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On applicability of the far-field approximation to the analysis of light scattering by particulate media

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ABSTRACT

Problems of the theory of light scattering by densely packed discrete random media are analyzed with the model, considering such medium as a semi-infinite layer composed of randomly oriented clusters. Each of the clusters is assumed to be in the far zones of all other clusters. Under this approach, the numerical solution of the radiative transfer equation and the equation for weak localization of waves yields the characteristics of radiation reflected by the medium. Since in these equations an elementary volume of the medium is assumed to be represented by randomly oriented clusters, the near-field effects, as well as the irregular shape and heterogeneity of the scatterers, are partially taken into account. The model results are compared to the currently available laboratory measurements of the intensity and the degree of linear polarization of nonabsorbing samples (MgO, Al_2O_3, and SiO_2) composed the scatterers smaller than the wavelength in size. The scattering characteristics of the samples with different (though not very high) packing densities are considered. In the frames of the applied model, some of the calculated phase profiles of polarization well agree with the measured ones. This allowed us to estimate the relative concentration of scatterers in the media and their sizes. At the same time, the measured phase dependences of intensity are poorly fitted with the models. This suggests that some scattering mechanisms remained beyond the frames the considered model; these mechanisms noticeably influence the intensity of radiation reflected by the medium, while their effect on the linear polarization is negligible.

1. Introduction

A theory of multiple scattering by discrete random media is in demand in many fields of science and, specifically, in physics of planets and other celestial bodies and physics of atmospheric aerosols. For the recent years, a significant volume of the ground-based and space-born data of observations of the Solar System bodies in a wide spectral range has been accumulated. To interpret these data, a number of laboratory measurements of the light-scattering characteristics of different samples were performed (e.g., [1–3] and references therein), which allowed of a substantial progress in understanding the nature of the surfaces of celestial bodies. This, in turn, stimulated further observations of the Solar System bodies and, especially, ground-based polarimetric measurements in the optical spectral range (e.g., [4] and references therein). However, in spite of a large amount of observational data, no noticeable progress has been achieved in their interpretation and, especially, in the quantitative estimates.

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One of the causes is that a theory (or a reliable model) of scattering of electromagnetic waves by closely packed discrete random media is lacking. This problem is also urgent for the physics of atmospheres, where the contribution of the surface should be removed from the measured signal so that the aerosol characteristics can be retrieved from the visible and infrared spectral measurements onboard satellites or aircrafts (see, e.g., [5] and references therein). In these spectral ranges, some surface areas of the Earth and other celestial bodies (snow, soil, etc.) are represented by a closely packed discrete medium composed of the scatterers with sizes of around the wavelength of the probing radiation.

The problems facing the theory of multiple scattering by closely packed discrete random media are well known. They are connected with the near-field effects that should be taken into account [6]. To include the near-field interaction into the analysis of the light scattering by discrete media turned out to be extremely complicated. Because of this, one of the tools for studying the scattering processes in closely packed media is to numerically simulate light scattering by large aggregates of particles [7–10]. Unfortunately, such a modeling cannot be applied to quantitative interpretation of the results of laboratory measurements or observations of atmosphereless celestial bodies, since the sizes of aggregates that can be processed by currently available computers are of the same scale or smaller than the path, along which the extinction diminishes the intensity by a factor of *e*. In discrete media the exponential decrease of intensity is determined by the imaginary part of the effective refractive index of the medium (see, e.g., [11,12]). For sparse media this part of the effective refractive index is proportional to the concentration and the mean extinction cross-section of scatterers in the medium (see, e.g., [11–13]). In closely packed media, as distinct from sparse ones, the imaginary part of the effective refractive index nonlinearly depends on the scatterers' concentration; moreover, for nonabsorbing media composed of scatterers comparable to the wavelength in size or smaller, it can be negligible or even go to zero [11,12,14]. In addition, in such media, at the distances of several sizes of the scatterers, the role of mutual shadowing of scatterers may be significant [15]. As a result, the light-scattering characteristics of the medium also depend on its surface relief. However, from the light-scattering modeling with aggregates of particles, the tendencies in the changes of the scattering characteristics of aggregates with increasing the number of constituents can be revealed and, consequently, the behavior of the scattering characteristics of a closely packed medium can be predicted to some extent.

As distinct from closely packed media, for sparse media, the far-zone approximation can be used, which radically simplifies all of the calculations. If the positions of scatterers are random, only the ladder and cyclical diagrams can be taken into consideration from the whole variety of scattering diagrams in the Bethe-Salpeter equation. (Recall that the ladder and cyclical diagrams correspond to the energy transfer and the constructive interference in the backscattering domain, respectively.) Under the Twersky approximation (see, e.g., [13]), it is relatively easy to derive the equations for the sums of ladder and cyclical diagrams [6,13]. The sum of ladder diagrams corresponds to the noncoherent (diffuse) scattering and analytically represents the well-known radiative-transfer equation, while the sum of cyclical diagrams corresponds to the weak localization effect. The latter is described by the equation derived for a plane-parallel medium [6].

The efficiency of the far-zone approximation in the analysis of the light-scattering characteristics of media allows the Monte-Carlo method to be rather simply applied to numerical simulations of light scattering [16,17]. In the frames of such models of light scattering by a random medium, there were attempts to interpret, at least qualitatively, the results of observations of atmosphereless celestial bodies [18,19] and laboratory measurements of the light-scattering characteristics of some particulate samples [20,21].

Though the conditions defining the far-field zone are well known (see, e.g., [13]), they are merely mathematical interrelations and do not make it possible to estimate the critical concentration of scatterers in the media, to which these models can be still applied. To find the quantitative limits of applicability of such models, laboratory measurements of the light-scattering characteristics of media with thoroughly controlled parameters (the medium boundary, concentration, refractive index, scatterers' sizes, etc.) would be useful. However, due to experimental difficulties, a number of such measurements is very low (see, e.g., [22,23] and references therein). At the same time, quite a number of results were reported on the laboratory measurements of one or two Stokes parameters of light reflected by different samples, where only some of the samples' parameters are controlled (e.g., [1,2,24]). These measurements may be compared to the far-zone approximation models of light scattering by a random medium. This would allow the potential of such models, if applied to densely packed media, to be estimated. To perform such an analysis is a purpose of the present paper.

First, we introduce the model of a discrete random medium that is used in calculations of the light-scattering characteristics. Then, we compare the results of calculations to those of laboratory measurements of intensity and linear polarization of light reflected by different nonabsorbing samples composed of MgO, Al_2O_3, and SiO_2 particles [1]. The choice of the materials and sizes of particles in the samples will be explained below. Unfortunately, not all of the samples' parameters required for the accurate modeling were controlled in [1]. At the same time, the data of measurements are reported for two states of the samples – before and after the compression. Consequently, the applicability of the model can be estimated under increasing the concentration of scatterers in the medium. The obtained results are discussed and summarized in the last section

2. The medium model used for light-scattering calculations

To numerically simulate a densely packed medium, we use the model suggested in a paper [20]. In this model the medium is assumed to be an optically thick infinite plane-parallel layer containing randomly oriented clusters of