The scattering matrix of large Libyan desert particles

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Abstract

We measured the complete scattering matrix as a function of the scattering angle of a Sahara dust sample which was collected from the upper part of a dune in Libya (hereafter Libyan dust sample). This sample mainly consists of large particles since small particles were blown up by the wind. Measurements were done at a wavelength of 632.8 nm in the angle range 4-174 degrees. The Libyan dust sample has $r_{\text{eff}} = 124.75$ μm and $v_{\text{eff}} = 0.15$. Therefore, it is an interesting test case for the Ray Optics Approximation (ROA) that provides accurate results for particles with curvature radii much larger than the wavelength. In addition to the ROA we investigate whether a ray-optics method employing Gaussian random shapes [1] can reproduce the experimental scattering matrix for the Libyan dust sample. Moreover, we use a modified ROA model that takes the small-scale surface roughness and internal inhomogeneities of the particles into account using heuristic ad hoc schemes [2]. Model particle shapes used in the simulations are based on a statistical shape analysis of our sample.

1 Libyan dust particles

Desert dust particles have irregularly round shapes with small-scale surface roughness. Examples of images of particles of our Libyan dust sample taken with a Field Emission Scanning Electron Microscope (FESEM) and an optical microscope are shown in Fig. 1, panels (a) and (b), respectively. A statistical shape model called the Gaussian random sphere geometry [1, 3] was adapted to characterize the shape of the particles in the sample. The shape analysis was performed exactly as in [4] for quasi-spherical ice crystals.

The normalized projected-surface-area distribution, $S(logr)$ was measured using a Fritsch laser particle sizer [5] that employs a diffraction method without making any assumptions about the refractive indices of the particles. The measured $S(logr)$ was transformed into a normalized number distribution as a function of r, $n(r)$. From the retrieved number distribution we obtained the values of the effective radius, r_{eff}=124.75 μm, and effective variance, v_{eff}=0.15 [6]. For modeling purposes we fitted a trimodal lognormal number distribution to the retrieved normalized number distribution, $n(r)$, of our sample as $n(r) = \sum_{i=1}^{3} n_i(r)$, with

$$n_i(r) = \frac{f_i}{\sqrt{2\pi} ln(10) log(\sigma_i) r} exp\left\{-\frac{[log(r) - log(R_i)]^2}{2 log(\sigma_i)^2}\right\}, \tag{1}$$

where f_i is a dimensionless parameter, σ_i the geometric standard deviation, and R_i the geometric mean radius. In Fig. 2 we present the retrieved normalized number distribution together with the best-fit trimodal lognormal number distribution.

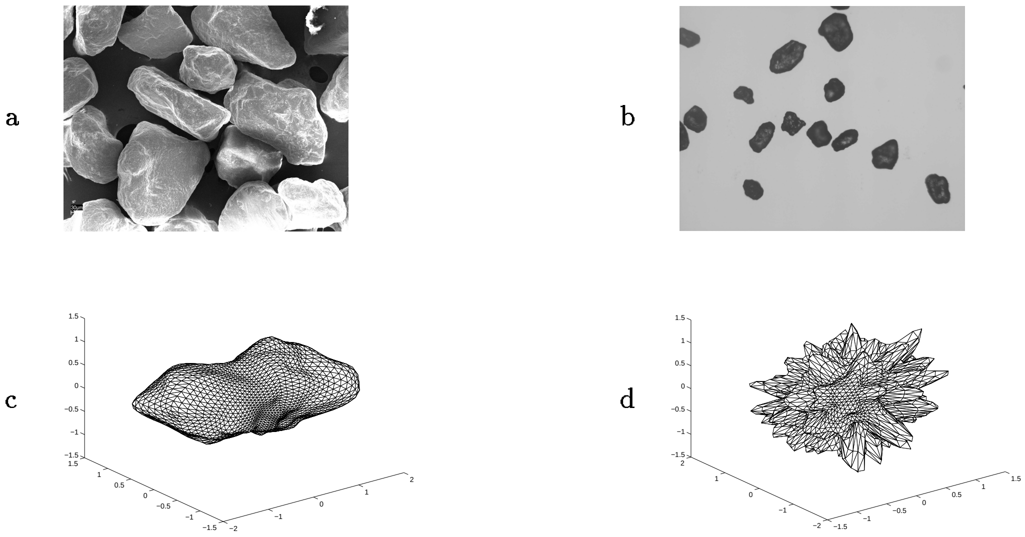

Figure 1: FESEM (a), and optical microscope images (b) of the Libyan dust sample. Panels (c) and (d) present images of a realistic and a unrealistic spiky model particle, respectively.

