INTERSTELLAR EXTINCTION IN THE MAGELLANIC CLOUDS

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ABSTRACT

The extinction properties of interstellar dust in the Large and Small Magellanic Clouds have been systematically investigated, using recent UV observations of early type Cloud members along with complementary visible data. The extinction curves differ systematically from the standard Galactic curve. The latter shows a broad absorption feature centred near 2200Å in virtually all sight lines but this is absent or only weakly present in the SMC; also the SMC extinction in the far UV is the largest known relative to E_{B-V}. Dust in the LMC appears to be intermediate in extinction properties between the SMC and normal Galactic material. However, exceptions from the average extinction curves have been found in both Clouds.

Model computations show that the range of grain sizes and their number distribution law may not be significantly different in the Clouds and the Galaxy; the difference in extinction laws can be accounted for by varying the graphite contribution relative to silicate.

1. INTRODUCTION

Extinction due to scattering and absorption occurs when starlight passes through a medium containing small particles. The wavelength dependence of extinction over a long wavelength range is a diagnostic of the grain-constituents and their sizes and size distributions. In the Magellanic Clouds, the nearest extragalactic systems, we have the opportunity of studying the interstellar extinction from comparison of individual spectra of reddened and unreddened stars of similar types.

It is well established that the abundances of heavy elements relative to H are significantly lower in the Magellanic Clouds than in

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the Sun and nearby Galactic HII regions (Pagel et al. 1978, Lequeux et al. 1979, Dufour et al. 1982). A probable site of grain formation is the atmosphere of cool stars. It may be that the underabundance of heavy elements in stellar atmosphere could affect the production and compostion of dust grains. A systematic investigation of extinction properties of dust in the Magellanic Clouds would, therefore, yield important information on the question of their origin and the chemical enrichment of the interstellar medium in these galaxies. An accurately determined extinction curve in the LMC and SMC would also enable us to derive the intrinsic flux distributions of the Magellanic Cloud members. Their distances being well determined, their absolute flux distributions would provide important stellar physical parameters such as angular diameters, radii and effective temperatures.

Earlier work of Brück et al. (1970) on the measurement of interstellar extinction in the visible range indicated that the ratio of UV slope to BV slope is not significantly different from the Galactic mean value. The first positive suggestion of differences in the UV extinction shortward of 3000Å between the Galaxy and the LMC was made by Borgman et al. (1975) from measurements of the surface brightness distribution using the ANS data in the 30 Doradus region. Because of many assumptions involved, the analysis of this surface photometry led to discordant results (Borgman 1978, Koornneef 1978, Nandy et al. 1979). A survey on a systematic basis using the conventional method of comparing the flux distributions of individual stars with different extinctions, was undertaken by several authors after the launch of the International Ultraviolet Explorer. In this article the current observational situation is summarised. The available data are examined in order to look for regional variations, if any, in the extinction curves and to determine mean LMC and SMC extinction curves. Specific grain models which might account for the observations, and some possible explanations thereof are discussed.

2. OBSERVATIONS

The survey of OB stars in the Magellanic Clouds currently available (Rousseau et al. 1978, Azzopardi et al. 1975, Ardeberg et al. 1977) is limited to V $\sim$ 14.00. At the distance of the Magellanic Clouds most of these must be supergiants. The average reddening E_{B-V} of these supergiants is not large, about $\sim$ 0.1 in the LMC and $\sim$ 0.07 in the SMC; the foreground reddening is $\sim$ 0.05. However, in the Large Magellanic Cloud there are several moderately reddened supergiants with E_{B-V} > 0.2; the majority being located in the 30 Doradus region. In the SMC only a small sample of supergiants have E_{B-V} > 0.2; they are located near the core and Wing. (A few OB stars with large B-V values turned out to be unreddened and the large value of B-V is due to the presence of a red companion.)

The UV observations (1150 - 3350Å) were obtained with the International Ultraviolet Explorer (Boggess et al. 1978) in both long

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and short wavelength channels in low dispersion mode ($\Delta\lambda \sim 6Å$) through the large aperture (Koornneef et al. 1981, Nandy et al. 1980, 1981, Rocca-Volmerange et al. 1981, Lequeux et al. 1982). Complementary visible spectra of a representative sample of LMC members were obtained with the ESO 3.6m telescope and the SAAO 1.9m telescope; observations at J (1.2μm), H (1.65μm) and K (2.20μm) were made by Koornneef (1981) and Morgan and Nandy (1982). The ground based coverage of the SMC members is limited to published UBV photometry (Ardeberg and Maurice 1977; Azzopardi and Vigneau 1975).

