1. INTRODUCTION

The Small Magellanic Cloud (SMC), one of our nearest neighbours, contains considerably less heavy elements and dust than the Galaxy (Bouchet et al. 1985; Welty et al. 1997). In addition, dust in the SMC seems to be different from dust in the Galaxy (Prévot et al. 1984; Pei 1992). For example, a typical extinction curve of the SMC is almost linear with inverse wavelength and does not show a presence of the UV bump at 2175 Å (Prévot et al. 1984; Thompson et al. 1988). Recently, Rodrigues et al. (1997) have measured the linear polarization for a sample of the SMC stars in the optical and found that the wavelength of maximum polarization is generally smaller than that in the Galaxy. The low metallicity of the SMC implies that it should be at an early stage of its chemical evolution, thus resembling in this respect galaxies at high redshifts. A strong support to this view has come from the discovery that the dust in starburst galaxies, apparently the only type of galaxies found so far for redshifts $z > 2.5$, has an extinction law remarkably similar to that in the SMC (Gordon, Calzetti, & Witt 1997).

Several attempts have been made to model the dust in the SMC. Bromage & Nandy (1983) and Pei (1992) modelled some SMC mean extinction curves using the dust mixture of spherical graphite and silicate grains with a power-law size distribution (Mathis, Rumpl & Nordsieck 1977, hereafter MRN; Draine & Lee 1984). Bromage & Nandy (1983) and Pei (1992) have shown that an MRN-like mixture with a lower fractional mass of graphite grains in comparison to silicate grains, and with other parameters as in the Galaxy, can satisfactorily explain the SMC extinction. Pei (1992) even succeeded to fit the SMC extinction law with silicate grains alone. Rodrigues et al. (1997) made model fits to both extinction and polarization for two stars in the SMC, AzV 398 and AzV 456, representing lines of sight with different properties. The authors have found that the mixture of bare silicate and amorphous carbon, or graphite spheres together with silicate cylinders with an MRN-like power-law size distribution explains quite well both the extinction and the polarization.

However, the SMC dust models proposed so far are too simplistic concerning both the choice of grain constituents and grain-size distributions. Recently, Mathis (1996), Li & Greenberg (1997) and Zubko, Krelowski, & Wegner (1998) have presented more sophisticated models of Galactic dust using core-mantle, multilayer and composite grains which are much more physically justified than the models previously considered. Note that the models by Zubko et al. (1998) were calculated with the regularization approach (Zubko 1997) which is a very efficient method capable of deriving optimum and unique size distributions in a general form for any predefined mixture of grains by simultaneously fitting the extinction curve, the elemental abundances and the mass-fraction constraints. The uniqueness of the grain size distributions follows from the mathematical nature of the problem when we need to solve a Fredholm integral equation of the first order, being a typical ill-posed problem. The regularization approach reduces this problem to minimization of a strongly convex quadratic functional. The latter problem was strictly proved to have a single solution. See for more details, e.g. Groetsch (1984), Tikhonov et al. (1990) or Zubko (1997). This method can be expanded to allow one to deduce the uncertainty in the solution based on the data uncertainty, but this is beyond the scope of this letter (Zubko 1999, in preparation).

Recently, Gordon & Clayton (1998) have derived the extinction curves for four SMC stars with several improvements in comparison to previous studies: higher $S/N$ IUE spectra, and a more careful choice of the pairs of reddened and comparison stars. The sightlines toward three stars: AzV 18, 214, and 398, located in the SMC bar pass through the regions of active star formation and exhibit similar extinction law. The sightline toward the star AzV 456, located in the SMC wing, passes through a much more quiescent region of star formation and shows a Galaxy-like extinction with the 2175 Å UV bump. The purpose of the present Letter is to report the first SMC dust models calculated with the regularization approach to the new high quality extinction curves. We modelled the extinction to...
ward the star AzV 398 which is thought to be a typical SMC bar sightline (Rodrigues et al. 1997; Gordon & Clayton 1998). The results of the study which includes all the four stars will be presented in a forthcoming paper.

