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On the Absorption and Emission Properties of Interstellar Grains

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Abstract. Our current understanding of the absorption and emission properties of interstellar grains are reviewed. The constraints placed by the Kramers-Kronig relation on the wavelength-dependence and the maximum allowable quantity of the dust absorption are discussed. Comparisons of the opacities (mass absorption coefficients) derived from interstellar dust models with those directly estimated from observations are presented.

1. INTRODUCTION

Interstellar dust reveals its presence in astrophysical environments and its (both positive and negative) role in astrophysics mainly through its interaction with electromagnetic radiation (see Li [38] for a recent review):

- *obscuring* distant stars by the *absorption* and *scattering* of starlight by dust (the combined effects of absorption and scattering are called *extinction*);
- *reddening* starlight because the extinction is stronger for blue light than for red;
- generating “*reflection nebulae*” by the *scattering* of starlight by dust in interstellar clouds near one or more bright stars;
- generating the “*diffuse Galactic light*” seen in all directions in the sky by the diffuse scattering of starlight of stars located near the Galactic plane;
- generating *X-ray halos* by the small-angle dust scattering of X-ray sources;
- *polarizing* starlight as a result of preferential extinction of one linear polarization over another by aligned nonspherical dust;
- *heating* the interstellar gas by ejecting photoelectrons created by the absorption of energetic photons;
- and *radiating* away the absorbed short-wavelength radiation at longer wavelengths from near infrared (IR) to millimeter (mm) in the form of *thermal emission*, with a small fraction at far-red wavelengths as *luminescence*.

In order to correct for the effects of interstellar extinction and deredden the reddened starlight, it is essential to understand the absorption and scattering properties of interstellar grains at short wavelengths (particularly in the optical and ultraviolet [UV]). The knowledge of the optical and UV properties of interstellar dust is also essential for interstellar chemistry modeling since the attenuation of UV photons by dust in molecular clouds protects molecules from being photodissociated. The knowledge of the dust emission properties at longer wavelengths are important (i) for interpreting the IR and submillimeter (submm) observations of emission from dust and tracing the physical conditions of the emitting regions, (ii) for understanding the process of star formation for which the dust is not only a building block but also radiates away the gravitational energy of collapsing clouds (in the form of IR emission) and therefore making star formation possible, and (iii) for understanding the heating and cooling of the interstellar medium (ISM) for which interstellar dust is a dominant heating source by providing photoelectrons (in the diffuse ISM) and an important cooling agent in dense regions by radiating in the IR (see Li & Greenberg [45] for a review).

Ideally, if we know the size, shape, geometry and chemical composition (and therefore the dielectric function) of an interstellar grain, we can calculate its absorption and scattering cross sections as a function of wavelength. If we also know the intensity of the illuminating radiation field, we should be able to calculate the equilibrium temperature or temperature distribution of the grain from its absorption cross section and therefore predict its IR emission spectrum.

However, our current knowledge of the grain size, shape, geometry and chemical composition is very limited; the nature of interstellar dust itself is actually mainly derived from its interaction with radiation (see Li [38] for a review):

