	7638	1±0.5	0.03
	103	16049	4.5±1	0.12
	107	10315, 22373	< 1	0.11
	119	10323, 16050	6±2	0.10
	120	10319[a]	5±1	0.14:
	124	8292	2±1	0.14
	142	18909[a]	< 1	0.20
	143	16051[a]	2.5±1	0.36
	145	10316	< 1	0.02
	159	6590	2±1	0.09
	191	16052	4±1	0.16
AV	214	22372[a]	8±2	0.27
	398	22361[a]	15±3	0.37

[a] Exposure times ≧ 40 min

typical reddening curve (Prévot et al., 1984), their far-UV spectrum are quite too steep (and a dereddening with the galactic law is not adequate either as a negative depression at 2200 Å appears). In fact, the observed ultraviolet colours of both stars are those of typical not-reddened O stars. This could be interpreted as if the colour excesses *E(B–V)* were fictitious due to the presence of a faint close-by red companion which would contaminate also the infrared measurements. Unfortunately, when adopting the above intrinsic colours, it is not possible to find an adequate companion able to explain all the observed colours and faint enough not to appear on the visible spectrum.

On the other hand, Sk 82 is a bright supergiant with possible peculiar spectral features; Walborn (1977) notices that Hβ and Hγ are apparently filled in by emission. Sk 124 is a very bright Hα emission star (S45 in the list of Henize, 1956). Also, our spectrum of Sk 197 shows Balmer lines Hβ, Hγ and Hδ strongly in emission. These features which reveal atmospheric extensions in bright supergiants can account qualitatively for the anomalous infrared colour excesses observed; it is known that bright early supergiants and emission-line stars often exhibit infrared excesses which are believed to result from free-free emission in a plasma surrounding the star (see for instance Underhill and Doazan, 1982); we verified that the infrared excesses visible in Fig. 1 are of the same order of magnitude as those analyzed by Underhill in Chap. 4 of Underhill and Doazan.

In addition we must stress that the *UBV* colours of AV 214 are somewhat uncertain, due to the presence of a nearby star ($d \sim 8''$, $\theta \sim 75°$, $\Delta m_B \sim 2.8$) which might have contaminated the measurements made through the largest diaphragms.

Consequently, we decided to eliminate the five objects showing infrared excesses from our discussion. We shall examine the behaviour of AV 214 without rejecting it a priori because we just suspect its photometry to be possibly perturbed. Meanwhile we are waiting for new spectrographic observations of all these stars in the region of the sodium D lines in order to reveal possible duplicities not yet detected.

2.3. Reddening ratio and the SMC extinction curve

A least square solution was calculated for determining the slopes of the reddening lines. It includes all stars except Sk 32, Sk 82, Sk 124, Sk 142, and Sk 197. This gives:

$$E(U-V)/E(B-V) = 1.81 \pm 0.11$$
$$E(V-J)/E(B-V) = 2.02 \pm 0.13$$
$$E(V-H)/E(B-V) = 2.36 \pm 0.15$$
$$E(V-K)/E(B-V) = 2.47 \pm 0.16 .$$

Omitting the star AV 214 from the least square solutions does not change the obtained values by more than 0.08.

When compared to the Galaxy, the first ratio is found in good agreement with the classical value 1.72. The three following ratios seem to have lower values than the galactic ones given e.g. by Whittet and Van Breda (1980) or by Koornneef (1983b). They are also lower than the values determined by Koornneef (1982) for the LMC. The comparison is given in Fig. 2. However the standard errors for each ratio are rather large: these errors and the problem mentioned above with the intrinsic colours made it questionable to consider as significant the differences between the Galaxy, the LMC and the SMC values.

The ratio of total to selective extinction *R*, can be determined by using the relation:

$$R = 1.10\, E(V-K)/E(B-V)$$

which is exact only for the theoretical curve No. 15 of Van de Hulst (1949) but which is in fact practically insensitive to the grain size distribution. We obtained in this way

$$R = 2.72 \pm 0.21 .$$

Although smaller, this value is in rough agreement with the determinations quoted above as well as those made by Morgan and Nandy (1982) for the LMC and by Feast and Whitelock (1984) for the SMC.

We conclude that our determination of the ratio of total to selective absorption for the SMC does not differ significantly from the LMC or the mean Galactic values.

