Interstellar Dust Grains

Ranjan Gupta[1] and D.B. Vaidya[2]

[1] IUCAA, Post Bag 4, Ganeshkhind, Pune-411007, India
[2] ICCSIR, Navrangpura, Ahmedabad-380009, India

rag@iucaa.ernet.in and deepak.vaidya@iccsir.org

Abstract

Recent studies indicate that the interstellar dust grains are irregular in shape and are inhomogeneous (porous, fluffy and composites) in composition. We propose a composite grain model, which simultaneously fits the observed interstellar extinction, polarization, IR emission and reduces/lowers the abundance constraints. The model consists of a host silicate spheroid and inclusions of graphite. We use the Discrete Dipole Approximation (DDA) to calculate the extinction cross-sections for these composite grains. We compare the average observed extinction curve with the composite grain model extinction curves.

§1 Introduction

It is highly unlikely that the interstellar grains have regular shapes (i.e. spherical, cylindrical or spheroidal) or that they are homogeneous in composition and structure. The collected interplanetary particles are highly porous and consist of loosely aggregated collections of sub-grains (Brownlee, 1987). Mathis and Whiffen (1989), Henning and Stognienko (1993), Wolff et. al., (1994) and Bazell and Dwek (1990) have considered that interstellar grains too have this morphology and composition. Further, the elemental abundances derived from the observed interstellar extinction do not favour the homogeneous composition for the interstellar grains. The optical properties of these composite and porous particles should be quite different from those of solid homogeneous particles. Unfortunately, it is not yet possible to rigorously treat the absorption and scattering of light by composite (inhomogeneous) or irregularly shaped particles. Lynds & Wickramasinghe (1968), and Wickramasinghe & Nandy (1971) have used coated/core-mantle particles as interstellar grain models. In general, there are two approaches to calculate the optical properties of the inhomogeneous (porous) particles. One approach is to use the finite element method e.g. Discrete Dipole Approximation (DDA) (Draine 1988). The second approach is the application of the Effective Medium Theories (EMTs). In EMT the inhomogeneous particle is replaced by a homogeneous one with some averaged 'effective' dielectric function (for discussion on EMT see e.g. Bohren and Huffman 1983). The effects related to the fluctuations of the dielectric function within the inhomogeneous structures such as surface roughness and spatial distributions of the components can not be treated by the averaging approach of the EMTs. The DDA, on the other hand, allows the consideration of irregular shape effects and special distribution of the particles. (Wolff etal 1994, 1998). We use the DDA (see e.g. Vaidya etal, 2001, 2007) to study the extinction properties of the composite grains. We calculate the extinction efficiencies for the composite spheroidal grains, made up of the host silicate spheroid with embedded inclusions of graphite, in the wavelength region 3.4-0.10 μm. Using the extinction efficiencies of the composite grains we evaluate the interstellar extinction curve. We also estimate the cosmic abundances of silicon and carbon for the grain models which reproduce the observed interstellar extinction curve. We note here, that, the composite grain model, with the host silicate and graphite inclusions, has also been used to interpret the observed IR emission from circumstellar dust (Vaidya and Gupta, 2011). It should also be noted here that several dust models have been suggested in the last 40-50 years and there are excellent reviews available (e.g. Lynds & Wickramasinghe, 1968, Savage & Mathis, 1979, Mathis, 1990, Draine, 2003). In section 2 we describe the composite grain model and the DDA method. In section 3 we present the results and discuss the implications. The main conclusions are given in section 4.

§2 Recent Dust Models

Interstellar dust models have evolved with the advance of observational data. The spherical grain model, consisting silicate and graphite particles, with a power law size distribution, called the MRN model (Mathis etal 1977) is the most commonly used model to interpret the observed interstellar extinction. However, the Infrared Astronomical Satellite (IRAS) sky-survey provided the observational evidence for the incompleteness of the MRN model. IRAS observations showed an excess of excess of 12 and 25 μm emission over that expected from dust, heated by the interstellar radiation field and radiating at the equilibrium dust temperature. Thus, IRAS observations showed the importance of the IR emission as a constraint on interstellar dust models. Interstellar polarization, that accompanies the extinction, requires that the grains must be non spherical, also provides an additional constraint on interstellar dust models (see e.g. Li & Greenberg, 1997). Mathis (1996), Dwek (1997) and Zubko et al (2004) have proposed a composite grain models, consisting silicates, carbon and vacuum to overcome the abundance constraints. Vaidya and Gupta (1997, 1999) and Vaidya etal (2001, 2007 & 2011) have also proposed porous and composite grain models, to interpret the observed interstellar extinction, linear polarization and infrared emission from dust.