- from the interstellar extinction curve which displays an almost linear rise with inverse wavelength (λ^{-1}) from the near-IR to the near-UV and a steep rise into the far-UV one can conclude that interstellar grains must span a wide range of sizes, containing appreciable numbers of *submicron*-sized grains as well as *nanometer*-sized grains;
- from the wavelength dependence of the interstellar polarization which peaks at $\lambda \sim 0.55\,\mu$m, one can conclude that some fraction of the interstellar grains must be nonspherical and aligned by some process, with a characteristic size of $\sim 0.1\,\mu$m;
- from the scattering properties measured for interstellar dust which are characterized by a quite high albedo ($\sim$0.6) in the near-IR and optical and a quite high asymmetry factor (typically $\sim$0.6–0.8 in the optical) one can infer that a considerable fraction of the dust must be dielectric and the predominantly forward-scattering grains are in the submicron size range;
- from the IR emission spectrum of the diffuse ISM which is characterized by a modified black-body of $\lambda^{-1.7}B_\lambda$(T=19.5 K) peaking at $\sim 130\,\mu$m in the wavelength range of $80\,\mu\text{m} \lesssim \lambda \lesssim 1000\,\mu$m, and a substantial amount of emission at $\lambda \lesssim 60\,\mu$m which far exceeds what would be expected from dust at $T \approx 20$ K, one can conclude that in the diffuse ISM, (1) the bulk interstellar dust is in the *submicron* size range and heated to an *equilibrium temperature* around $T \sim 20$ K, responsible for the emission at $\lambda \gtrsim 60\,\mu$m; and (2) there also exists an appreciable amount of *ultrasmall* grains in the size range of a few angstrom to a few nanometers which are *stochastically heated by single UV photons* to high temperatures ($T > 50$ K), responsible for the emission at $\lambda \lesssim 60\,\mu$m (see Li [39]);
- from the spectroscopic absorption features at 9.7, 18 μm and 3.4 μm and emission features at 3.3, 6.2, 7.7, 8.6 and 11.3 μm which are collectively known as the "UIR" (unidentified IR) bands, one can conclude that interstellar dust consists of appreciable amounts of amorphous silicates (of which the Si-O stretching mode and the

O-Si-O bending mode are respectively responsible for the 9.7 and 18 μm features), aliphatic hydrocarbon dust (of which the C-H stretching mode is responsible for the 3.4 μm feature), and aromatic hydrocarbon molecules (of which the C-H and C-C stretching and bending vibrational modes are responsible for the 3.3, 6.2, 7.7, 8.6 and 11.3 μm "UIR" features), although the exact nature of the carriers of the 3.4 μm feature and the "UIR" features remain unknown.

The inferences from observations for interstellar dust summarized above are quite general and model-independent. But these inferences are not sufficient to quantitatively derive the absorption and emission properties of interstellar grains. For a quantitative investigation, one needs to make *prior* specific assumptions concerning the grain size, shape, geometry and chemical composition which are still not well constrained by the currently available observational data. To this end, one needs to adopt a specific grain model in which the physical characteristics of interstellar dust are fully specified. While a wide variety of grains models have been proposed to explain the interstellar extinction, scattering, polarization, IR emission and elemental depletion, so far no single model can satisfy *all* the observational constraints (see Li [39] and Dwek [22] for recent reviews).

In view of this, in this article I will first try to *place constraints on the absorption and emission properties of interstellar dust based on general physical arguments; these constraints are essentially model-independent*.

In astrophysical literature, the most frequently used quantities describing the dust absorption and emission properties are the *mass absorption coefficient* (also known as "*opacity*") $\kappa_{\rm abs}$ with a unit of $\rm cm^2\,g^{-1}$, and the *emissivity* ε_λ, defined as the energy emitted per unit wavelength per unit time per unit solid angle per unit mass, with a unit of $\rm erg\,s^{-1}\,sr^{-1}\,cm^{-1}\,g^{-1}$. The Kirchhoff's law relates ε_λ to $\kappa_{\rm abs}$ through $\varepsilon_\lambda = \kappa_{\rm abs}(\lambda)\,B_\lambda(T)$ if the dust is large enough to attain an equilibrium temperature T when exposed to the radiation field, or $\varepsilon_\lambda = \kappa_{\rm abs}(\lambda)\int_0^\infty dT\,B_\lambda(T)dP/dT$ if the dust is so small that it is subject to single-photon heating and experiences "temperature spikes", where B_λ is the Planck function, dP is the probability for the dust to have a temperature in $[T, T+dT]$. Other often used quantities are the *absorption cross section* $C_{\rm abs}$ and absorption efficiency $Q_{\rm abs}$, with the latter defined as the absorption cross section $C_{\rm abs}$ divided by the geometrical cross sectional area $C_{\rm geo}$ of the grain projected onto a plane perpendicular to the incident electromagnetic radiation beam (Bohren & Huffman [8]). For spherical grains of radii a, $C_{\rm geo} = \pi a^2$ so that $Q_{\rm abs} = C_{\rm abs}/\pi a^2$. By definition, $\kappa_{\rm abs} = C_{\rm abs}/m = C_{\rm abs}/(V\rho)$, where m, V and ρ are respectively the dust mass, volume, and mass density; for spherical grains, $\kappa_{\rm abs} = 3Q_{\rm abs}/(4a\rho)$.