3. REDUCTION

The extinction has been derived from comparison of the moderately reddened and little reddened stars in the Clouds. It is important that they be of similar spectral types and luminosity classes. The principal stellar features observed in the low dispersion UV spectra of early type supergiants are the CIVλ1550 and SiIVλ1400 doublets. They are detected in the supergiants as late as B5-B6. The strengths of these lines (equivalent width in Å) as a function of spectral types for the MC members have been studied by Hutchings (1982) and Houziaux et al. (this symposium). But the accuracy of spectral types determined from these lines is not better than ± 2 subclasses (Nandy et al. in preparation). Within this uncertainty the quoted spectral types and the spectral type determined from UBV photometry of the sample of the Cloud members studied here are consistent with the strength of CIV and SiIV absorption.

Also dominant in the spectra of B supergiants are the spectral lines due to FeIII causing a broad depression about 200Å wide in the continuum near 1920Å first detected in the S2/68 spectra of the Galactic supergiants. This feature is luminosity sensitive, but its strength can vary significantly amongst the supergiants and the difference does not necessarily imply a mismatch of temperature. Any mismatch of this feature in reddened and comparison stars would produce an apparent feature near 1920Å in the extinction curve derived by the comparison method. The effect of this mismatch was estimated and the extinction curve in the spectral region 2000-1800Å was corrected (for the details of the method see Koornneef & Code 1981, Nandy et al. 1981).

The visible spectra were reduced to give data points averaged over $\sim$ 50Å intervals from λ^{-1} = 1.66μm^{-1} to λ^{-1} = 2.54μm^{-1}. In order to compare the extinction curves derived from different pairs of reddened and little reddened Magellanic Cloud members, the curves were normalised to $A_V = 0$ and $E_{B-V} = 1$ (we have adopted λ^{-1} = 1.83μm^{-1} for V-band, 2.30μm^{-1} for B-band and 2.90μm^{-1} for U-band).

Photometric error and error due to spectral type mismatch are the major sources of the errors of the extinction curves derived from the comparison method. The error arising from spectral type mismatch is

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wavelength dependent. For example, for a B1 star an error of one subclass causes an error of ±0.02 near the V-band, ∿ ±0.0.1 near 3000Å rising to ∿ ±0.3 near 1500Å. Photometric accuracy is, on average, ∿ ±0.02 in the visible and ∿ ±0.05 in the wavelength range 2900-2400Å for fluxes averaged over 10Å, but is much lower, ∿ ±0.1 near 2200Å (2400-1900Å) and longward of 2900Å. The error of $\Delta m(\lambda)$ due to the uncertainty of the wavelength determination is < .03.

It is known that many early-type supergiants have long term variability. According to Appenzeller (1972) this may range up to 0.03 mag in V. Nothing is known about the possible variations in the stars studied here. Since the visible and ultraviolet observations are not simultaneous, the possibility exists that there may be uncertainty in V magnitude of about the same amount.

4. RESULTS

4.1 Interstellar extinction in the Large Magellanic Cloud

About half of our samples are located around the outer portion of the 30 Doradus nebula (within 1 kpc from the core), but the rest are well outside. It is, therefore, possible to look for differences in extinction properties between the 30 Doradus region and the rest of the LMC, and we have divided the data into two parts accordingly.