2. EMPIRICAL DATA

We transform the extinction curve for AzV 398, derived by Gordon & Clayton (1998) in the standard form: $E(\lambda) = \frac{\tau(\lambda)-\tau(V)}{\tau(B)-\tau(V)}$, to the extinction cross section per H atom:

$$\frac{\tau(\lambda)}{N_H} = 0.921 \frac{E(B-V)}{N_H} \left[ E(\lambda) + R_V \right]$$

where $\tau$ is the optical thickness, $E(B-V)$ is the $B-V$ colour excess, $R_V$ is the total-to-selective extinction ratio, and $N_H$ is the column number density of hydrogen. For $N_H$ we take the value $1.5\times10^{22}$ cm$^{-2}$ from Bouchez et al. (1985), corresponding to atomic hydrogen. Since the sightline toward AzV 398 is associated with an H II region (Gordon & Clayton 1998), it is likely that the contribution of molecular hydrogen to $N_H$ is negligibly small (for sightlines not passing through the SMC bar this may not be the case, see Lequeux 1994). The value for $E(B-V)=0.37$ was also taken from Bouchez et al. (1985) and $R_V=2.87$ from Gordon & Clayton (1998).

The elemental abundances (gas + dust), currently adopted for the SMC, were taken from Welyt et al. (1997): C/H=46 p.p.m. (atoms per 10$^6$ H atoms) or 7.66±0.13 dex, O/H=107 p.p.m. or 8.03±0.10 dex, Si/H=10 p.p.m. or 7.00±0.18 dex, Mg/H=9.1 p.p.m. or 6.96±0.12 dex, and Fe/H=6.6 p.p.m. or 6.82±0.13 dex. Note that these values are 2–5 times less than the respective Galactic abundances following recent revision (Snow & Witt 1996; Cardelli et al. 1996). Since we have no information on the amounts of elements in dust and gas separately in the SMC, we simply assume in this study that as in the Galaxy 42% of carbon (~20 p.p.m.), 37% of oxygen (~40 p.p.m.), and all silicon, magnesium and iron are locked up in dust (Cardelli et al. 1996; Zubko et al. 1998). The actual amount of elements locked up in dust is uncertain, but one may expect even lower amounts of elements in dust because the SMC is less chemically processed than our Galaxy.

Recently, Witt, Gordon, & Furton (1998) and Ledoux et al. (1998) proposed that the silicon nanoparticles might be the source of the extended red emission (ERE) in our Galaxy. Zubko, Smith, & Witt (1999) have modeled the mean Galactic extinction curve with the silicon nanoparticles involved and have shown that this hypothesis is consistent with the available data on extinction, elemental abundances and the ERE. On the other hand, Perrin, Darbon, & Sivan (1995) and Darbon, Perrin, & Sivan (1998) have revealed ERE in extragalactic objects showing active star formation: the starburst galaxy M82 and the nebula 30 Doradus in the Large Magellanic Cloud, respectively. Since the sightline toward AzV 398 passes through a star-forming region, we may expect to observe ERE from there as well. We thus included the silicon nanoparticles in our modeling. As in Zubko et al. (1999), we used the silicon core–SiO$_2$ mantle model of silicon nanoparticles with optical constants of nanosized silicon from Koshida et al. (1993). We also included in present study the grain constituents (graphite, silicate, SiC, organic refractory, amorphous carbon, water ice and others) and respective optical constants previously used by Zubko et al. (1998).