In §2 I will apply the Kramers-Kronig relation to place a lower limit on β (the wavelength dependence exponent index of $\kappa_{\rm abs}$) and an upper limit on the absolute value of $\kappa_{\rm abs}$. The state of our knowledge of interstellar grain opacity will be presented in §3 (with a focus on β) and in §4 (with a focus on the absolute value of $\kappa_{\rm abs}$), followed by a summary in §5.

2. CONSTRAINTS FROM THE KRAMERS-KRONIG RELATION

As already mentioned in §1, with specific assumptions made concerning the grain size, shape, geometry and composition, *in principle* one can calculate the absorption cross section $C_{\rm abs}$ and the opacity $\kappa_{\rm abs}$ as a function of wavelength. But this is limited to spherical grains; even for grains with such simple shapes as spheroids and cylinders, the calculation is complicated and limited to small size parameters defined as $2\pi a/\lambda$. As a result, astronomers often adopt a simplified formula

$$\kappa_{\rm abs}(\lambda) = \begin{cases} \kappa_0 \ , & \lambda < \lambda_0 \ , \\ \kappa_0 \left(\lambda/\lambda_0\right)^{-\beta} \ , & \lambda \geq \lambda_0 \ , \end{cases} \tag{1}$$

where λ_0 and the exponent index β are usually treated as free parameters, while κ_0 is often taken from experimental measurements of cosmic dust analogs or values predicted from interstellar dust models; or

$$\left(Q_{\rm abs}/a\right)(\lambda) = \begin{cases} \left(Q_{\rm abs}/a\right)_0 \ , & \lambda < \lambda_0 \ , \\ \left(Q_{\rm abs}/a\right)_0 \left(\lambda/\lambda_0\right)^{-\beta} \ , & \lambda \geq \lambda_0 \ , \end{cases} \tag{2}$$

where again λ_0 and β are free parameters and $\left(Q_{\rm abs}/a\right)_0$ is usually taken from model calculations.

The Kramers-Kronig dispersion relation, originally deduced by Kronig [33] and Kramers [32] from the classical Lorentz theory of dispersion of light, connects the real (m'; dispersive) and imaginary (m''; absorptive) parts of the index of refraction ($m[\lambda] = m' + i\,m''$) based on the fundamental requirement of *causality*. Purcell [55] found that the Kramers-Kronig relation can be used to relate the extinction cross section integrated over the entire wavelength range to the dust volume V

$$\int_0^\infty C_{\rm ext}(\lambda)\,d\lambda = 3\pi^2 F V \ \ , \tag{3}$$

where $C_{\rm ext}$ is the extinction cross section, and F, a dimensionless factor, is the orientationally-averaged polarizability relative to the polarizability of an equal-volume conducting sphere, depending only upon the grain shape and the static (zero-frequency) dielectric constant ε_0 of the grain material (Purcell [55]; Draine [18]). Since $C_{\rm ext}$ is the sum of the absorption $C_{\rm abs}$ and scattering $C_{\rm abs}$ cross sections both of which are positive numbers at all wavelengths, replacing $C_{\rm ext}$ by $C_{\rm abs}$ in the left-hand-side of Eq.(3) would give a lower limit on its right-hand-side; therefore we can write Eq.(3) as

$$\int_0^\infty \kappa_{\rm abs}(\lambda)\,d\lambda < 3\pi^2 F/\rho \ \ . \tag{4}$$

It is immediately seen in Eq.(4) that β should be larger than 1 for $\lambda \rightarrow \infty$ since F is a finite number and the integration in the left-hand-side of Eq.(4) should be convergent (also see Emerson [23]), although we cannot rule out $\beta \leq 1$ over a finite range of wavelengths.

