ON THE MODEL OF DUST IN THE SMALL MAGELLANIC CLOUD

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Received 1998 October 28; accepted 1998 December 28; published 1999 February 9

ABSTRACT

We present here dust models for the Small Magellanic Cloud bar calculated for the first time with the regularization approach. A simple mixture of the core-mantle and/or composite grains (mostly made from silicates and organic refractory), together with silicon nanoparticles, is consistent with the following: (1) the observed extinction toward AzV 398 (a typical SMC bar sight line), (2) the elemental abundances, and (3) the strength of the interstellar radiation field. We predict the expected extended red emission. The proposed dust models can also be tested by looking for the expected extended red emission.

Subject headings: dust, extinction — galaxies: individual (Small Magellanic Cloud) — galaxies: ISM — Magellanic Clouds

1. INTRODUCTION

The Small Magellanic Cloud (SMC), one of our nearest neighbors, 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 the presence of a 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. Strong support for 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) modeled 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 with silicate grains, and with other parameters as in the Galaxy, can satisfactorily explain the SMC extinction. Pei (1992) even succeeded in fitting 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 the choice of both grain constituents and grain-size distributions. Recently, Mathis (1996), Li & Greenberg (1997), and Zubko, Krekowsi, & Wegner (1998) have presented more sophisticated models of Galactic dust using core-mantle, multilayer, and composite grains that are much more physically justified than the models considered previously. Note that the models by Zubko et al. (1998) were calculated with the regularization approach (Zubko 1997), which is a very efficient method that is 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, which is a typical ill-posed problem. The regularization approach reduces this problem to the minimization of a strongly convex quadratic functional. The latter problem was strictly proved to have a single solution (for more details, see Groetsch 1984, Tikhonov et al. 1990, or Zubko 1997). This method can be expanded in order 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).

Recently, Gordon & Clayton (1998) have derived the extinction curves for four SMC stars, with several improvements in comparison with previous studies: higher signal-to-noise ratio IUE spectra and a more careful choice of the pairs of reddened and comparison stars. The sight lines toward three stars, AzV 18, 214, and 398, located in the SMC bar pass through the regions of active star formation and exhibit a similar extinction law. The sight line 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 modeled the extinction toward the star AzV 398, which is thought to be a typical SMC bar sight line (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 $E(\lambda) = \frac{\lambda}{\lambda_0}$, where $\lambda_0 = 5500$ Å. The results of the study, which includes all the four stars, will be presented in a forthcoming paper.
$[\tau(\lambda) - \tau(V)]/[\tau(B) - \tau(V)]$, to the extinction cross section per H atom:

$$\frac{\tau(\lambda)}{N_H} = 0.921 \frac{E(B - V)}{N_H} [E(\lambda) + R_v],$$  

(1)

where $\tau$ is the optical thickness, $E(B - V)$ is the $B - V$ color 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 $1.5 \times 10^{22} \text{ cm}^{-2}$ from Bouclèt et al. (1985), which corresponds to atomic hydrogen. Since the sight line 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 sight lines 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 Bouclèt 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 Welty et al. (1997): $C/H = 46$ parts per million (ppm) (atoms per $10^6$ H atoms) or 7.66 ± 0.13 dex, $O/H = 107$ ppm or 8.03 ± 0.10 dex, $Si/H = 10$ ppm or 7.00 ± 0.18 dex, $Mg/H = 9.1$ ppm or 6.96 ± 0.12 dex, and $Fe/H = 6.6$ ppm or 6.82 ± 0.13 dex. Note that these values are 2–5 times less than the respective Galactic abundances following a 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 ppm), 37% of oxygen (~40 ppm), 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 they 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 sight line 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 mantle model of silicon nanoparticles with optical constants of nano-sized silicon from Koshiba et al. (1993). We also included in the 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 that would simultaneously fit the extinction, consume the allowed amounts of chemical elements, and include silicon nanoparticles (analogous to the Galactic case; Zubko et al. 1999). We report in this Letter three simple models that fulfill all the above requirements. The results are presented in Figures 1 and 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 also containing small amounts of amorphous carbon. The total mass fraction of the 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 that are formed in molecular clouds can be processed by the UV radiation into an 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%. This means that the conditions in the SMC (the ISRF intensity and the duration of the exposure by the UV radiation) are probably favorable for converting icy mantles into an organic refractory but not for the further processing of an 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 that are based on the silicate core–organic refractory mantle (composite) grains are referred to as G (M) models. The GM model is a combination of the G and M models and contains both core-mantle and composite grains. As shown in Figure 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 a preference to 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 that is consumed is contained in an organic refractory. Approximately equal amounts of silicon are locked up in the silicon nanoparticles (~5 ppm) and in other components (~5–6 ppm). Silicate core–organic refractory mantle grains prevail by mass in almost all the cases. Note that the dust composition in our models is drastically different from that in previous SMC models, which were based on a 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 instead are optimized to reproduce the extinction curve and to obey the abundance constraints simultaneously.