3. MODELS OF EXTINCTION

We performed extensive work on modeling the extinction curve for AzV 398, searching for the physically reasonable mixtures of dust constituents. Our goal was to find the models which would simultaneously fit the extinction, consume the allowed amounts of chemical elements and include silicon nanoparticles (by analogy with the Galactic case, Zubko et al. 1999). We report in this Letter three simple models which fulfill all the above requirements. The results are presented in Figs 1–2 and Table 1. The model grains are mostly made up of two species: silicate (MgFeSiO$_4$) and organic refractory residue, which coexist either in core(silicate)-mantle(organic refractory) or in spherical porous composite grains with the latter containing also small amounts of amorphous carbon. The total mass fraction of silicate + organic refractory is about 0.9. The other important model component is the silicon nanoparticles, which are found to have a mass fraction of about 0.07–0.085.

The fact that organic refractory is among the major grain constituents is in good agreement with the expectations that the interstellar radiation field (ISRF) in the SMC is stronger than in the Galaxy (Lequeux et al. 1994) since the icy mantles on silicate grains formed in molecular clouds can be processed by the UV radiation into organic refractory (Greenberg & Li 1996). Note especially that our attempts to include silicate and SiC grains coated by either amorphous carbon or water ice mantles and also bare carbonaceous (graphite, amorphous carbon), silicate and SiC grains resulted in very low mass fractions of such grains, typically less than 1 per cent. This means that the conditions in the SMC (ISRF intensity, duration of the exposure by the UV radiation) are probably favourable for converting icy mantles into organic refractory, but not for the further processing of organic refractory into amorphous carbon. In contrast to the SMC, the presence of icy mantles may be allowed for the dust grains in the Galactic diffuse medium (Zubko et al. 1998).

Following Zubko et al. (1998), the models based on the silicate core–organic refractory mantle (composite) grains are referred to as G (M) models. The GM model is a combination of G and M models and contains both core-mantle and composite grains. As shown in Fig. 1 all the above models fit the extinction curve quite well. The size distributions of both core-mantle and composite grains are quite wide and cover both small and larger grains with the preference to the grains of sizes 10–100 nm. Silicon nanoparticles have a diameter of 3.0 nm by definition. All the models consume the maximum amounts of carbon, oxygen and silicon allowed for dust and slightly less for magnesium and iron. All the carbon consumed is contained in organic refractory. Approximately equal amounts of silicon are locked up in the silicon nanoparticles (4–5 p.p.m.) and in other components (5–6 p.p.m.). Silicate core–organic refractory mantle grains prevail by mass in all the cases. Note that the dust composition in our models is drastically different from that in previous SMC models, which were based on modification of the standard MRN model (Pei 1992, Rodrigues et al. 1997). The grain size distributions...
in our models are not a simple power law, as assumed in the previous models, but are rather optimized to reproduce the extinction curve and to simultaneously obey the abundance constraints.

Since we do not know presently the wavelength-dependent intensity of the ISRF in the SMC and, in addition, the existing extinction curves for the SMC have a UV boundary at around 0.13 µm, we are unable to estimate the fraction of the UV photons absorbed by the silicon nanoparticles. In the Galaxy, Gordon et al. (1998) found this fraction to be 0.10±0.03. However, as was found by Zubko et al. (1999), the mass fraction of silicon nanoparticles may serve as a good indicator in this case. The values of this quantity derived for the models presented above: 0.07, 0.071, and 0.085 suggest that the SMC is similar to the Galaxy, and therefore should also be a source of significant ERE. Moreover, the proximity of the silicon nanoparticle mass fractions obtained by modeling rather different extinction laws: Galactic and SMC, with different chemical constraints and different dust models suggests that silicon nanoparticles and ERE may be a universal phenomena in galaxies.

It is evident from Fig. 1 and Table 1 that each of the models presented is almost equally good (as indicated by $\mu$) in fulfilling the requirements formulated above, with the G model being slightly more preferable. In order to discriminate between the models, we calculated the model scattering properties, albedo and asymmetry parameter, which are displayed in Fig. 2. We compare our results with the observational data for the Galaxy taken from Gordon et al. (1999), the mass fraction of silicon nanoparticles and ERE may be a universal phenomena in galaxies.