§2.1 Composite Grain Models

As mentioned earlier, there is no exact theory to study the scattering properties of the composite grains. Hence, we need to use approximations. We use the Discrete Dipole Approximation (DDA) (see e.g. Draine, 1988)

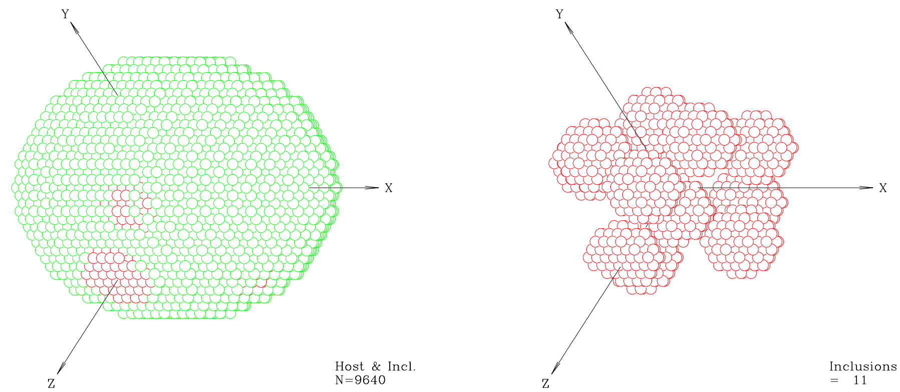

Figure 1. Left is a typical non-spherical composite grain with a total of N=9640 dipoles where the inclusions embedded in the host spheroid are shown such that only the ones placed at the outer periphery are seen. On the right shows the inclusions (Vaidya et al, 2007).

for this purpose. The composite grains consist host silicate spheroids and graphite inclusions. For the description on the composite grain models, and details on the DDA code, see e.g. Vaidya etal (2007). As an illustration, we show a composite grain model with the host spheroid containing number of dipoles, N=9640 and 11 inclusions, see Figure 1.

§3 Extinction Efficiency of Composite Grains

We have studied the extinction for the composite spheroidal grains with three axial ratios (i.e. 1.33, 1.5 & 2.0), corresponding to the grain models with the number of dipoles N=9640, 25896 and 14440 respectively, for three volume fraction of inclusions (10%, 20% and 303.40-0.10 μm. Figure 2 shows the variation in the extinction efficiency, Q_{ext}, with the volume fraction of the inclusions, for the composite grain model with N=9640.

§3.1 Interstellar Extinction Curve

Using the extinction efficiencies and the power law size distributions (Mathis etal, 1977), we evaluate the interstellar extinction curve. Figure 3 shows the model extinction curve with the observed interstellar extinction (Vaidya etal 2007). The model curve deviates from the observed curve in the UV region (beyond $\sim$ 1500Å). This result indicates that a third component of very small particles in the composite grain model may be required (see Weingartner & Draine 2001). Recently, we have analysed several extinction curves observed by the International Ultraviolet Explorer (IUE) satellite and the work is under progress (2011).