Coming back to the problem of the intrinsic colours of supergiants in the SMC, the LMC and the Galaxy, we consider that attempts to derive infrared intrinsic colours of LMC stars such as done by Morgan and Nandy (1982) are based on a much too small sample to present a real advantage upon a coherent set of colours derived from extensive galactic material. This explains why we prefer to adopt the results of the unification work performed by Koornneef (1983b). The choice of $(B-V)_0$ as the reference colour is optimum since nearly all published systems give values of $(B-V)_0$ close enough to involve differences in the reddening line slopes not larger than 2.5%.

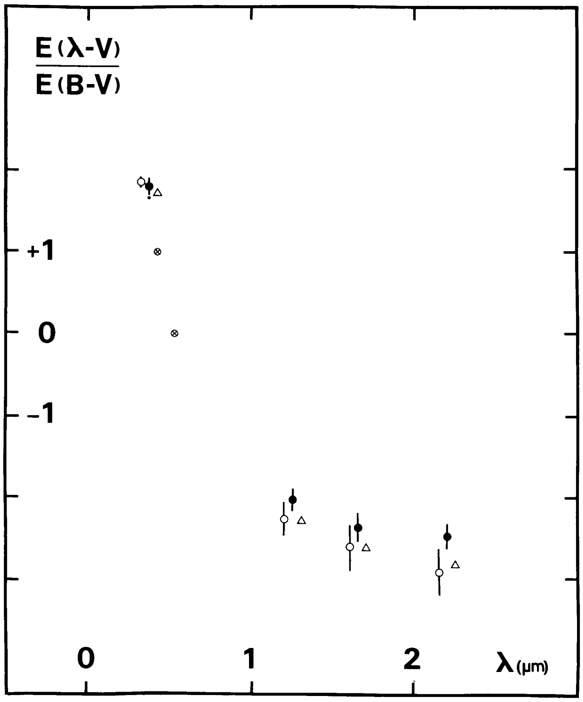

Fig. 2. Slopes of the various reddening lines of Fig. 1 for the SMC (filled circles) compared with those for the LMC (open circles) and for the Galaxy (open triangles). The LMC values are from Koornneef (1982) and the galactic ones from Koornneef (1983b). The small dot at *U* wavelength represents the value derived for the SMC by Prévot et al. (1984) using the pair method. Encircled crosses at *B* and *V* wavelengths result from normalization

We present in Fig. 3 the SMC extinction curve from infrared to ultraviolet, normalized to $E(B-V) = 1.0$ and $A_V = 0$. The infrared part corresponds to the results of the present work, the ultraviolet points are taken from Prévot et al. (1984). It illustrates well the absence of significant differences with the LMC and the galactic curves in the infrared, the visible and the near-UV, while large differences appear in the far-UV. A general discussion of interstellar extinction in the SMC will be made in a forthcoming paper.

3. Lyman alpha observations and gas-to-dust ratios

The column density of interstellar atomic hydrogen in front of a star can be derived from the profile of the Lyman alpha interstellar absorption line in its spectrum. The optical depth in this line, assuming a pure damping profile, is given by Bohlin (1975):

$$\tau_\lambda = 4.26\ 10^{-20} N_H/(\lambda - \lambda_0)^2 ,$$

where N_H is the column density of atomic hydrogen, λ the wavelength and λ_0 the central wavelength of the line. As shown by Koornneef (1982) the contribution of the stellar Lyman alpha line can be neglected for our early-type stars.

All the programme stars except Sk 65 and Sk 197 have been observed with the IUE satellite with the Short Wavelength Primary (SWP) camera in the low resolution mode. Most observations have

