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ELECTROMAGNETIC SCATTERING BY A POLYDISPERSION OF SMALL CHARGED COSMIC DUST PARTICLES

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(Invited paper)

ABSTRACT. Some recent studies on extended red emissions suggest the presence of very small dust particles in the Universe. The sizes of these particles vary from 1 nm to some tens of nanometers, thus situating them deeply in the Rayleigh region if computations are made for visible or near infrared. The optical response of such particles can be a function of the surface charge. In this study we analyse the effect of surface electric potential on the total optical thickness and scattering phase function of the cosmic dust particles. The results are compared with those obtained for electrically neutral dust.

1. Introduction

Dust particles may coexist in the cosmic space as complex populations differing in size- and shape- distributions, chemical properties and consequently optical behaviors. These particles are responsible for shaping the extinction curves of distant objects, because dust grains absorb, scatter and re-emit electromagnetic radiation. On the one hand, the theoretical analysis of interstellar extinction, polarization, and scattered light, is a powerful tool for obtaining information on the nature of the material and the size distribution of particles in space. On the other hand, the microphysical characteristics of cosmic dust particles (CDPs) are needed for the correct interpretation of the observed spectra. The properties of CDPs show a strong relation to the processes participating in their formation. It is assumed that a large portion of interstellar dust particles can be produced in circumstellar shells of luminous carbon stars [1]. The early studies indicate that CDPs can be much smaller than typical interplanetary dust particles [2]. For instance, a presence of very small (nano-sized) silicate particles with radii about 20 nm has been suggested to envelope AB Aur [3]. The size distribution of cosmic dust particles is traditionally simulated by a power law $f(a) \propto a^{-q}$ (known as MRN model), where a is the effective radius of dust particle, and q is value that parametrize the size distribution $f(a)$. On average, $q \approx 3.5$. Among the sizes, the optical response of a particle strongly depends on the complex refractive index and wavelength λ of the incident radiation. Nevertheless, the small CDPs are scarcely electrically neutral. In accordance with [4], the surface potential on silicate dust particles interacting with the Solar System can reach the value of +45V. Li and Draine [5] analyzed the effect of both neutral and charged silicon nanoparticles on the IR emission

spectra showing that both produce a strong emission feature at 20 μm. However, the optical behavior of electrically charged cosmic dust particles have been studied only recently [6] showing that charged particles may respond to the incident wavelength in a different manner than the corresponding neutral particle. Following this finding, we evaluate here the contribution of small nanoparticles to the theoretical optical thickness and scattering phase function of CDPs in the Rayleigh regime. The potential consequences for inversions of CDP extinction curves are indicated.

2. Expansion coefficients

Spherical particles are well-conditioned model particles that allow the application of the separation of variables method in an exact solution of the Maxwell equations subject to boundary conditions [7]. Applying expansions in terms of vector harmonics, the scattering coefficients can be determined based on the continuity requirement for the tangential electromagnetic field components at the interface between the scatterer and the surrounding medium. In Mie scattering, the expansion coefficients read

$$\begin{aligned} a_n &= \frac{\mu_0^{-1}\psi_n(x)\,\psi_n'(mx) - m\mu_1^{-1}\psi_n'(x)\,\psi_n(mx)}{\mu_0^{-1}\xi_n(x)\,\psi_n'(mx) - m\mu_1^{-1}\xi_n'(x)\,\psi_n(mx)}, \\ b_n &= \frac{\mu_0^{-1}\psi_n'(x)\,\psi_n(mx) - m\mu_1^{-1}\psi_n(x)\,\psi_n'(mx)}{\mu_0^{-1}\xi_n'(x)\,\psi_n(mx) - m\mu_1^{-1}\xi_n(x)\,\psi_n'(mx)}, \\ \psi_n(\varrho) &= \varrho\, j_n(\varrho)\,, \quad \xi_n(\varrho) = \varrho\, h_n^{(1)}(\varrho)\,, \end{aligned} \tag{1}$$

where we have used the denotation consistent with [7]. Note, that the prime denotes differentiation with respect to the argument and subscripts 1 and 0 designate the particle interior and surrounding medium, respectively. If the skin depth of the particle is very small, the surface current has to be taken into account in the boundary conditions, resulting in the modified formulae for the expansion coefficients [6]

$$\begin{aligned} a_n &= \frac{\mu_0^{-1}\psi_n(x)\,\psi_n'(mx) - m\mu_1^{-1}\psi_n'(x)\,\psi_n(mx) - i\omega k^{-1}\sigma_s\psi_n'(x)\,\psi_n'(mx)}{\mu_0^{-1}\xi_n(x)\,\psi_n'(mx) - m\mu_1^{-1}\xi_n'(x)\,\psi_n(mx) - i\omega k^{-1}\sigma_s\xi_n'(x)\,\psi_n'(mx)}, \\ b_n &= \frac{\mu_0^{-1}\psi_n'(x)\,\psi_n(mx) - m\mu_1^{-1}\psi_n(x)\,\psi_n'(mx) + i\omega k^{-1}\sigma_s\psi_n(x)\,\psi_n(mx)}{\mu_0^{-1}\xi_n'(x)\,\psi_n(mx) - m\mu_1^{-1}\xi_n(x)\,\psi_n'(mx) + i\omega k^{-1}\sigma_s\xi_n(x)\,\psi_n(mx)}. \end{aligned} \tag{2}$$

Here we have used the conventional Drude's approach [8] that is known as a classical phenomenological model for the conductivity. Based on Eq. (2) we have computed the bulk optical properties of particles satisfying the MRN model. The comparative computations are made also for neutral CDPs to demonstrate the effects of surface charges.