§3.2 Linear Polarization

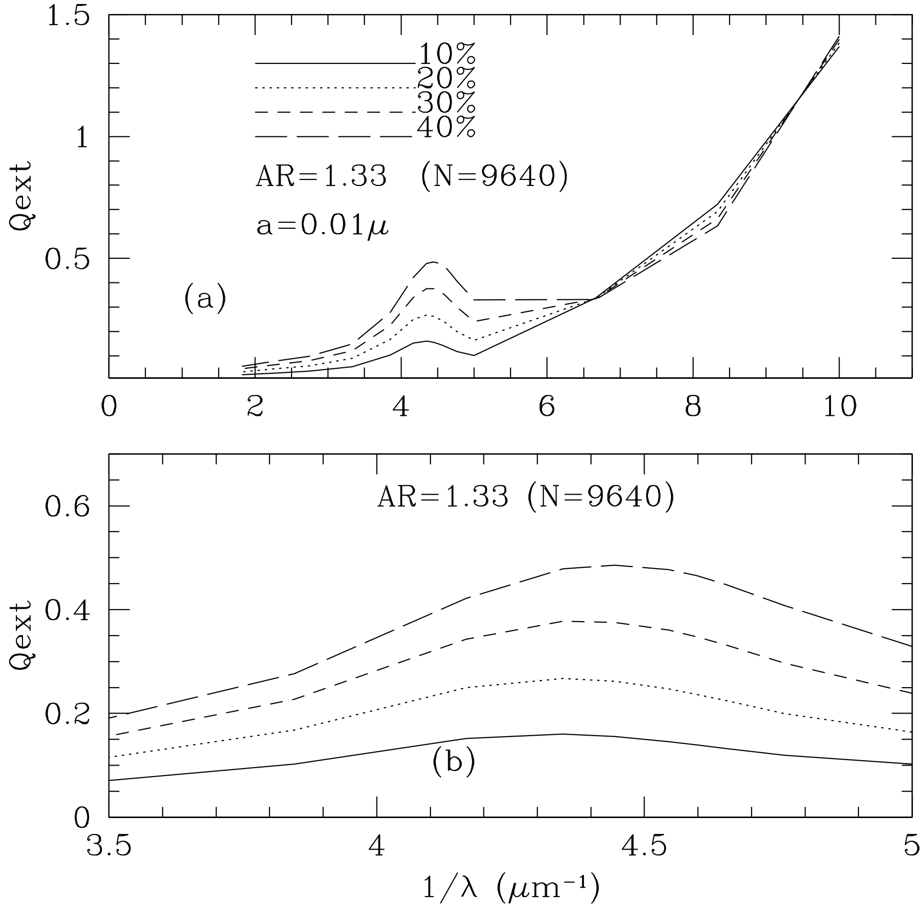

Figure 2. Extinction efficiencies for composite grains of size 0.01 μm with host spheroids containing N=9640 (Axial ratio AR=1.33) in the wavelength region 3.40-0.10 μm are shown in the top panel and bottom panel shows the expanded region of 0.55-0.20 μm (see Vaidya et al, 2007).