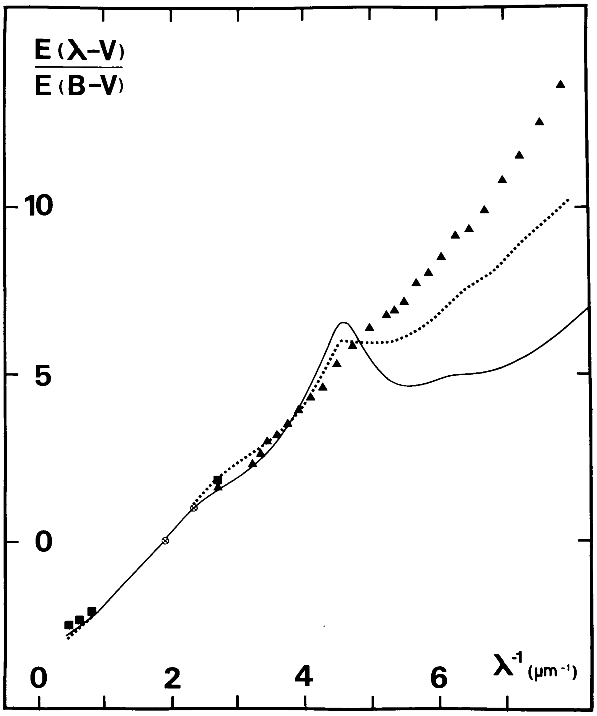

Fig. 3. The SMC extinction curve from 2.2 μm to 130 nm resulting from the present work (squares) and from Prévot et al. (1984) (triangles). The heavy line represents the galactic law [Savage and Mathis (1979), plus Koornneef (1983b) for the infrared] and the dotted line represents the LMC curve [mean of Nandy et al. (1981) and Koornneef and Code (1981) for the ultraviolet, and Koornneef (1982) for the infrared]. Encircled crosses at B and V wavelengths result from normalization

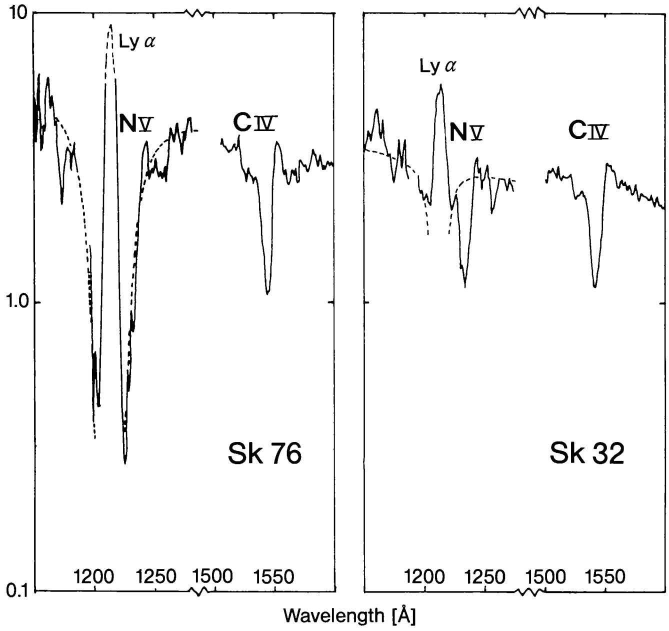

Fig. 4. Two examples of determination of the column density of atomic hydrogen N_H from low-resolution IUE spectra. For the two stars Sk 76 and Sk 32 we show a portion of the dereddened spectrum around Lyman alpha and another portion around the C IV λ1550 line. The spectrum shows interstellar Lyman alpha absorption at the center of which a strong geocoronal Lyman alpha emission is present. A part of the spectrum is missing on the blue side due to a reseau mark and the red side is affected by the N V stellar P Cygni line. This line is supposed to have the same velocity profile as the C IV line which is also shown. The best fitting theoretical Lyman alpha profile is indicated as a dotted curve. It corresponds to $N_H = 11\ 10^{21}\ \mathrm{cm}^{-2}$ for Sk 76 and $1\ 10^{21}\ \mathrm{cm}^{-2}$ for Sk 32

been obtained by us, but we also used a few spectra from the IUE archives. The spectra have been reduced using an extrapolation of the standard IUE calibration towards the short-wavelength side of Lyman alpha; the spectra were also dereddened using our determination of the colour excess of each star and an extrapolation of the far-UV SMC extinction curve (Prévot et al., 1984). The results are quite insensitive to these extrapolations. As shown in Fig. 4 the center of the Lyman alpha absorption is occupied by the strong geocoronal Lyman alpha emission. The shape of this emission can be derived from the observation of those stars which have a very strong Lyman alpha absorption: its profile is almost triangular and goes down to negligible levels at ± 12 Å from the center in the worst cases. The main problems in the derivation of the column densities, which are large in the SMC and correspond to broad interstellar lines, are not with the geocoronal emission. We have indeed tested this point by comparing determinations of the hydrogen column densities on spectra of the same LMC stars observed with the large aperture of IUE, where the geocoronal Lyman alpha line is strong, and with the small aperture for which the geocoronal line is weak and narrow: the results are the same within the errors. The problems are rather with 1) the poor signal to noise level on the blue side of Lyman alpha 2) a reseau mark at about 1187 Å and mainly 3) the N V stellar line and a few interstellar lines on the red side of Lyman alpha (see Fig. 4). Assuming that the N V line velocity profile is identical to that of the C IV profile, it is possible to define which parts of the spectrum are left unaffected. We then matched these parts with blackbody spectra, which fit reasonably well the stellar continuum, affected by theoretical Lyman alpha absorption profiles (smoothing these profiles with the IUE point spread function has a negligible effect on the results). We give in Table 3 the column densities N_H measured in this way, with an estimate of the uncertainties. The uncertainties are not random errors but rather of systematic character: they result mainly from an estimate of the effect of the stellar and interstellar lines around Lyman alpha. We have been quite generous in estimating them, so that the true N_H are almost certainly within the limits given in Table 3. Figure 5 displays N_H as a function of the colour excess $E(B-V)$ for the programme stars. The colour excesses in Table 3 and Fig. 5 are calculated using the spectral types and $B-V$ of Table 1 and the intrinsic colours from Johnson (1966). We must keep in mind that the uncertainties on the colour excesses are at least of the order of ± 0.03 mag.

