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ON ANOMALOUS DIELECTRIC FUNCTION OF INTERSTELLAR GRAIN IN FAR INFRARED

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ABSTRACT. We show that the fact that the thermal radiation from small particles follows the Wien law instead of the Planck one should lead to the anomalous wavelength dependence of the far-infrared emission efficiency of interstellar grain substance. We claim that photoconductivity of interstellar grains induced by the ultraviolet radiation from a hot star may account for this dependence.

Key words: dust, extinction.

1. Introduction

Interstellar dust plays important role in evolution of both the entire Universe and separate astrophysical objects (galaxies, nebulae, stars). It is the reason for a great number of papers on investigation of properties of various dust conglomerates to appear (see, for example, (Dwek & Arendt 1992; Siebenmorgen 1993; Williams 1997; Hughes, Dunlop & Rawlings 1997; Mathis 1998; Duley & Poole 1998; Howk & Savage 1998) and references therein).

The information about the spectral dependence of extinction of optically thin dust clouds and their radiation spectra is usually obtained from experiment. It is assumed that by this information one can reconstruct the composition, temperature and mass of dust conglomerates in the following way (Spitzer 1978; Bochkarev 1990). Indeed, the spectral dependence of extinction in the visual and UV range allows one to estimate the sizes of dust grains. The peculiarities of extinction in near IR region give the information about the spectra of absorption of the dust matter (what gives a possibility to identify the dust material). The IR spectrum of radiation informs us about the temperature of dust grains. The total IR luminosity of a dust conglomerate can be used for estimation of its mass.

This seemingly perfect scheme for investigation of interstellar dust must be changed if one takes into account that for the description of radiation of small dust grains one should use instead of the Planck formula (with the Rayleigh-Jeans tail in IR) the Wien one (Altman 1999).

In the present paper we will analyze the known far-infrared spectra of interstellar grains illuminated by a hot star as a rule. The use of the Wien formula will allow us to reveal the anomalous spectral dependence of the interstellar grain dielectric function. In order to explain this dependence we predict the photoconductivity mechanism of light absorption in grains of interstellar dust.

2. Anomalous dielectric function of dust

Specifically, the observed radiation flux at a given wavelength λ from a dust conglomerate takes the form (Pipher, Duthie & Savedoff 1978):

$$F_\lambda = 3D\Omega B_\lambda\left(T_g\right)\tau, \tag{1}$$

where Ω is the beam size, $B_\lambda\left(T_g\right)$ is the Planck function, T_g is the grain temperature and the optical depth of the dust cloud τ (which is considerably less than unity) is proportional to the grain absorption efficiency at the wavelength λ (Bohren & Huffman 1983):

$$Q_{abs}\left(\lambda\right) = 3D\frac{8\pi a}{\lambda}\mathrm{Im}\frac{\epsilon-1}{\epsilon+2}. \tag{2}$$

Here a is the radius of a grain (which is considered spherical) and $\epsilon = 3D\epsilon' + i\epsilon''$ is the complex dielectric function of the grain substance at the wavelength λ. Eq.(2) can be transformed into

$$Q_{abs}\left(\lambda\right) = 3D\frac{24\pi a}{\lambda}\frac{\epsilon''}{\left(\epsilon'+2\right)^2+\left(\epsilon''\right)^2}. \tag{3}$$

Since usually $\epsilon'' \ll \epsilon'$ and within the IR range $\epsilon' \approx$ *const* it is considered that it is possible to reconstruct the spectral dependency of ϵ'' by the observed flux F_λ, taking into account that in the IR the Planck function is given by the Rayleigh-Jeans tail $B_\lambda\left(T_g\right) \propto \lambda^{-4}$.

Therefore

$$Q_{abs}(\lambda) \propto \frac{F_\lambda}{B_\lambda(T_g)} \propto F_\lambda \lambda^4 \equiv \lambda^{-\beta} \qquad (4)$$

In different experiments (Pipher et al. 1978; Thronson & Harper 1979; Rowan-Robinson 1979; Chini et al. 1984; Rengarajan et al. 1985; Hughes et al. 1997; Eyres et al. 1997) the exponent β (which is defined in accordance with Eq.(4)) has been obtained to be ≈ 1 and therefore $\epsilon'' \propto Q_{abs}(\lambda)\lambda \approx const.$

We, however, think that this result can not be correct. Indeed, as it is shown in (Altman 1999) the intensity of thermal radiation from a small grain should contain the Wien function $B^W_\lambda(T_g)$ instead of the Planck one:

$$B^W_\lambda(T_g) = 3DB_\lambda(T_g)\left[1 - \exp\left(-\frac{hc}{\lambda k T_g}\right)\right]. \qquad (5)$$

This function should replace $B_\lambda(T_g)$ in Eq.(1) and Eq.(4). Then, because the IR asymptotic behavior of the Wien function is $B^W_\lambda(T_g) \propto \lambda^{-5}$ the correct spectral dependency of ϵ'' which corresponds to the experimentally observed β should be $\epsilon''(\lambda) \propto \lambda \sim 1/\nu$.