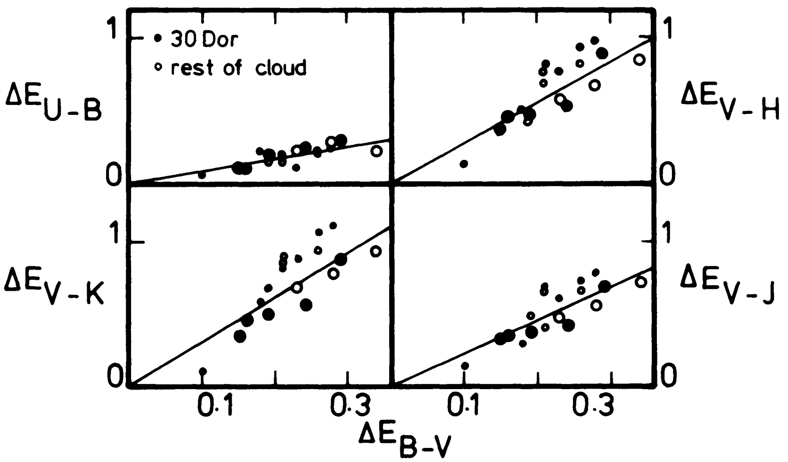

Figure 1. Comparison of infrared and (U-B) colour excesses between the 30 Doradus region and the rest of the Cloud. Larger symbols are given weight = 2.

The values of extinction in the infrared and at the wavelength of the U band have been re-determined in the following way. The colour excesses ΔE_{U-B}, ΔE_{V-J}, ΔE_{V-H}, ΔE_{V-K} as a function of ΔE_{B-V} are shown in Fig. 1. Δ indicates the difference between reddened and comparison stars and different symbols are used for the 30 Doradus region and the rest of the Cloud. UBV data and spectral types are taken from Feast et al. (1960), Rousseau et al. (1978) and Walborn (1980). Wherever possible, more than one comparison star has been used; the mean values are shown in Fig. 1 by larger symbols and are given higher weights (weight = 2).

Since no systematic difference exists between the two sets of data, all the data points have been used to obtain the mean extinction at J, H, K and U bands normalised to $A_V = 0$ and $E_{B-V} = 1$. These values are obtained from the slope of best fit line passing through the origin. (They are not significantly different from the values obtained by Koornneef (1981) and Nandy and Morgan (1981, 1982)).

The visible spectra were obtained for 5 reddened stars (3 of them being located in the 30 Doradus region) and a similar number of comparison stars. Extinction in the visible wavelength range has been measured in the following way:- A set of extinction curves was derived for each of the reddened stars, using more than one comparison star, and a mean extinction curve was determined for each reddened star. This reduced the errors introduced by possible spectral type mismatch. The extinction in magnitude, $\Delta m(\lambda)$ was normalised to $\Delta m = 0$ at $1/\lambda = 1.82\mu m^{-1}$ and $\Delta m = 1$ at $1/\lambda = 2.30\mu m^{-1}$. Within the observational errors the individual extinction curves in the visible agreed well, thereby allowing a mean extinction curve to be constructed.

Individual extinction curves and colour excesses E(λ-V) vs E(B-V) in the UV wavelength range for the sample of LMC members discussed here have been published (see Nandy et al. 1980, 1981; Koornneef and Code 1981). Except for SK 69-108, a heavily reddened star located in the Bar, the extinction curves for all stars are similar within the errors. There appears to be no difference in the extinction law between the 30 Doradus region and the other parts of the LMC.

It should be noted that a number of reddened stars in the sample of Nandy et al. (1980, 1981) are more luminous than the comparison stars by up to 2 magnitudes. The fact that the luminosity sensitive 1920Å feature is also weak in the comparison stars raises the question of whether the luminosity effect is present in the extinction curves shortward of 1700Å, since the continuum fluxes of the luminous stars shortward of 1700Å could be intrinsically weaker than those of the less luminous stars (Humphries et al. 1975). However, this is not the case for the following reasons:

(a) Two reddened O stars which do not show 1920Å features have the same high UV extinction as others.

(b) The mean extinction curves derived from reddened stars with $-8.5 < M_V < -7.5$, and from those with $-7.5 < M_V < -6.5$ agree within the errors of observations.

(c) The difference in absolute magnitudes between the reddened and comparison stars in the sample of Koornneef et al. (1981) is

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slight, yet their mean extinction curve is not significantly different from that of Nandy et al. (1981).

All the available UV observations excluding SK 69-108 are combined to obtain a mean extinction curve for the LMC which is shown in Fig. 2; the comparison of the LMC extinction law with the mean Galactic law (Seaton 1979) is also shown. The Galactic extinction curve shows a change in slope in the blue region near $1/\lambda \sim 2.3\mu m^{-1}$. This is also observed in the LMC curve. In the UV range the LMC curve differs from the Galactic curve in respect of the λ2200 feature and far UV extinction (see Section 5).