The MRN distribution is conventionally used in astrophysics of submicron-sized particles. As the size distribution of very small particles will differ from MRN, we will deal also with other types of distributions in a later paper.

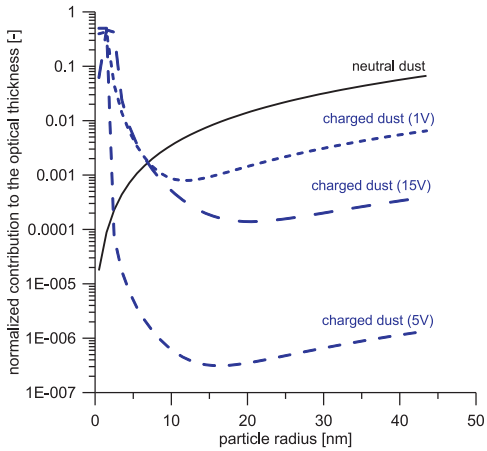

Figure 1. The function $d\tau_{cdp}(a)/da$ given in relative units and computed in accordance with Eq. 3 for λ = 3 μm.

3. Numerical results

A numerical experiment on bulk scattering phase function and optical thickness has been made for silicon nanoparticles with radii randing from 1 nm to 45 nm. Particles of these sizes were also discussed by Zubko et al. [2], who suggested the refractive index to be $m \approx$ 1.6+0.0i at large wavelengths (consult Fig. 1 ibidem). For non-absorbing particles the efficiency factors for extinction Q_{ext} and scattering Q_{sca} coincide, implying the optical thickness of a polydisperse system of CDPs to be

$$\tau_{cdp}(\lambda) = \pi \int_{1nm}^{45nm} a^2 \, F(a) \, Q_{sca}(a, \lambda) \, da \, , \tag{3}$$

where $F(a)$ is the columnar size distribution, i.e. $f(a)$ integrated over the path length from observer toward the observed object. The Rayleigh theory dictates Q_{sca} is proportional to a^4 when $a << \lambda$. To identify the effect of MRN polydispersion easily, we have chosen q =-4. Then $d\tau_{cdp}/da$ should behave like a^2 in the Mie formalism. Nevertheless, the surface charge can change this functional behavior dramatically, when the incident wavelength is in resonance with surface excitations [9]. We evaluate the contribution of the underintegral function in Eq. (3) to the overall value of τ_{cdp} for charged and neutral CDPs assuming a wavelength λ=3μm. The results presented in Fig. (1) are normalized to τ_{cdp}. As the neutral particles grow in size, their contribution to the τ_{cdp} increases as a^2. This indicates that the smallest neutral particles normally cannot influence the measured extinction, even if their concentration increases by one or two orders of magnitude. The charged particles differing in the surface potentials show the minima of $d\tau_{cdp}/da$ between 10 nm and 20 nm (Fig. 1), thus implying a potential impact of surface charge on variability of τ_{cdp}. As a consequence, the same size distributions $f(a)$ may translate to different spectral profiles of τ_{cdp}. Therefore the presence of surface charges on the smallest particles can influence the retrieval accuracy of $f(a)$ if using the Mie formulae for neutral particles. The uncertainty of $f(a)$ strongly depends on size, voltage, and other factors discussed in [6].

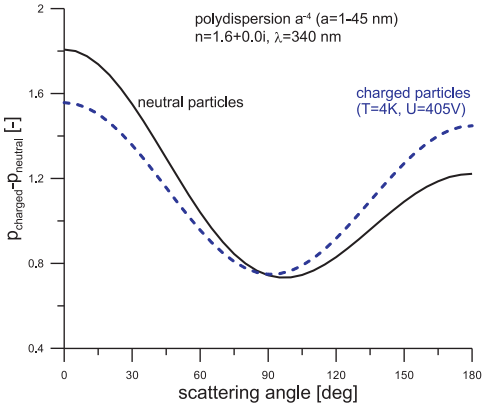

Figure 2. A normalized scattering phase functions of neutral nanosilicate particles and the charged particles under high voltage conditions (405V).

The surface charges on cosmic dust particles may also modify the scattering patterns in Rayleigh regime. If for typical voltages (not exceeding 45V) the difference between scattering patterns of neutral and charged CDPs is below 0.5%, the situation changes significantly under high voltage conditions. The normalized scattering phase functions computed for neutral and charged CDPs with surface potential of 405V are compared in Fig. (2). In both numerical experiments we assumed 4K as a temperature of cold dust.

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