Some stars present problems and should be eliminated from the discussion of a correlation between N_H and $E(B-V)$. They are the same which were already discussed in Sect. 2.2 as showing infrared excesses. We just add that their colours might be peculiar and strong deviations in their far-UV extinction curve may be expected, like for other emission-line stars in the Magellanic Clouds (Shore and Sanduleak, 1984). In addition, Sk 143 poses a special problem, already discussed by Lequeux et al. (1982). When dereddened by $E(B-V) = 0.36$ and the far-UV typical SMC reddening curve, its far-UV spectrum is incredibly steep. Lequeux et al. (1982) found that this star has a reddening law close to the galactic one, a result supported by the exceptional presence of a strong 2200 Å extinction excess. There is no reason to suspect the colour excess of this star, hence the observed $N_H/E(B-V)$ ratio in its direction is close to the galactic value. The ratio $N_H/E(B-V)$ and the far-UV extinction law of Sk 143 deviate so much from the average that we

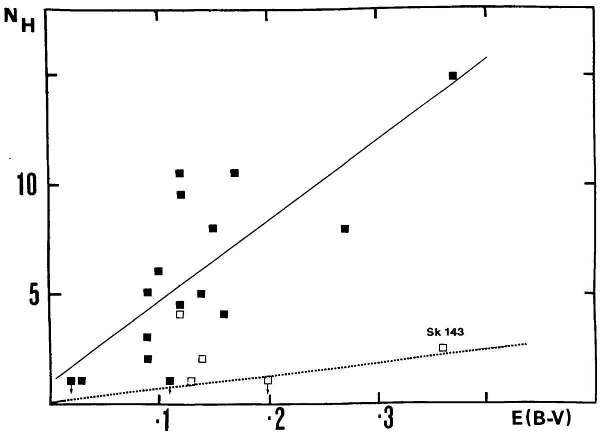

Fig. 5. The relation between the column density of atomic hydrogen N_H (in 10^{21} atoms cm^{-2}) and the colour excess $E(B\!-\!V)$ in SMC stars. N_H is derived from interstellar Lyman alpha observations, and the estimated errors are indicated. $E(B\!-\!V)$ is obtained from our photometry using the intrinsic colours $(B\!-\!V)_0$ of Johnson (1966). For reasons discussed in the text, the open squares correspond to stars not used in the derivation of the $N_H/E(B\!-\!V)$ ratio. The dotted line represents the galactic relation (Bohlin et al., 1978)

do not include them in the correlation, as well as Sk 32, Sk 82, Sk 124, and Sk 142. These stars are symbolized by open squares in Fig. 5.

The 16 remaining stars give a positive correlation between N_H and $E(B\!-\!V)$, with rather large deviations which must be partly real. A least square fit gives:

$$N_H = 3.7\ 10^{22}\,[E(B\!-\!V)+0.02]\ \mathrm{atom\ cm^{-2}\,mag^{-1}}$$

with a standard error on the slope $\pm 0.32\ 10^{22}$.