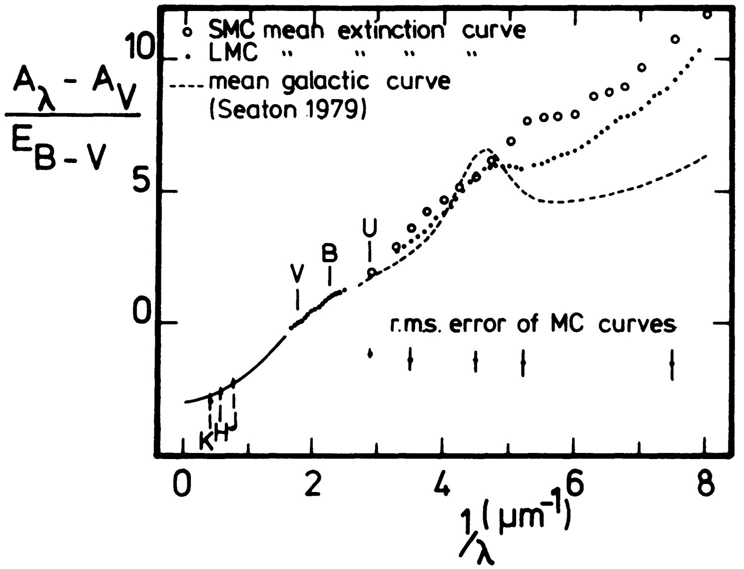

Figure 2. The comparison of the mean LMC and SMC extinction curves with the mean Galactic curve of Seaton (1979). The solid line is van de Hulst curve No. 15 (1949).

Although there is no evidence of systematic difference in extinction curves between the 30 Doradus region and the rest of the Cloud, exceptions have been found due to local anomalies. SK 69-108 which is heavily obscured and located in a region south of the LMC Bar exhibits an extinction curve similar to the Galactic mean curve. Koornneef and Mathis (1981) and Savage (private communication) have reported that the UV extinction properties of dust near the core of the 30 Doradus region are not as extreme as the mean LMC law in respect of the 2200Å feature and far UV extinction. They have suggested that the dust-to-gas ratio might affect the grain properties. Clearly there is a need for further observations.

4.2 The ratio of total-to-selective extinction for the LMC

R, the ratio of total-to-selective extinction measures the amount of dust present causing visible extinction and is an important quantity in many theories of star formation. The value of R is determined by extrapolating the extinction curve to $1/\lambda = 0$. This extrapolation

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to infinite wavelength depends on the model. It is assumed that the extinction in the visible has been mainly caused by dielectric particles (see Section 5). For $2\pi a/\lambda << 1$ the extinction efficiency of the particles varies as λ^{-4} and the shape of the extinction curve between $\lambda = 2.2\mu m$ and $\lambda \rightarrow \infty$ is not strongly dependent on species. Using van de Hulst curve no. 15 (1949) the ratio R is given by $R = 1.10(E_{V-K}/E_{B-V})$. With the value of 3.0 ± 0.2 for E_{V-K}/E_{B-V}, the ratio R for the LMC is found to be 3.3 with the uncertainty of ∿ ±0.2. Within this error, the value of R is the same as the mean value of R for the Galaxy (Whittet and van Breda 1980). There is no guarantee that this extrapolation is valid and further observations at longer wavelengths are desirable. However, recent study of the wavelength dependence of interstellar polarisation for a sample of 22 LMC members over a range of E_{B-V} by Clayton et al. (1983) shows that the average value of λ_{max}, the wavelength where maximum polarisation occurs is 0.58μm ± 0.05. The value of R derived for the LMC is close to that given by the empirical relation $R = 5.5 < \lambda_{max} >$ for Galactic stars found by Serkowski et al. (1975).