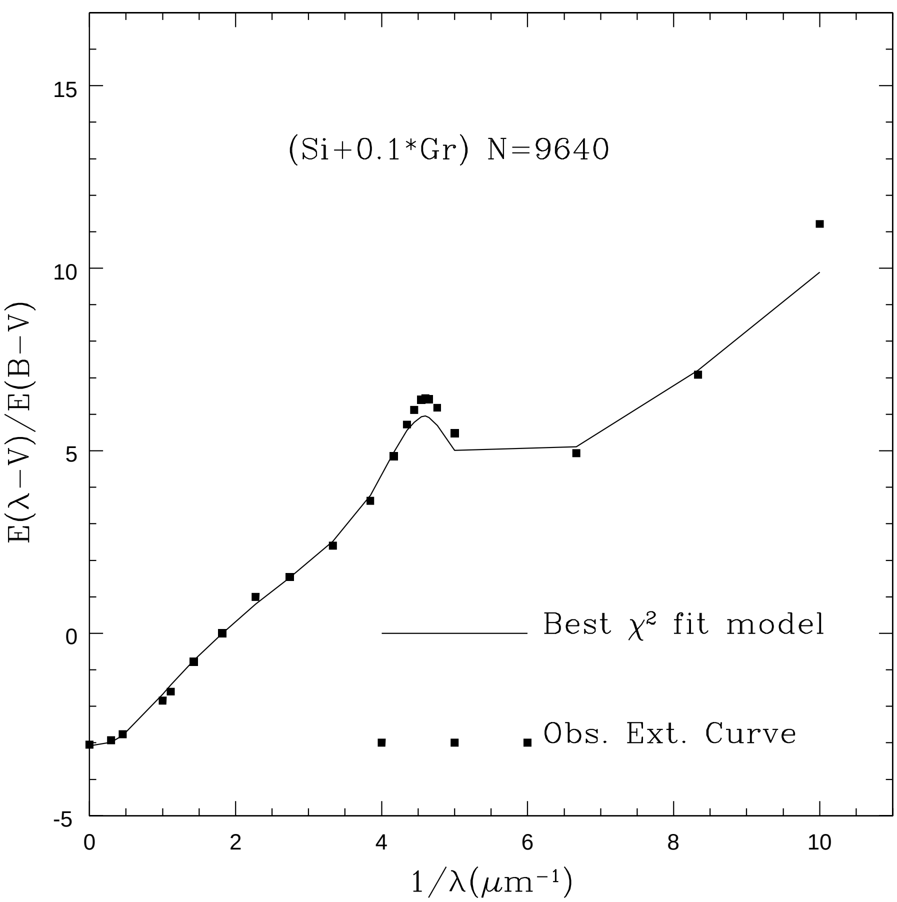

Figure 3. Comparison of the observed interstellar curve with the best-fitting model curve (Vaidya et al, 2007).

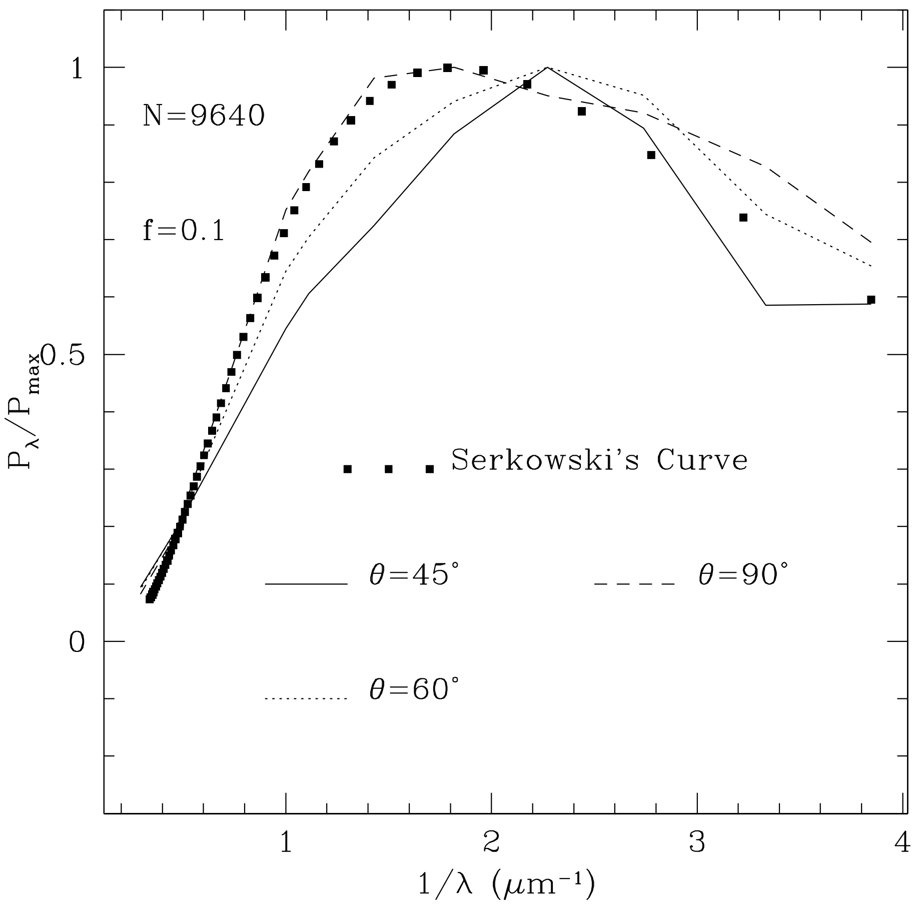

Figure 4. Linear Polarization for composite grains for N=9640 with volume fraction of graphite f=0.1, compared with the Serkowski's law (Vaidya et al, 2007).

In Figure 4, we show the linear polarization efficiency, $|Q_{pol}| = Q_{ext}(E) - Q_{ext}(H)$, for the composite grain model, with N=9640, at three orientation angles. and the comparison with Serkowski curve (Serkowsky etal 1975, Whittet 2003). The results on the composite grains for linear polarization indicate that most of the polarization is produced by the silicate material. Our results are consistent with those obtained by Mathis (1979) and Wolf et al (1993).