Such a behavior of ϵ'' against frequency ν indicates the conductivity mechanism of light absorption at low frequencies, specifically (Landau & Lifshitz 1982),

$$\epsilon'' = 3D\frac{\sigma_e}{2\pi\epsilon_0\nu}, \qquad (6)$$

where σ_e is the conductivity of the substance and ϵ_0 is the dielectric permittivity of vacuum. The prevailing of the conductivity mechanism of light absorption over the phonon one (the latter would give

$\epsilon''(\lambda) \propto \nu$ (Seki & Yamamoto 1980)) at the grain temperature (~ 50 K) can not be due to the thermal induced conductivity. On our opinion this conductivity mechanism is due to the photoconductivity induced by the external high-energy radiation from the hot nucleus of the duct conglomerate.

3. Photoconductivity of a dust grain

Let us estimate the equilibrium concentration of photoconductivity electrons in a grain. Assume that the grain substance be solid dielectric with the energy gap E_g. We will consider that a photon of the energy above E_g, colliding the grain, creates an electron-hole pair with probability one (Bonch-Bruevich & Kalashnikov 1977). If the central region of the dust conglomerate has the temperature T_s and the radius R_s, and the grain is located at the distance R_g from the center then the generation rate of electron-hole pairs in the grain may be estimated as

$$\frac{dN}{dt} = 3D\int_0^{hc/E_g} \frac{\pi B_\lambda(T_s)}{(hc/\lambda)}\left(\frac{R_s}{R_g}\right)^2 \pi a^2 d\lambda. \qquad (7)$$

Performing integration in Eq.(7) we obtain

$$\frac{dN}{dt} \approx \frac{15\sigma T_s^3}{\pi^4 k_B}\left(\frac{R_s}{R_g}\right)^2 \pi a^2 f(x), \qquad (8)$$

where k_B is the Boltzmann constant, σ is the Stefan-Boltzmann constant, $x = 3DE_g/(k_B T_s)$ and $f(x) \equiv (x^2 + 2x + 2)\exp(-x)$.

Taking into account that the equilibrium electron concentration n_e corresponds to the situation when the generation rate is equal to the rate of electron-hole recombination we can write (see, for example, (Bonch-Bruevich & Kalashnikov 1977))

$$\frac{dN}{dt} = 3D\sigma_c v\frac{4\pi}{3}a^3 n_e^2, \qquad (9)$$

where σ_c is the recombination cross section and v is the electron velocity at the grain temperature. Then we find

$$n_e = 3D\left[\frac{45\sigma T_s^3}{4\pi^4 k_B}\left(\frac{R_s}{R_g}\right)^2 \frac{f(x)}{\sigma_c v a}\right]^{1/2}. \qquad (10)$$

For typical values $T_s = 3D30000$ K, $\mathrm{E}_g = 3D6$ eV, $(R_s/R_g)^2 = 3D10^{-12}$, $a = 3D10^{-8}$ m, $\sigma_c = 3D10^{-22}$ m^2 and $v_e = 3D5\times10^4 \mathrm{m\ s}^{-1}$ we get $n_e \approx 6\times10^{20}\mathrm{m}^{-3}$. The electron conductivity of the grain substance can be calculated by the formula $\sigma_e = 3Den_e\mu_e$, where e is the electron charge and μ_e is the electron mobility. Choosing $\mu_e = 3D0.01\mathrm{m}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$ (which is appropriate for wide energy gap dielectrics) we obtain $\sigma_e \approx 1\Omega^{-1}\mathrm{m}^{-1}$. For $\lambda = 3D150\mu$m this conductivity gives a contribution to ϵ'' of order of 10^{-2} and for longer wavelengths ϵ'' due to photoconductivity overcomes the phonon part (which, for instance, for possible grain substance - MgO (Mathis 1996) is of order 10^{-3} at this wavelength (Jasperse et al. 1966)) and becomes the leading term so that Eq.(6) holds.

Note, that the value of ϵ'' restored from the typical mass-absorption coefficient 0.15 $\mathrm{m}^2\mathrm{kg}^{-1}$ (Hughes et al. 1997) of a grain at wavelength 800μm with the help of Eq.(3) is of order 10^0. Such a big value of ϵ'' can be explained only on the base of the conductivity mechanism of absorption (Bohren & Huffman 1983).

4. Summary

Summarizing we point out that when the IR spectra of interstellar dust grains are under investigation one should use the Wien formula for restoration of dust substance properties. For the known experimental spectra it brought us to the conclusion that the interstellar grain substance is characterized by the anomalous dielectric function. To explain this anomaly we put forward the assertion that the dielectric losses in interstellar dust, in the IR at least, are due to the photoconductivity of dust grains induced by strong ultraviolet radiation from the hot central star. The estimation we made showed the possibility of such a mechanism. We also think that the existence of the hot photoinduced electrons in the dust substance may lead to some peculiarities of dust extinction in visual and UV regions.

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