2 Results and discussion

In Fig. 3 we present the measured scattering matrix elements, $F_{i,j}$, as a function of the scattering angle for the Libyan dust sample at 632.8 nm. The measurements were performed with the Amsterdam light scattering facility [7]. F_{11} is normalized to unity at 30 degrees. The measured scattering matrix follow the general trends presented by irregular mineral particles (see e.g. [8]).

The measured results for the Libyan dust sample were used to investigate whether the Ray Optics Approximation, ROA, can reproduce its scattering matrix as a function of the scattering angle. Firstly, we analyzed our experimental results with the traditional ROA method by varying the real and imaginary parts of the refractive index. As mentioned, model particle shapes were based on a shape analysis of the particles. Fig. 1, panel (c) presents an image of our retrieved model particle. We could not obtain simultaneous good fits for all scattering matrix elements by systematically changing the value of the real and imaginary parts of the refractive index for realistic shapes (dashed gray lines, Fig. 3). Encouraged by the success obtained in previous simulations [8, 2], we tried to improve our fits by enhancing the surface roughness of the particles i.e. the spikiness of our model particles (Fig. 1, panel (d)). The assumption of these unrealistically spiky particles improved the fits especially for $F_{11}(\theta)$ and $F_{22}(\theta)/F_{11}(\theta)$ (solid gray lines, Fig. 3). Apparently, spikiness can actually mimic diffuse surface scattering.

Secondly, we studied the effects of including Lambertian surface elements to simulate diffuse surface scattering and internal Lambertian screens to incorporate the effect of internal inhomogeneity. The ROA simulation with the best-fit Lambertian parameters improved the agreement with the measurements for $F_{11}(\theta)$, $F_{22}(\theta)/F_{11}(\theta)$, and $F_{34}(\theta)/F_{11}(\theta)$ (dashed black lines, Fig. 3). The improvement required, however, the decrease of the value of the imaginary part of the refractive index k to $4{\cdot}10^{-5}$ from the first-guess value $4{\cdot}10^{-4}$. In any case even by including the Lambertian schemes, we could not get reasonably good fits for all elements of the scattering matrix as functions of the scattering angle. Further, we tried to improve the fits to the experimental data by assuming unrealistic spiky particles with the inclusion of Lambertian schemes. The increase of the spikiness (Fig. 1, panel (d)), produces better fits for almost all elements of the scattering matrix (solid black lines, Fig. 3).

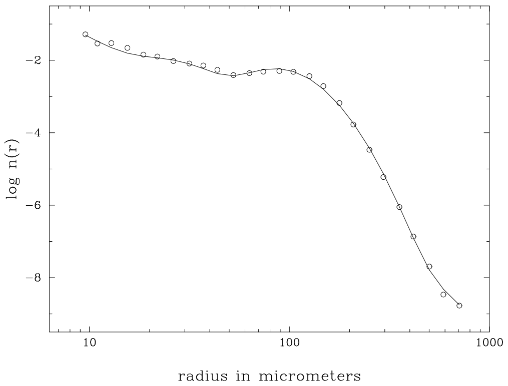

Figure 2: Fitted trimodal log-normal size distribution (solid line) and the normalized number distribution, $n(r)$ (circles), as deduced from the normalized projected-surface-area distribution. The fit resulted in the following parameters: f_1=200.63, f_2=0.24, f_3=0.45; σ_1=4.5, σ_2=1.5, and σ_3=1.4; R_1=9.0 10^{-2}, R_2=28.8, and R_3=96.5 (μm). Number distributions for radii below about 10 micron were found to be below detection limits.