Astronomers often use the opacity $\kappa_{\rm abs}$ of the formula described in Eq.(1) to fit the far-IR, submm and mm photometric data and then estimate the dust mass of interstellar clouds:

$$m_{\rm dust} = \frac{d^2 F_\lambda}{\kappa_{\rm abs}(\lambda)\,B_\lambda(T)} \ \ , \tag{5}$$

where d is the distance of the cloud, T is the dust temperature, F_λ is the measured flux density at wavelength λ. By fitting the photometric data points, one first derives the best-fit parameters β, λ_0, and T. For a given κ_0, one then estimates $m_{\rm dust}$ from Eq.(5). In this way, various groups of astronomers have reported the detection of appreciable amounts of very cold dust ($T < 10\,{\rm K}$) both in the Milky Way and in external galaxies (Reach et al. [56]; Chini et al. [14]; Krügel et al. [35]; Siebenmorgen, Krügel, & Chini [59]; Boulanger et al. [10]; Popescu et al. [54]; Galliano et al. [24]; Dumke, Krause, & Wielebinski [20]).

As can be seen in Eq.(5), if the dust temperature is very low, one then has to invoke a large amount of dust to account for the measured flux densities. This often leads to too large a dust-to-gas ratio to be consistent with that expected from the metallicity of the region where the very cold dust is detected (e.g. see Dumke et al. [20]), unless the opacity $\kappa_{\rm abs}$ is very large. It has been suggested that such a large $\kappa_{\rm abs}$ can be achieved by fractal or porous dust (Reach et al. [56]; Dumke et al. [20]). Can $\kappa_{\rm abs}$ be really so large for physically realistic grains? At a first glance of Eq.(4), this appears plausible if the dust is sufficiently porous (so that its mass density ρ is sufficiently small). However, one should keep in mind that for a porous grain, the decrease in ρ will be offset by a decrease in F because the effective static dielectric constant ε_0 becomes smaller when the dust becomes porous, leading to a smaller F factor (see Fig. 1 in Purcell [55] and Fig. 15 in Draine [18]).

Similarly, if one would rather use $Q_{\rm abs}/a$ of Eq.(2) instead of $\kappa_{\rm abs}$ of Eq.(1), we can also apply the Kramers-Kronig relation to place (1) a lower limit on β – β cannot be smaller than or equal to 1 at all wavelengths, and (2) an upper limit on $(Q_{\rm abs}/a)_0$ from

$$\int_0^\infty (Q_{\rm abs}/a)\,(\lambda)\,d\lambda < 4\pi^2 F \quad . \tag{6}$$

Finally, the best-fit parameters β, λ_0, and T should be physically reasonable. This can be checked by comparing the best-fit temperature T with the dust equilibrium temperature $T_{\rm d}$ calculated from the energy balance between absorption and emission

$$\int_0^\infty \kappa_{\rm abs}(\lambda)\,cu_\lambda\,d\lambda = \int_0^\infty \kappa_{\rm abs}(\lambda)4\pi B_\lambda(T_{\rm d})\,d\lambda \quad , \tag{7}$$

where c is the speed of light, and u_λ is the energy density of the radiation field. Alternatively, one can check whether the strength of the radiation field required by $T_{\rm d} \approx T$ is in good agreement with the physical conditions of the environment where the dust is located.

3. OPACITY: WAVELENGTH-DEPENDENCE EXPONENT INDEX

It is seen in §2 that the Kramers-Kronig relation requires $\beta > 1$ for $\lambda \to \infty$. For the Milky Way diffuse ISM, the $100\,\mu$m–1 mm dust emission spectrum obtained by the *Diffuse Infrared Background Experiment* (DIRBE) instrument on the *Cosmic Background Explorer* (COBE) satellite is well fitted by the product of a single Planck curve of $T \approx 17.5\,{\rm K}$ and an opacity law characterized by $\beta \approx 2$ (i.e. $\kappa_{\rm abs} \propto \lambda^{-2}$; Boulanger et al. [10]), although other sets of T and β are also able to provide (almost) equally good fits to the observed emission spectrum (e.g. $T \approx 19.5\,\mathrm{K}$ and $\beta \approx 1.7$; see Draine [17]). But we should emphasize here that it is never flatter than $\beta \approx 1.65$ (Draine [17]).