In the Galaxy, however, an important fraction of the interstellar gas can be under the form of molecular hydrogen on lines of sight with colour excesses $\gtrsim 0.2$. We know nothing on molecular hydrogen in the SMC, but it could be present in appreciable amounts on the line of sight of the two most reddened stars, AV 214 and AV 398. If we do not keep them in the correlation, we obtain:

$$N_H = 5.2\ 10^{22}\,[E(B\!-\!V)-0.01]\ \mathrm{atom\ cm^{-2}\,mag^{-1}}$$

with a standard error on the slope $\pm 0.62\ 10^{22}$; this might be more representative of the gas-to-dust ratio. The intercept for $N_H=0$ should in principle correspond to a E(B–V) very close to the galactic foreground colour excess, which is estimated to be of the order of 0.02 mag (McNamara and Feltz, 1980). However the errors are too large to allow a determination of the foreground extinction by this method.

Our determinations of $N_H/E(B\!-\!V)$ can be compared to those for the Galaxy. Bohlin et al. (1978) find $N_H/E(B\!-\!V) = 4.8\ 10^{21}$ atom cm^{-2} mag^{-1} and $N(\mathrm{H}+2\mathrm{H}_2)/E(B\!-\!V) = 5.8\ 10^{21}$ atom cm^{-2} mag^{-1}. Strictly speaking, it is the first figure which should be compared to our numbers: thus the $N_H/E(B\!-\!V)$ ratio in the SMC is between 8 and 12 times the galactic ratio. The LMC one is $2\ 10^{22}$ atom cm^{-2} mag^{-1}, about 4 times galactic (Koornneef, 1982). Since interstellar dust is made of heavy elements which are less abundant in the LMC than in the Galaxy, and even less in the SMC, such a trend is indeed expected if the efficiency of dust formation is similar in all three galaxies.

4. Conclusion

From infrared and optical photometric observations and spectroscopic observations on a sample of 23 early-type stars in the SMC, we have determined the SMC extinction law in the infrared and the visible. We obtain in particular a ratio of total extinction to colour excess $R = A_V/E(B\!-\!V) = 2.72 \pm 0.21$. This value is somewhat smaller than the canonical galactic value of 3.1. It would be premature, however, to state that the difference is significant, because the SMC extinction curve is sensitive to errors in the photometry [the most reddened star we could find in the SMC is AV 398, with $E(B\!-\!V) = 0.37$ only], and to the adopted intrinsic colours of the SMC supergiants, for which we lack direct determinations. For the LMC, Koornneef (1982) also found a galactic infrared and visible extinction curve. This is somewhat surprising since the SMC and to a smaller extent the LMC differ strongly from the Galaxy in chemical composition and other properties. Bromage and Nandy (1983) and Lequeux et al. (1983) have suggested that the absence of the 2200 Å absorption feature in most SMC stars is due to a lack of graphite grains, probably connected to the very large underabundance of carbon in the SMC (Dufour et al., 1982). If graphite is completely absent and if the size distribution of silicate grains, the other supposed component of interstellar dust in the model of Mathis et al. (1977), is similar to that in the Galaxy, the ratio $R = A_V/E(B\!-\!V)$ should be approximately equal to 2.0 (Mathis et al., 1983, Table C1). Our determination of R for the SMC is somewhat smaller than the galactic value, but not as low as 2. A possible consequence is that graphite plays less role in the visible than assumed by Mathis et al. (1977); this implies in turn that the graphite grains which are responsible for the 2200 Å feature are small, with radii of at most a few hundreths of µm. If this is true, the size distribution of silicate grains which now give almost all the extinction in the infrared and the visible has to be modified with respect to that of the model, in the direction of a larger fraction of big grains. A detailed discussion of this problem will be given in a forthcoming publication.

In spite of the small differences in the visible and infrared extinction curves of the SMC, the LMC and the Galaxy, there are large differences in their gas-to-dust ratio. We find that the ratio of the column density N_H to the colour excess is about 8 times that of the Galaxy, while Koornneef (1982) finds it in the LMC to be 4 times galactic. This ratio is inversely correlated with the abundance of oxygen and hence probably silicon, which goes roughly as the ratios 1/10 : 1/4 : 1 (see e.g. Lequeux et al., 1979). This is expected since the interstellar dust which gives the extinction in the visible is presumably mainly made of silicates.

One of the interests of the present study is that data are now available on infrared and visible extinction and on gas-to-dust ratio for galaxies spanning an order of magnitude in heavy element abundances. This range of abundances encompasses most of the galaxies for which abundance determinations exist, with only a few exceptions (Pagel and Edmunds, 1981). Relatively safe extinction corrections are now possible for these objects.

Acknowledgements. We are grateful to the VILSPA Staff and to the ESO night assistants who made possible the ultraviolet and ground based observations.

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