4.3 Interstellar extinction in the Small Magellanic Cloud

The first ultraviolet extinction curves for the SMC were obtained by Rocca-Volmerange et al. (1981) and Hutchings (1982) who reported that the extinction curves do not show the λ2200 feature and the far UV extinction is even higher than in the LMC. The results were based on a very small sample of reddened and comparison stars with a small difference in colour excess. Further observations of considerably reddened stars located near the core and the Wing of the SMC and comparison stars were obtained by Nandy et al. 1982. The extinction curves obtained from new pairs confirm earlier results. Irrespective of the location of the reddened stars in the SMC, the individual extinction curves are similar, although exceptions have been found due to local anomalies [possible examples are SK143 (Lequeux et al. 1982) and BBB338 (Nandy et al. 1982)]. In order to derive a mean extinction curve for the SMC we have used the results of Rocca-Volmerange et al. (1981) for SK13 and SK124, the pairs BBB280 comp. star SK32, HD4976 comp. star SK57 (Nandy et al. 1982) and additional pairs SK85 comp. star SK32, AZZ393 comp. star SK32. The comparison of the mean LMC, SMC and Galactic extinction curves is shown in Fig. 2. The error of the mean SMC curve may well be larger than those plotted in Fig. 3; since there are still some uncertainties about cancellation of stellar FeIII lines near 1920Å. These are to be carefully reinvestigated in future, but do not affect the main conclusions, viz. the λ2200 feature, so dominant in our Galaxy, is conspicuous by its absence in the SMC, and the far UV extinction is significantly larger than in the LMC.

5. DISCUSSION

The results presented here show that there is an overall similarity of individual extinction curves in both Clouds suggesting that

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the "normal" LMC and SMC extinction curves are essentially defined (although anomalies have been found as discussed earlier). The comparison of the LMC extinction with the mean Galactic curve for the solar neighbourhood (Seaton 1979) shows two important differences:-

(a) the 2200Å feature is weaker in the LMC (by a factor ∿ 2);

(b) the extinction shortward of 2000Å is considerably higher in the LMC than in the Galaxy.

At the wavelength of the U-band and between 3300Å and 2700Å the LMC extinction values are higher than the Galactic values. This difference was noted by Koornneef and Code (1981) but is well within 2σ and may not be significant. In the visible and infrared wavelength range the LMC and Galactic extinction curves are similar.

The SMC curve is "extreme" in the sense of showing no λ2200 feature (or very weak) and the largest known far ultraviolet exctinction relative to E_{B-V}. There is almost a $1/\lambda$ dependence of $(A_\lambda - A_V)/E_{B-V}$ over the whole range from 1.8 to 8.5μm^{-1}.

As a first approximation to the composition of dust in the Magellanic Clouds we adopt the model proposed by Mathis and co-workers (1977, 1981). According to these authors the simplest dust model that accurately predicts the normal Galactic interstellar extinction observations is a mixture of uncoated graphite and silicate grains with a power law size distribution function $n(a) \propto a^{-3.5}$. Bierman and Harwit (1980) have supported the power law distribution on physical grounds. The model of Mathis et al. (1977) fits the general constraints imposed by element abundances; the particle radii range from ∿ 0.25μm to 0.01μm for silicate, and from 0.25μm to 0.005μm for graphite. Small uncoated graphite provides the "2200" feature in this model.

It is shown in Fig. 3 that this type of model fits the "normal" SMC extinction curve, the only difference being that the graphite contribution to Q_{ext} is at least a factor of seven weaker in the SMC than in the Galaxy (Bromage and Nandy 1983). A fit can be obtained to the LMC curve by increasing the graphite contribution. For example, as shown in Fig. 3 the "normal" LMC extinction curve can be approximated with 35% of the graphite:silicate ratio of the Galactic case (Bromage and Nandy in preparation).

It should be emphasised that the dust model derived by fitting to the extinction curve is not unique; it may be possible to obtain good fits by arbitrarily changing the optical constants, and compensating for this by changes in the size distribution function, or by addition of extra particale types. However, Fig. 3 indicates that the range of grain sizes and their number distribution law as proposed by Mathis et al. (1977) for the Galaxy are not necessarily different in the Magellanic Clouds, only the basic graphite:silicate ratio has to change. The apparently low value of the graphite:silicate ratio in

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the Clouds may have underlying important significance. Bromage and Nandy (1983) have considered several possibilities for this low ratio and have argued that graphite grain formation may have a low efficiency in the Clouds due to a low overall C/O abundance ratio. Carbon abundance in the Clouds has been derived by Dufour et al. (1982) from the UV and ground based observations of the HII regions. They conclude that C/O is very low, ∿ 1/7 in SMC HII regions and ∿ 1/3 in the LMC HII regions. Condensation of graphite grain from stellar atmospheres would be very unlikely in the SMC if C/O << 1. The fact that the extinction properties of the LMC dust are intermediate between the Galactic and SMC ones might be connected with the intermediate C/O ratio in this Cloud.