Smaller β in the submm and mm wavelength range has been reported for cold molecular cores (e.g. Walker et al. [63]: $\beta \approx 0.9-1.8$), circumstellar disks around young stars (e.g. Beckwith & Sargent [4]: $\beta \approx -1$–1; Mannings & Emerson [47]: $\beta \approx 0.6$; Koerner, Chandler, & Sargent [28]: $\beta \approx 0.6$), and circumstellar envelopes around evolved stars (e.g. Knapp, Sandell, & Robson [27]: $\beta \approx 0.9$) including the prototypical carbon star IRC + 10126 (Campbell et al. [13]: $\beta \approx 1$).

However, these results are not unique since the dust temperature and density gradients in the clouds, disks or envelopes have not been taken into account in deriving β – the β exponent was usually estimated by fitting the submm and mm spectral energy distribution by a modified black-body $\lambda^{-\beta} B_\lambda(T)$ under the "optically-thin" assumption, with β and T as adjustable parameters. If the dust spatial distribution is not constrained, the very same emission spectrum can be equally well fitted by models with different β values.

As a matter of fact, an asymptotic value of $\beta \approx 2$ (i.e. $\kappa_{\rm abs} \propto \lambda^{-2}$) is expected for both dielectric and conducting *spherical* grains: in the Rayleigh regime (where the wavelength is much larger than the grain size)

$$\kappa_{\rm abs} \approx \frac{18\pi}{\lambda\rho}\frac{\varepsilon_2}{(\varepsilon_1+2)^2+\varepsilon_2^2} \quad , \tag{8}$$

where $\varepsilon(\lambda) = \varepsilon_1 + i\,\varepsilon_2$ is the complex dielectric function of the grain at wavelength λ. For dielectric spheres, $\kappa_{\rm abs} \propto \lambda^{-1}\varepsilon_2 \propto \lambda^{-2}$ as $\lambda \to \infty$ since ε_1 approaches a constant ($\gg \varepsilon_2$) while $\varepsilon_2 \propto \lambda^{-1}$; for metallic spheres with a conductivity of σ, $\kappa_{\rm abs} \propto \lambda^{-1}\varepsilon_2^{-1} \propto \lambda^{-2}$ as $\lambda \to \infty$ since $\varepsilon_2 = 2\lambda\sigma/c \propto \lambda$ and $\varepsilon_1 \ll \varepsilon_2$. Even for *dielectric* grains with such an extreme shape as needle-like prolate spheroids (of semiaxes l along the symmetry axis and a perpendicular to the symmetry axis), in the Rayleigh regime we expect $\kappa_{\rm abs} \propto \lambda^{-2}$:

$$\kappa_{\rm abs} \approx \frac{2\pi}{3\lambda\rho}\frac{\varepsilon_2}{\left[L_\parallel(\varepsilon_1-1)+1\right]^2+\left(L_\parallel\varepsilon_2\right)^2} \tag{9}$$

where $L_\parallel \approx (a/l)^2 \ln(l/a)$ is the depolarization factor parallels to the symmetry axis; since for dielectric needles $\varepsilon_1 \to$ constant and $L_\parallel(\varepsilon_1-1)+1 \gg L_\parallel\varepsilon_2$, therefore $\kappa_{\rm abs} \propto \lambda^{-1}\varepsilon_2 \propto \lambda^{-2}$ (see Li [36] for a detailed discussion). Only for *both* conducting *and* extremely-shaped grains $\kappa_{\rm abs}$ can still be large at very long wavelengths. But even for those grains, the Kramers-Kronig relation places an upper limit on the wavelength range over which large $\kappa_{\rm abs}$ can be attainable (see Li & Dwek [43] for details). The Kramers-Kronig relation has also been applied to interstellar dust models to see if the subsolar interstellar abundance problem can be solved by fluffy dust (Li [40]) and to TiC nanoparticles to relate their UV absorption strength to their quantities in protoplanetary nebulae (Li [37]).

