Modern models of interstellar dust

V.G. Zubko$^{1,2}$ *

$^1$Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel
$^2$On leave from the Main Astronomical Observatory, NAS, Kiev, Ukraine

The new observational data on interstellar dust, obtained during the past few years, in particular, revised ISM elemental abundances, the polarization curve from the far UV to the near IR, spectra of dust infrared emission, extended red emission (ERE), are in serious conflict with existing dust models. We proposed here to use the regularization approach as a base for developing a modern dust model, which attempts to self-consistently explain most of the available observational data.

1. Why is dust important for astronomy?

Dust plays an important role in various cosmic environments: circumstellar shells, star-forming regions, protoplanetary nebulae, interstellar and intergalactic medium (for a review see Dorschner & Henning [1995]). The dust grains absorb, scatter and re-emit the electromagnetic radiation from various cosmic objects. The dust grains contribute to the thermal equilibrium of interstellar matter. Various chemical and physical processes, e.g. formation of molecules, take place on the surfaces of dust grains. Thus, the knowledge of the properties of cosmic dust is important for: 1) the correct interpretation of the observed spectra of objects seen through intervening dust and the observations of radiation emitted from, or scattered by dust and 2) modeling of objects where dust is a major constituent.

We may mention a few dust models which were most popular until recently. One of them is the so-called MRN model (Mathis, Rumple & Nordsieck [1977]): a mixture of spherical bare graphite and silicate grains, having a power law size distribution $f(a) \sim a^{-3.5}$ over the range of sizes 0.005 – 0.25 $\mu$m. This model was further developed by Draine & Lee (1984), Mathis & Whiffen (1989), Kim, Martin & Hendry (1994), Mathis (1996). Another dust model was proposed by Hong & Greenberg (1978): small bare graphite grains (for explanation of the 217.5 nm hump) and silicate grains covered by the organic refractory mantles produced by UV photolysis of dirty ices which are formed on the grains in molecular clouds. It was assumed that such complicated silicate grains obey some exponential cubic size distribution. This model was further developed by Greenberg (1983), Greenberg & Li (1996), Li & Greenberg (1997). Both above-mentioned models were in rather good agreement with the mean Galactic extinction and polarization laws, provided the cosmic elemental abundances are equal to solar abundances.

2. New observational data on cosmic dust

During the past few years considerable progress has been achieved in obtaining new observational data on interstellar dust. Here are some of the most important findings:

(a) It became clear that the chemical compositions of the general interstellar medium and the Sun are not the same, as was previously assumed: the cosmic elemental abundances appear to be 60–70 per cent of the solar abundances (Snow & Witt 1996).

(b) The analysis of high signal-to-noise spectra of interstellar carbon and oxygen in a few directions obtained with the Goddard High Resolution Spectrograph aboard the Hubble

* e-mail: <zubko@phquasar.technion.ac.il>
Space Telescope, produced the first reliable estimates of the mean gas-phase abundances of interstellar carbon: $10^6 \text{C/H} \approx 140 \pm 20$ and oxygen $10^6 \text{O/H} \approx 310 \pm 20$ (Cardelli et al. 1996).

(c) It was found that the dust albedo in the near-IR, 0.6–0.8, considerably exceeds the albedo predicted by the standard dust models (Witt et al. 1994; Lehtinen & Mattila 1996). Recently, Witt et al. (1997) derived estimates of both albedo and asymmetry parameter of dust in the diffuse medium in the far-UV, which are generally consistent with expectations.

(d) Far-UV polarization observations have been performed (Clayton et al. 1992; Somerville et al. 1994; Clayton et al. 1995), and produced the wavelength-dependent interstellar polarization curves from the far-UV down to the near-IR.

(e) The infrared emission from the diffuse interstellar medium in the range 3.5–1000 $\mu$m has been measured for the first time with COBE/DIRBE and FIRAS (Bernard et al. 1994; Dwek et al. 1997; Sodroski et al. 1997; Lagache et al. 1998).

(f) The so-called extended red emission (ERE) in the 500–800 nm spectral range has been detected in the general interstellar medium (Gordon et al. 1998; Somorou & Gulathakurta 1998). Witt et al. (1998) and Ledoux et al. (1998) independently proposed that silicon nanoparticles might be the source of the ERE.