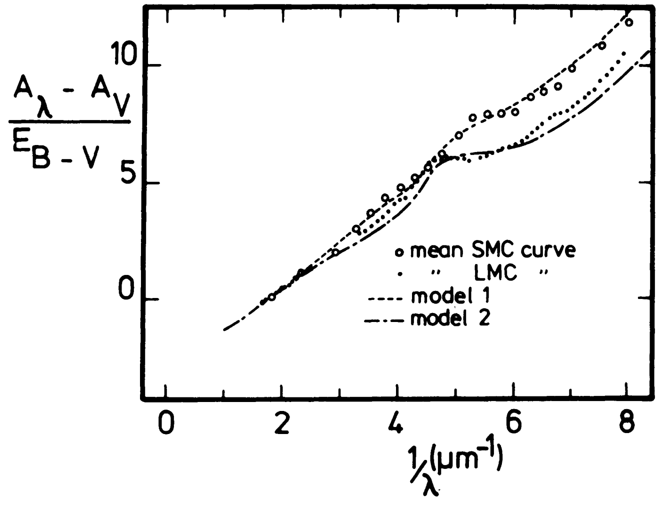

Figure 3. Model fitting to the mean LMC and SMC extinction curves. Model 1 - graphite contribution = nil; Model 2 - graphite contribution = 35% of Galactic value.

However it is known that the accuracy of carbon abundance measurement is limited by IUE detector sensitivity (see for example Maslen et al. (1982). Further work is necessary to establish a possible link between the apparent absence or underabundance of graphite grains and gas-phase depletion in the Clouds.

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DISCUSSION

Searle: The variations in the UV extinction law that you discuss may be one aspect of a more general phenomenon. I have recently determined the reddeneing law in M31 from spectrophotometry of its globular clusters. There is a radial change in this reddening law in the wavelength range 3300 to 10,000Å, across the disk of M31. At a galactocentric distance of 12 kpc, the M31 reddening law resembles that of the solar neighborhood. The ultraviolet extinction, for a given E(B-V), increases with decreasing galactocentric distance.
Hutchings: IUE spectra of M33 objects by Massey and myself show that an extinction law similar to that in the LMC applies there.
Davidson: A parenthetical remark: Several years ago there was a slightly silly dispute about the possible reddening of quasars. Some people insisted that such reddening was negligible because the 2200Å feature was not seen. But there is some evidence that reddening perceptibly affects the UV emission lines, at least, of quasars. So this combination of attributes may indicate something about carbon/oxygen ratios in quasars - a poorly known topic.
de Boer: It is worthwhile, I think, to draw attention to the work of Blair Savage and his collaborators (Meyer and Savage, ApJ 248, 545) on extinction in the UV. From UV photometry with the ANS, and later with the IUE satellite, they showed that the extinction in the UV differs a lot from star to star in the Milky Way. Actually, one cannot trust any value of E(B-V) that is derived entirely from UV observations. It is a pity that people working on UV spectra of extragalactic objects are not yet sufficiently aware of the problems due to differing extinction curves.
Dopita: What happens at wavelengths smaller than 912Å?
Nandy: That I do not know in detail. The laboratory data are conflicting.
Koornneef: What happens to the value on R if you take the graphite out of the Mathis Rumpl Nordsieck-mixture?
Nandy: A MRN-mixture with graphite-contribution = nil gives the value of $R \simeq 2.6$. At present we don't know its value for the SMC.
Savage: In reply to the question of M.Dopita, I recall that graphite has a second but stronger extinction bump at about 800Å. Amplifying what Klaas de Boer just said, indeed I like to caution everybody about using average extinction curves in correcting their UV data for the presence of dust. Studies of stars within the Milky Way and now in the LMC and SMC have shown that the difference in extinction from region to region can be enormous. Within the Milky Way $E(\lambda-V)/E(B-V)$ has been shown to vary from about 4 to 10 at 1300Å. The only safe approach is to obtain information about extinction along the line of sight to stars near to the object of interest. An example of this approach is contained in the paper by Savage and Fitzpatrick (this symposium).