The inverse-square dependence of $\kappa_{\rm abs}$ on wavelength derived above applies to both crystalline and amorphous materials (see Tielens & Allamandola [61] for a detailed discussion). Exceptions to this are amorphous layered materials and very small amorphous grains in both of which the phonons are limited to two dimensions and their phonon spectrum is thus proportional to the frequency. Therefore, for both amorphous layered materials and very small amorphous grains the far-IR opacity is in inverse proportional to wavelength, i.e. $\kappa_{\rm abs} \propto \lambda^{-1}$ (Seki & Yamamoto [58]; Tielens & Allamandola [61]). Indeed, the experimentally measured far-IR absorption spectrum of amorphous carbon shows a $\kappa_{\rm abs} \propto \lambda^{-1}$ dependence at $5\,\mu{\rm m} < \lambda < 340\,\mu{\rm m}$ (Koike, Hasegawa, & Manabe [29]). If there is some degree of cross-linking between the layers in the amorphous layered grains, we would expect $1 < \beta < 2$ (Tielens & Allamandola [61]). This can explain the experimental far-IR absorption spectra of layer-lattice silicates which were found to have $1.25 < \beta < 1.5$ at $50\,\mu{\rm m} < \lambda < 300\,\mu{\rm m}$ (Day [15]). For very small amorphous grains, if the IR absorption due to internal bulk modes (for which the density of states frequency spectrum is proportional to λ^{-2}) is not negligible compared to that due to surface vibrational modes (for which the frequency spectrum is proportional to λ^{-1}), we would also expect $1 < \beta < 2$ (Seki & Yamamoto [57]).

If there exists a distribution of grain sizes, ranging from small grains in the Rayleigh regime for which $\beta \sim 2$ and very large grains in the geometric optics limit for which $\beta \sim 0$, we would expect β to be intermediate between 0 and 2. This can explain the small β values of dense regions such as molecular cloud cores, protostellar nebulae and protoplanetary disks where grain growth occurs (e.g. see Miyake & Nakagawa [50]).

The exponent index β is temperature-dependent, as measured by Agladze et al. [1] for silicates at $T = 1.2$–$30\,{\rm K}$ and $\lambda = 700$–$2900\,\mu{\rm m}$, and by Mennella et al. [49] for silicates and carbon dust at $T = 24$–$295\,{\rm K}$ and $\lambda = 20$–$2000\,\mu{\rm m}$. Agladze et al. [1] found that at $T = 1.2$–$30\,{\rm K}$, β first increases with increasing T, after reaching a maximum at $T \sim 10$–$15\,{\rm K}$ it starts to decrease with increasing T. Agladze et al. [1] attributed this to a two-level population effect (Bösch [9]): because of the temperature-dependence of the two-level density of states (i.e. the variation in temperature results in the population change between the two levels), the exponent index β is also temperature dependent. In contrast, Mennella et al. [49] found that β increases by $\sim$10%–50% from $T = 295\,{\rm K}$ to $24\,{\rm K}$, depending on the grain material (e.g. the variation of β with T for crystalline silicates is not as marked as for amorphous silicates). The increase of β with decreasing T at $T = 24$–$295\,{\rm K}$ is due to the weakening of the long wavelength absorption as T decreases because at lower temperatures fewer vibrational modes are activated. Finally, it is noteworthy that the inverse temperature dependence of β has been reported by Dupac et al. [21] for a variety of regions.

4. OPACITY: ABSOLUTE VALUES

In literature, one of the widely adopted opacities is that of Hildebrand [26]:

$$\kappa_{\rm abs}\,({\rm cm^2\,g^{-1}}) \approx \begin{cases} 2.50\times10^3\,(\lambda/\mu{\rm m})^{-1}, & 50\,\mu{\rm m} < \lambda \le 250\,\mu{\rm m}\ , \\ 6.25\times10^5\,(\lambda/\mu{\rm m})^{-2}, & \lambda > 250\,\mu{\rm m}\ . \end{cases} \tag{10}$$

Hildebrand [26] arrived at the above values from first estimating $\kappa_{\rm abs}(125\mu{\rm m})$ and then assuming $\beta \approx 1$ for $\lambda < 250\,\mu{\rm m}$ and $\beta \approx 2$ for $\lambda > 250\,\mu{\rm m}$. He estimated the $125\,\mu{\rm m}$ opacity from $\kappa_{\rm abs}(125\mu{\rm m}) = 3Q_{\rm abs}(125\mu{\rm m})/(4a\rho) =$

$3/(4a\rho)\,[Q_{\rm abs}(125\mu{\rm m})/Q_{\rm ext}({\rm UV})]\,Q_{\rm ext}({\rm UV})$ by taking $a = 0.1\,\mu$m, $\rho = 3\,{\rm g\,cm^{-3}}$, $Q_{\rm ext}({\rm UV}) = 3$, and $Q_{\rm ext}({\rm UV})/Q_{\rm abs}(125\mu{\rm m}) = 4000$, where $Q_{\rm ext}({\rm UV})$ is the ultraviolet extinction efficiency at $\lambda \sim$0.15–0.30 μm.