3. Previous work on modeling of interstellar dust

With the wealth of new data it became clear that practically all dust models, proposed before 1995 (Dorschner & Henning 1995), face a serious crisis in explaining the new observational data. No attempts were undertaken so far to build a dust model which would accommodate most of the data recently acquired. However, some important theoretical steps have been done towards such the model. In particular, Mathis (1996), Zubko et al. (1996, 1998) and Li & Greenberg (1997) proposed more sophisticated dust models on the base of composite, core-mantle and multilayer grains with the main goal to explain the interstellar extinction using the revised elemental abundances. Li & Greenberg (1997) have made an attempt to analyse the interstellar extinction and polarization, taking into account the new chemical abundances. Dwek (1997) has tried to model the extinction and infrared emission together. Note that the approaches used by Mathis (1996), Dwek (1997) and Li & Greenberg (1997) were based on the predefined grain-size distributions: power law or Gaussian and, therefore, cannot be considered as leading to the best solution. Kim et al. (1994) and Kim & Martin (1994, 1995, 1996) have modelled the interstellar extinction and polarization using the Maximum Entropy Method (MEM). However, the authors treated separately the extinction and the polarization rather than self-consistently. In addition, as was noted by Zubko et al. (1996), the MEM cannot produce a unique solution, because some default solution should be specified prior to the calculations. As a rule, the default is not known a priori and this introduces some uncertainty into the final result.

Recently, Zubko (1997) has proposed the regularization approach for modeling of interstellar dust. To the best of our knowledge, it is the only tool which is capable of deriving an optimum and unique grain-size distribution in a general form for any predefined mixture of model grains. In addition, the regularization approach directly takes into account the mathematical nature of the problem, being an ill-posed inverse problem. A few years ago the author started to develop a computer program based on the regularization approach. In its present state, this program is capable of building a model of interstellar dust by a self-consistent analysis of an extinction curve, scattering properties: albedo and asymmetry parameter, elemental abundances and mass fraction constraints. Currently, the program works with spherical grains which may be homogeneous (their
optical properties are calculated with the standard Mie approach), multilayer (author’s original approach) or of composite structure (EMT/Mie approach). The first models of both circumstellar and interstellar dust derived with the program appear to be very promising (Zubko 1997; Zubko et al. 1996, 1998).

4. What should a modern dust model fulfill?

In our view, an ideal model of interstellar dust, which could be constructed in near future, should fulfill the following requirements:

(a) it should be a unified dust model, that is, it should accommodate most existing observational data on extinction, polarization, elemental abundances and so on.

(b) it should use dust particles of more realistic structure: composites, fractal, core-mantle and multilayer grains, both spherical and non-spherical;

(c) it should allow more grain species, and use the optical properties, preferably based on laboratory measurements of cosmic analogue grains;

(d) it should handle the grain-size distributions in the most general form rather than in some prescribed form, e.g. a power law or a Gaussian; this approach should provide an optimum solution.

The best-fit model will be derived using the regularization approach, which in addition to the already mentioned advantages, will allow one to easily include other observational constraints in the future. One of the by-products of this work will be a well-documented program for generating a self-consistent model of interstellar dust, which will be available upon request.

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References

Bernard J.-P., Boulanger F., Desert F.X. et al. 1994, “Dust emission of galactic cirrus from DIRBE observations”, A&A 291, L5
Cardelli J.A., Meyer D.M., Jura M., Savage B.D. 1996, “The abundance of interstellar carbon”, ApJ 467, 334
Clayton G.C., Wolff M.J., Allen R.G., Lupie O. 1995, “Ultraviolet interstellar linear polarization. 2: The wavelength dependence”, ApJ 445, 947
Clayton G.C., Anderson C.M., Magalhães A.M. et al. 1992, “The first spectropolarimetric study of the wavelength dependence of interstellar polarization in the ultraviolet”, ApJ 385, L53
Dorschner J., Henning Th. 1995, “Dust metamorphosis in the Galaxy”, A&AR 6, 271
Draine B.T., Lee H.M. 1984, “Optical properties of interstellar graphite and silicate grains”, ApJ 285, 89
Dwek E. 1997, “Can composite fluffy dust particles solve the interstellar carbon crisis”, ApJ 484, 779
Dwek E., Arendt R.G., Fixsen D.J. et al. 1997, “Detection and characterization of cold interstellar dust and polycyclic aromatic hydrocarbon emission from COBE observations”, ApJ 475, 565
Gordon K.D., Witt A.N., Friedmann B.C. 1998, “Detection of extended red emission in the diffuse interstellar medium”, *ApJ* 498, 522