§3.3 Infrared Emission

We have calculated the infrared fluxes at various dust temperatures for the composite grains and compared with the IRAS-LRS observed data (Figure 5). The4se results on the composite grains indicate that the dust temperature between 200-300°K fit the observed IRAS-LRS curves and are

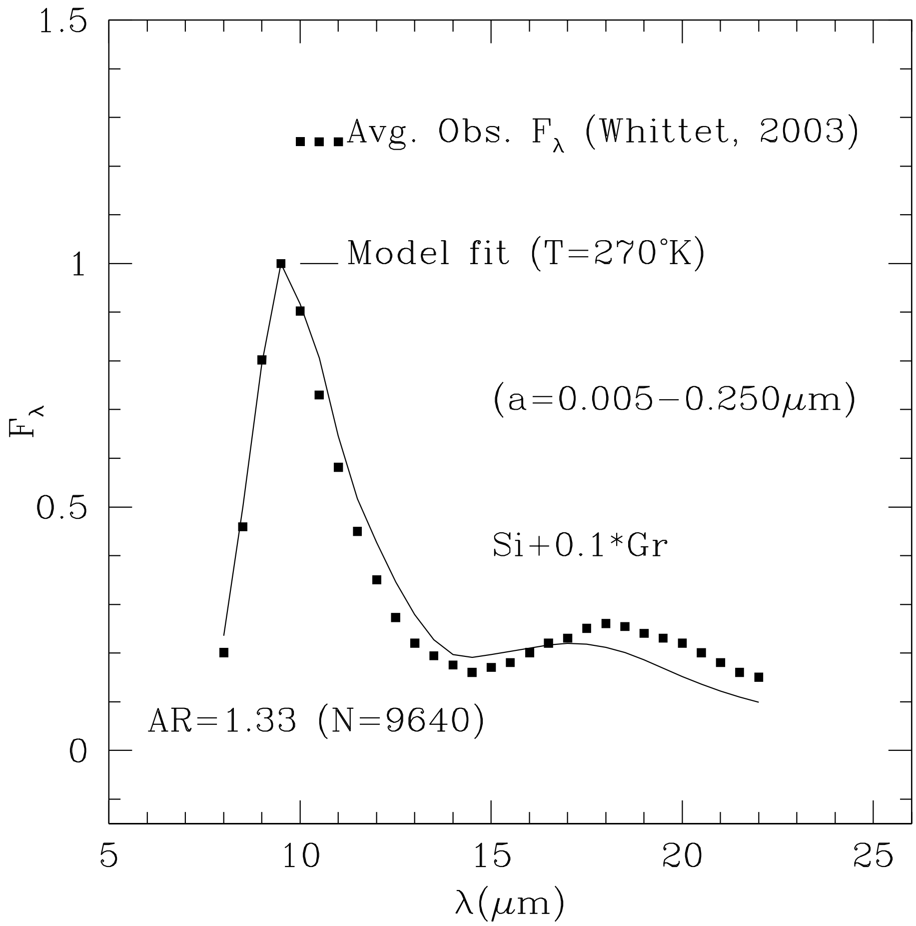

Figure 5. Best fit composite grain model (silicate with graphite inclusions) plotted with the average observed infrared flux for IRAS-LRS curve.

consistent with the dust temperature range between 200-400°K suggested by Voshchinnikov & Henning (2008). The flux ratio of the two features R=Flux(18μ)/Flux(10μ) varies from 0.2 to 0.6 compares well with that derived from the observed IRAS-LRS curves for the circumstellar dust (see Ossenkopf et al. 1992).

§3.4 Cosmic Abundances

We have estimated the cosmic elemental abundances, Si/H and C/H, for those composite grain models which reproduce the observed interstellar curve. We estimate C/H, to be between 160-180 ppm and Si/H between 24-28 ppm. It must be noted that these values are considerably lower than those predicted by the solid/bare grain dust models, but are still higher than the ISM values (Sofia 2001, Voshchinnikov & Henning, 2010).

§5 Further Studies On Grain Models

Composite dust models with other possible interstellar materials, (e.g. amorphous carbons, PAHs)as inclusions, are required to be consistent with all the observed properties in the interstellar dust. Laboratory study on the candidate materials (silicates and carbonaceous materials) is also important (Gustaffson et al, 2001). A synthetic approach combining the laboratory data and theoretical models would help greatly in understanding the properties of interstellar dust better.

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