The most recent silicate-graphite-PAHs interstellar dust model for the diffuse ISM (Li & Draine [41]) gives

$$\kappa_{\rm abs}\,({\rm cm^2\,g^{-1}}) \approx \begin{cases} 2.92\times10^{5}\,(\lambda/\mu{\rm m})^{-2}, & 20\,\mu{\rm m} < \lambda \le 700\,\mu{\rm m}\ , \\ 3.58\times10^{4}\,(\lambda/\mu{\rm m})^{-1.68}, & 700\,\mu{\rm m} < \lambda \le 10^{4}\,\mu{\rm m}\ , \end{cases} \tag{11}$$

while $\kappa_{\rm abs}(\lambda) \approx 4.6\times10^{5}\,(\lambda/\mu{\rm m})^{-2}\,{\rm cm^2\,g^{-1}}$ for the classical Draine & Lee [19] silicate-graphite model. The fluffy composite dust model of Mathis & Whiffen [48] has $\kappa_{\rm abs}(\lambda) \approx 2.4\times10^{5}\,(\lambda/\mu{\rm m})^{-1.6}\,{\rm cm^2\,g^{-1}}$ in the wavelength range of $100\,\mu{\rm m} < \lambda < 1000\,\mu{\rm m}$. The silicate core-carbonaceous mantle dust model of Li & Greenberg [44] gives $\kappa_{\rm abs}(\lambda) \approx 1.8\times10^{5}\,(\lambda/\mu{\rm m})^{-2}\,{\rm cm^2\,g^{-1}}$ for $30\,\mu{\rm m} < \lambda < 1000\,\mu{\rm m}$. We see that these $\kappa_{\rm abs}$ values differ by over one order-of-magnitude; e.g., the 1350 μm opacity calculated from the composite model [$\kappa_{\rm abs}(1350\mu{\rm m}) \approx 2.35\,{\rm cm^2\,g^{-1}}$; Mathis & Whiffen [48]] is higher than that from the silicate-graphite-PAHs model [$\kappa_{\rm abs}(1350\mu{\rm m}) \approx 0.20\,{\rm cm^2\,g^{-1}}$; Li & Draine [41]] by a factor of $\sim$12.

While the Mathis & Whiffen [48] composite dust model predicts an IR emission spectrum too flat to be consistent with the COBE-FIRAS observational spectrum, and the dust IR emission has not been calculated for the Li & Greenberg [44] core-mantle model which focuses on the near-IR to far-UV extinction and polarization, the silicate-graphite-PAHs model has been shown successful in reproducing the infrared emission spectra observed for the Milky Way (Li & Draine [41]), the Small Magellanic Cloud (Li & Draine [42]), and the ringed Sb galaxy NGC 7331 (Regan et al. [57], Smith et al. [60]). Therefore, at this moment the dust opacity calculated from the silicate-graphite-PAHs model is preferred.

It has recently been suggested that the long wavelength opacity can be estimated from the comparison of the visual or near-IR optical depth with the (optically thin) far-IR, submm and mm dust emission measured for the same region with high angular resolution, assuming that both the short wavelength extinction and the long wavelength emission are caused by the same dust (e.g. see Alton et al. [2,3], Bianchi et al. [5,6], Cambrésy et al. [12], Kramer et al. [30,31])

$$\frac{\tau_V}{S(\lambda)} = \frac{Q_{\rm ext}(V)}{Q_{\rm abs}(\lambda)}\frac{2.2\times10^{-18}}{B_\lambda(T)} \tag{12}$$