Greenberg J.M. 1989, in Allamandola L.J., Tielens A.G.G.M., eds, Proc. IAU Symp. 135, “Interstellar Dust”. Dordrecht: Kluwer, p. 345

Greenberg J.M., Li A. 1996, “What are the true astronomical silicates?”, *A&A* 309, 258

Hong S.S., Greenberg J.M. 1978, “On the size distribution of interstellar grains”, *A&A* 70, 695

Kim S.-H., Martin P.G., 1994, “The size distribution of interstellar dust grains as determined from polarization: Infinite cylinders”, *ApJ* 431, 783

Kim S.-H., Martin P.G., 1995, “The size distribution of interstellar dust grains as determined from polarization: Spheroids”, *ApJ* 444, 293

Kim S.-H., Martin P.G., 1996, “On the dust-to-gas ratio and large particles in the interstellar medium”, *ApJ* 462, 296

Kim S.-H., Martin P.G., Hendry P.D. 1994, “The size distribution of interstellar dust grains as determined from extinction”, *ApJ* 422, 164

Lagache G., Abergel A., Boulanger F., Puget J.-L. 1998, “The interstellar cold dust observed by COBE”, *A&A* 333, 709

Ledoux G., Ehbrecht M., Guillois O. et al. 1998, “Silicon as a candidate carrier for ERE”, *A&A* 333, L39

Lehtinen K., Mattila K. 1996, “Near-infrared surface brightness observations of the Thumbprint Nebula and determination of the albedo of interstellar grains”, *A&A* 309, 570

Li A., Greenberg J.M. 1997, “A unified model of interstellar dust”, *A&A* 323, 566

Mathis J.S. 1996, “Dust models with tight abundance constraints”, *ApJ* 472, 643

Mathis J.S., Whiffen G. 1989, “Composite interstellar grains”, *ApJ* 341, 808

Mathis J.S., Rumpl W., Nordsieck K.H. 1977, “The size distribution of interstellar grains”, *ApJ* 217, 425

Snow T.P., Witt A.N. 1996, “Interstellar depletions updated: where all the atoms went”, *ApJ* 468, L65

Sodroski T.J., Odegard N., Weiland J.L. et al. 1997, “A three-dimensional decomposition of the infrared emission from dust in the Milky Way”, *ApJ* 480, 173

Somerville W., Allen R.G., Carnochan D.J. et al. 1994, “Ultraviolet interstellar polarization observed with the Hubble Space Telescope”, *ApJ* 427, L47

Szomoru A., Guhathakurta P. 1998, “Optical Spectroscopy of galactic cirrus clouds: extended red emission in the diffuse interstellar medium”, *ApJ* 494, L93

Witt A.N., Friedmann B.C., Sasseen T.P. 1997, “Radiative transfer analysis of far-ultraviolet background observations obtained with the far ultraviolet space telescope”, *ApJ* 481, 809

Witt A.N., Gordon K.D., Furton D.G. 1998, “Silicon nanoparticles: source of extended red emission?”, *ApJ* 501, L111

Witt A.N., Lindell R.S., Block D.L., Evans R. 1994, “K’-band observations of The Evil Eye galaxy: are the optical and near-infrared dust albedos identical?”, *ApJ* 427, 227

Zubko V.G. 1997, “On the interpretation of the extinction curves of R Coronae Borealis stars”, *MNRAS* 289, 305

Zubko V.G., Krelowski J., Wegner W. 1996, “The size distribution of dust grains in single clouds – I. The analysis of extinction using multicomponent mixtures of bare spherical grains”, *MNRAS* 283, 577

Zubko V.G., Krelowski J., Wegner W. 1998, “The size distribution of dust grains in single clouds – II. The analysis of extinction using inhomogeneous grains”, *MNRAS* 294, 548