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# Light scattering by Gaussian particles with internal inclusions and roughened surfaces using ray optics

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A B S T R A C T

We study light scattering by Gaussian-random-sphere particles that are large compared to the wavelength of the incident light using ray optics that, in addition to Fresnellian reflection and refraction, accounts for diffuse scattering. We consider two types of diffusely scattering media. One type of media constitutes a uniform medium inside the particle, i.e. a diffuse internal medium. The second type of media constitutes a layer on the surface of the particle that is thin compared to the particle dimensions and acts as a diffuse external medium mimicking the particle surface roughness. We illustrate the effects of the diffuse media on the scattering characteristics for both cases and show that incorporating diffuse scatterers allows us to explain the scattering matrices measured experimentally for Saharan sand particles large compared to the wavelength.


## 1. Introduction

Natural dust particles exhibit irregular shapes, inhomogeneous internal compositions, and sub-micron-scale surface roughness [1]. No exact electromagnetic methods are available for the computation of light scattering by such particles that are the primary constituents in the regoliths of many atmosphereless solar-system objects and in the desert surfaces on the Earth.

Continuing the scattering studies for small solar-system particles large compared to the wavelength [2], terrestrial aerosol particles [3,4], as well as large Saharan sand particles [5], we combine the ray optics (e.g., [2]) and radiative-transfer treatments (e.g., [6]) to compute light scattering by irregular particles with either an internal or external medium of diffuse scatterers mimicking, e.g., inclusions inside the particle as well as surface roughness. This new approach is motivated by previous results obtained for a Saharan sand sample collected in Libya [5]. In that case, the comparison of the computational results with the measurements indicated that small-scale surface inhomogeneities play a crucial role in scattering by desert dust particles.

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In order to study the asymmetry parameters of large inhomogeneous particles, Mishchenko and Macke [8] developed a ray-tracing method combining Fresnellian (or specular) reflections and refractions with diffuse scattering within the interior of the particles. We establish an independent approach that, in addition to the case of internal scatterers, introduces diffuse media on the particle surfaces and accounts for all polarization effects in the interactions with the particle boundary and the diffuse scatterers. What we call ray optics with diffuse and specular interactions (RODS) is based on the ray-optics methods developed for Gaussian particles [2] and the multiple-scattering methods developed for coherent backscattering by random media of discrete scatterers [6]. The present modeling offers a radiative-transfer alternative for the Lambertian modeling carried out in Nousiainen et al. [4].

Thus, we make use of two types of diffusely scattering media. First, the diffuse scatterers can constitute an internal medium spanning uniformly across the particle interior (DIM, for diffuse internal medium). Second, they can constitute an external medium covering the surface of the particle (DEM, for diffuse external medium). Whereas the former medium is a true three-dimensional medium, the physical thickness of the latter is negligible as compared to the size of the particle, and diffuse scattering occurs within a single infinitesimal location on the surface.

In Section 2, we describe the essence of ray optics for scattering media consisting of both specularly reflecting and refracting surface elements and diffuse scatterers. In Section 3, we summarize the Gaussian-random-sphere geometry. In Section 4, we carry out a preliminary study of the implications of RODS and explain the measured scattering matrices of large Saharan sand particles. We summarize the conclusions and future prospects in Section 5.

## 2. Ray optics

The ray-optics treatment derives from those by [9,2,10]. We describe the particle in terms of its size using its mean-radial-distance size parameter $x = ka$, where $k$ is the wave number and $a$ is the mean radial distance from the origin to the particle surface (see Section 3). In considering vector geometric optics, a vector of Stokes parameters is related to every ray. At every boundary surface, reflection and refraction take place according to Snel's law and Fresnel's reflection and refraction matrices [11]. The radiative-transfer treatment is based on the methods in [6], where an extinction mean free-path length describes the propagation of radiation in a diffusely scattering medium, and scattering can be described by the single-scattering albedo and a scattering matrix. In the forward-diffraction portion, the two-dimensional silhouette is computed numerically for each sample shape, and diffraction is ensemble-averaged using the Kirchhoff approximation. Note the free software Siris available [7] for carrying out ray-tracing computations.

### 2.1. Cross sections and phase matrix

The ensemble-averaged scattering phase matrix $\boldsymbol{P}$ relates the Stokes vectors of the incident and scattered light $\boldsymbol{I}_{\rm i} = (I_{\rm i}, Q_{\rm i}, U_{\rm i}, V_{\rm i})^T$ and $\boldsymbol{I}_{\rm s} = (I_{\rm s}, Q_{\rm s}, U_{\rm s}, V_{\rm s})^T$, respectively,

$$\boldsymbol{I}_{\rm s} = \frac{\sigma_{\rm s}}{4\pi R^2}\boldsymbol{P}\cdot\boldsymbol{I}_{\rm i},$$
$$\int_{4\pi}\frac{d\Omega}{4\pi}P_{11} = 1, \tag{1}$$

where $\sigma_{\rm s}$ is the ensemble-averaged light-scattering cross section for unpolarized incident light, $R$ is the distance from the particle to the observer, and $P_{11}$ is the scattering phase function. For equal numbers of particles and their mirror particles in random orientation, $\boldsymbol{P}$ is block-diagonal with matrix elements $P_{11}$, $P_{12} = P_{21}$, $P_{22}$, $P_{33}$, $P_{34} = -P_{43}$, and $P_{44}$ fully describing the scattering process.

For particles large compared to the wavelength, $\sigma_{\rm s}$ and $\boldsymbol{P}$ can be divided into the forward-diffraction (superscript $D$) and ray-tracing parts ($RT$):

$$\sigma_{\rm s} = \sigma_{\rm s}^D + \sigma_{\rm s}^{RT},$$
$$\boldsymbol{P} = \frac{1}{\sigma_{\rm s}}(\sigma_{\rm s}^D\boldsymbol{P}^D + \sigma_{\rm s}^{RT}\boldsymbol{P}^{RT}),$$
$$\int_{4\pi}\frac{d\Omega}{4\pi}P_{11}^D = \int_{4\pi}\frac{d\Omega}{4\pi}P_{11}^{RT} = 1. \tag{2}$$

The present ray-optics approximation is defined so that, strictly,

$$\sigma_{\rm s}^D = \langle A\rangle,$$
$$\sigma_{\rm e} = \sigma_{\rm a} + \sigma_{\rm s} = 2\langle A\rangle, \tag{3}$$

where $\sigma_{\rm e}$ and $\sigma_{\rm a}$ are the ensemble-averaged extinction and absorption cross sections, and $\langle A\rangle$ is the ensemble-averaged cross-sectional area. The absorption cross section is solely due to ray tracing: $\sigma_{\rm a} = \sigma_{\rm a}^{RT}$. The single-particle albedo due to