Nousiainen et al. [2] obtained good agreement with the measurements on another Sahara dust sample already included in the *Amsterdam Light Scattering Database,* by assuming realistic shapes when the Lambertian schemes were applied. In that case, the $r_{\rm eff}$ and $v_{\rm eff}$ were equal to 8.2 μm and 4.0, respectively. Due to computational limitations, the size distribution had to be truncated so that particles smaller than 2 μm were not taken into account. Still, there was a relatively high contribution to the scattering by small particles. Apparently, the contribution of those small particles could mimic the scattering effects of the small-scale surface roughness. Another possibility could be that the surface roughness characteristics of the former Sahara dust sample are different from those of the Libyan dust sample. All our results clearly show that the single-scattering properties of the Libyan dust particles cannot be accurately modeled without accounting for the effects of surface roughness. Further, our study shows that to do that properly we need something different from the Lambertian elements. A more detailed account of the measurements and model calculations will be published [9].

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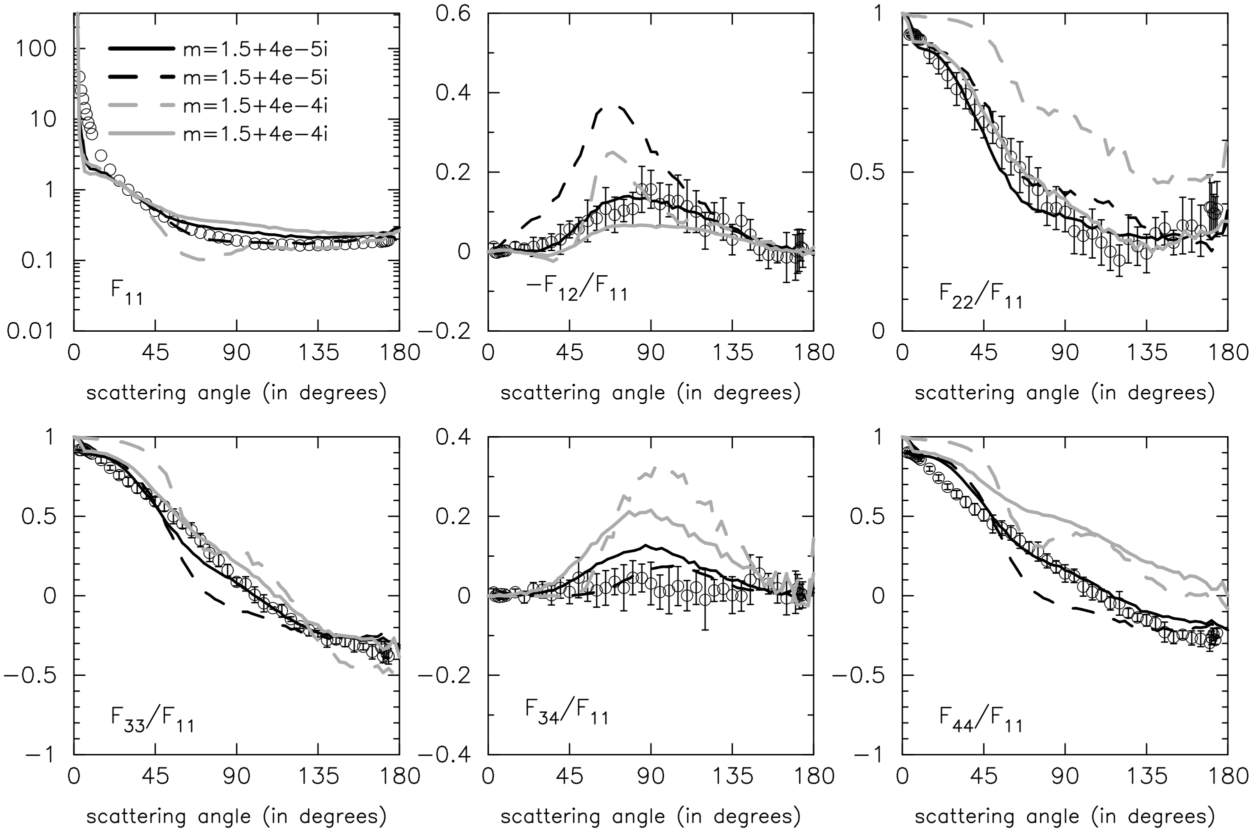

Figure 3: Measured scattering matrix elements as functions of the scattering angle at 632.8 nm for the Libyan sand sample (circles). The measurements are presented together with the best-fit cases. Dashed an solid gray lines correspond to traditional ROA calculations for realistic and unrealistic shapes of the particles, respectively. Dashed and solid black lines correspond to ROA calculations including Lambertian elements for realistic and unrealistic shapes of the particles, respectively.

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