where τ_V is the visual optical depth, $S(\lambda)$ is the surface brightness at wavelength λ, and $Q_{\rm ext}(V)$ is the extinction efficiency in the V-band ($\lambda = 5500$ Å). With the dust temperature T determined from a modified black-body $\lambda^{-\beta}B_\lambda(T)$ fit to the far-IR dust emission spectrum (β is not treated as a free parameter but taken to be a chosen number), $Q_{\rm abs}(\lambda)$ can be calculated from the far-IR, submm, or mm surface density $S(\lambda)$, and the measured visual optical depth τ_V [if what is measured is the near-IR color-excess, say $E(H-K)$, instead of τ_V, one can derive τ_V from $\tau_V \approx 14.6E(H-K)$]. In so doing, $Q_{\rm ext}(V)$ is usually taken to be ≈ 1.5.

The long wavelength κ_{abs} values recently determined using this method (Eq.[12]) are generally higher than those predicted from the dust models for the diffuse ISM. Although this can be explained by the fact that we are probably looking at dust in dense regions where the dust has accreted an ice mantle and coagulated into fluffy aggregates for which a higher κ_{abs} is expected (e.g. see Krügel & Siebenmorgen [34], Pollack et al. [52], Ossenkopf & Henning [51], Henning & Stognienko [25], Li & Lunine [46]), the method itself is subject to large uncertainties: (1) the grains responsible for the visual/near-IR extinction may not be the same as those responsible for the far-IR, submm and mm emission; the latter is more sensitive to large grains while the former is dominated by submicron-sized grains; (2) the dust temperature T may have been underestimated if the actual β is larger than chosen; and (3) the fact that in many cases the IRAS (*Infrared Astronomical Satellite*) 60 μm photometry was included in deriving the dust temperature T results in appreciable uncertainties since the 60 μm emission is dominated by stochastically heated ultrasmall grains; ignoring the temperature distributions of those grains would cause serious errors in estimating the dust mass (see Draine [16]) and therefore also in deriving the long wavelength opacity κ_{abs}. These problems could be solved by a detailed radiative transfer treatment of the interaction of the dust with starlight (e.g. Popescu et al. [53], Tuffs et al. [62]) together with a physical interstellar dust model (e.g. the silicate-graphite-PAHs model; see Li & Draine [41,42]).

Based on the laboratory measurements of the far-IR and mm absorption spectra of both amorphous and crystalline silicates as well as disordered carbon dust as a function of temperature, Agladze et al. [1] and Mennella et al. [49] found that not only the wavelength dependence exponent index β but also the absolute values of the absorption are temperature dependent: the far-IR and mm opacity systematically decreases (almost linearly) with decreasing temperature to $T \sim$10–15 K and then increases with decreasing temperature at very low temperature. While the linear dependence of κ_{abs} on T at $T >$ 10–15 K was interpreted by Mennella et al. [49] in terms of two-phonon difference processes, the inverse-temperature dependence of κ_{abs} on T at very low temperature was attributed to a two-level population effect (Agladze et al. [1]). Agladze et al. [1] and Mennella et al. [49] also found that the far-IR and mm opacity of amorphous materials are larger than that of their crystalline counterparts. This is because for amorphous materials, the loss of long-range order of the atomic arrangement leads to a relaxation of the selection rules that govern the excitation of vibrational modes so that all modes are infrared active, while for crystalline solids, only a small number of lattice vibrations are active.

5. SUMMARY

The wavelength-dependent mass absorption coefficient (opacity κ_{abs}) is a critical parameter in the determination of the total dust mass of IR-emitting dusty regions. The dust opacity shows marked variation with local conditions. Due to the incomplete understanding of the size, shape, composition and structure of dust grains, our knowledge of the long wavelength dust opacity is subject to large uncertainties. We apply the Kramers-Kronig relation to place a lower limit on the exponent index β and an upper limit on the absolute value of the opacity (§2), if the dust opacity is described as a power-law function of wavelength ($\kappa_{\rm abs} \sim \lambda^{-\beta}$). Our current knowledge of the wavelength dependence exponent index β (§3) and the absolute values of the opacity (§4) of interstellar dust is summarized in the context of interstellar grain models, laboratory measurements, and direct comparison of the short-wavelength extinction with the long wavelength thermal emission.

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