Since we do not know presently the wavelength-dependent intensity of the ISRF in the SMC and since, 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, Witt, & Friedmann (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 that are derived for the models presented above, 0.07, 0.071, and 0.085, suggest that the SMC is similar to the Galaxy and there-
Therefore should also be a source of significant ERE. Moreover, the proximity of the silicon nanoparticle mass fractions that are 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 Figure 1 and Table 1 that each of the models presented is almost equally good (as indicated by $\tilde{A}$) 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, the albedo, and the asymmetry parameter, which are displayed in Figure 2. We compare our results with the observational data for the Galaxy taken from Gordon et al. (1997) in order to illustrate the significantly different predictions for the SMC. The model albedos are quite close to one another for all wavelengths, whereas the model asymmetry parameter shows large differences, especially in the UV. In general, the model albedos are lower than their respective Galactic ones, except for the near-IR, where we may see an opposite effect. Only the asymmetry parameter of the M model is close to the respective Galactic values. Note that the albedos of Pei’s (1992) model of the SMC dust significantly exceed the albedos calculated in our models, and also the expected Galactic values (Fig. 2). Another possible means for choosing the most appropriate model may be the polarization data. We hope to in-

Fig. 1.—Size distributions of dust grains (left panels) and respective extinction curves (right panels), by fitting the extinction curve toward AžV 398. The G, M, and GM dust models are shown. The uncertainties of the size distributions were calculated using the method of statistical modeling by Zubko (1999).

Fig. 2.—Scattering properties: the albedo and the asymmetry parameter, which correspond to various dust models fitting the extinction curve toward AžV 398. The filled diamonds depict the observational data for the Galaxy taken from Gordon et al. (1997), and the open circles depict the albedo of Pei’s (1992) model of the SMC dust.
TABLE 1

| Model Components | C | Si | O | Mg | Fe | $f_{\text{max}}$ | M | $\mu$ |
|------------------|---|----|---|----|----|----------------|---|------|
| SMC Gas + Dust  | 46| 10 | 107| 9  | 7  |                |   |      |
| Dust .............| 20| 10 | 40 | 9  | 7  |                |   |      |
| G Silicate(0.4)-ORR(0.6) | 20 | 5  | 40 | 5  | 5  | 100.0          | 2.62–27 | 0.211 |
| Si(0.99)-SiO$_2$(0.01) | 0  | 5  | 0  | 0  | 0  | 8.5            |   |      |
| M Composites (45% porous) | 20 | 6  | 40 | 6  | 6  | 93.0           |   |      |
| Si(0.99)-SiO$_2$(0.01) | 0  | 4  | 0  | 0  | 0  | 7.0            |   |      |
| GM Silicate(0.5)-ORR(0.5) | 13 | 5  | 31 | 5  | 5  | 70.4           |   |      |
| Composites (45% porous) | 7  | 1  | 9  | 1  | 1  | 22.5           |   |      |
| Si(0.99)-SiO$_2$(0.01) | 0  | 4  | 0  | 0  | 0  | 7.1            |   |      |

Note.—The first two rows contain the SMC elemental abundances in gas + dust and dust. The following rows present the data for the models reported: elemental abundances in parts per million (atoms per 10$^6$ H atoms), mass fractions of each dust component ($f_{\text{max}}$), the total mass of dust matter in grams per H atom (M), and the values of $\mu$, characterizing a quality of a model (see Zubko, Kreilowski, & Wegner 1996 for more details). The volume fractions of grain constituents are noted in parentheses. The 45% porous composite grains contain mostly silicate (0.28 in model M and 0.23 in model GM) and organic refractory residue (ORR) (0.24 and 0.23), with a less amount of amorphous carbon of various forms (0.09 and 0.03).

clude these data in a self-consistent analysis in forthcoming papers.

In summary, we report here for the first time more refined models of the SMC bar dust that 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 nano-sized silicon. This conclusion is subject to some uncertainty because of 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 in the analysis for choosing the most appropriate dust model.

I thank Karl Gordon and Geoff Clayton for providing me with the extinction curve for AzV 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.

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