In summary, we report here for the first time more refined models of the SMC bar dust which are in good agreement with the observed extinction, elemental abundances, and the strength of the ISRF. The models were calculated by using the regularization approach. The major grain constituents were found to be silicates, organic refractory and nanosized silicon. This conclusion is subject to some uncertainty due to the uncertain element depletion patterns in the SMC. We predicted the scattering properties of our models, which are significantly different from the Galactic values. More observational constraints, e.g. the polarization data, are to be included into analysis to choose the most appropriate dust model.

I thank Karl Gordon and Geoff Clayton for providing me the extinction curve for A2V 398 in the electronic table. During my work, I benefited from many stimulating discussions with Ari Laor. This research was supported by a grant from the Israel Science Foundation.

REFERENCES

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Fig. 1.— Size distributions of dust grains (left panels) and respective extinction curves (right panels), fitting the extinction curve toward AzV 398. Shown are G, M and GM dust models. The uncertainties of the size distributions were calculated using the method of statistical modeling by Zubko (in preparation).

Fig. 2.— Scattering properties: albedo and asymmetry parameter, corresponding to various dust models fitting the extinction curve toward AzV 398. The diamonds depict the observational data for the Galaxy taken from Gordon et al. (1997) and the circles the albedo of Pei’s (1992) model of the SMC dust.
### Table 1
The main parameters of the models fitting the extinction toward AzV 398.

<table>
<thead>
<tr>
<th>Model</th>
<th>Components</th>
<th>C</th>
<th>Si</th>
<th>O</th>
<th>Mg</th>
<th>Fe</th>
<th>$f_{\text{mass}}$</th>
<th>$M$</th>
<th>$\bar{\mu}$</th>
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<tr>
<td>SMC</td>
<td>gas + dust</td>
<td>46</td>
<td>10</td>
<td>107</td>
<td>9</td>
<td>7</td>
<td></td>
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<tr>
<td></td>
<td>dust</td>
<td>20</td>
<td>10</td>
<td>40</td>
<td>9</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>20</td>
<td>10</td>
<td>40</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
<td>2.62-27</td>
<td>0.211</td>
</tr>
<tr>
<td></td>
<td>Silicate(0.4)-ORR(0.6)</td>
<td>20</td>
<td>5</td>
<td>40</td>
<td>5</td>
<td>5</td>
<td>91.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Si(0.99)-SiO$_2$(0.01)</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Composites (45%-porous)</td>
<td>20</td>
<td>10</td>
<td>40</td>
<td>6</td>
<td>6</td>
<td>100.0</td>
<td>2.81-27</td>
<td>0.269</td>
</tr>
<tr>
<td></td>
<td>Si(0.99)-SiO$_2$(0.01)</td>
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<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GM</td>
<td>Silicate(0.5)-ORR(0.5)</td>
<td>20</td>
<td>10</td>
<td>40</td>
<td>6</td>
<td>6</td>
<td>100.0</td>
<td>2.75-27</td>
<td>0.233</td>
</tr>
<tr>
<td></td>
<td>Composites (45%-porous)</td>
<td>13</td>
<td>5</td>
<td>31</td>
<td>5</td>
<td>5</td>
<td>70.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Si(0.99)-SiO$_2$(0.01)</td>
<td>7</td>
<td>1</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>22.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7.1</td>
<td></td>
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</table>

*First two lines contain the SMC elemental abundances in gas+dust and dust. Next lines present the data for the models reported: elemental abundances in ppm (atoms per $10^6$ H atoms), mass fractions of each dust component ($f_{\text{mass}}$), the total mass of dust matter in g per H atom ($M$) and the values of $\bar{\mu}$, characterizing a quality of a model (see Zubko et al. 1996 for more details). The volume fractions of grain constituents are noted in brackets. The 45%-porous composite grains mostly contain silicate (0.28 in model M and 0.23 in model GM) and organic refractory residue (ORR)(0.24 and 0.23) with less amount of amorphous carbon of various forms (0.09 and 0.03).*