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DEPOLARIZATION AND POLARIZATION OF LIGHT SCATTERING BY DUSTLIKE TROPOSPHERIC AEROSOLS

X. M. Sun, H. H. Wang, J. Shen, and W. Liu

School of Electrical and Electronic Engineering
Shandong University of Technology
Zibo, Shandong 255049, China

Abstract—Measurement of the polarization and depolarization characteristics of light scattering by aerosols is a powerful remote sensing technique for retrieving the microphysics of aerosol particles. In this paper, we model dust-like aerosols using mixtures polydisperse, randomly oriented spheroids with varying aspect ratios from 0.6 μm to 2.0 μm at the wavelength of 0.443 μm and 0.865 μm. The Stokes scattering matrix elements averaged over wide shape distributions of spheroids are compared with those computed for polydisperse randomly oriented single scattering spheroids. The shape-averaged phase function for a mixture of spheroids is smooth, featureless, and nearly flat at side-scattering angles and closely resembles those typically measured for natural sand and dust particles. The linear and circular depolarization ratios were computed using the rigorous T-matrix method. We also show that there is no simple relationships between the depolarization ratio and aspect ratio, and an single spheroidal shape particles cannot be used to model natural dust aerosols.

1. INTRODUCTION

Tropospheric aerosols are thought to cause a significant direct and indirect climate forcing, but the magnitude of this forcing remains highly uncertain because of poor knowledge of global aerosol characteristics and temporal changes [1]. Microphotographs of naturally occurring dust-like aerosols show highly variable shapes and great variability of the particle aspect ratio (ratio of the largest to the smallest particle dimensions), and laboratory and in situ

Corresponding author: X. M. Sun (xmsun@mail.xidian.edu.cn).

measurements for natural sand and dust particles show that in most case, phase function is relatively smooth and featureless, especially at side-scattering angles [2]. However, any particle shape, either spherical or nonspherical, produces its own shape-specific scattering pattern. Two well known examples are provided by halos produced by single or aggregated hexagonal particles and by rainbows produced by spheres [3, 4]. So, it makes questionable the ability of spherical or a single nonspherical shape to represent scattering properties of the natural sand and dust aerosols, but our calculation shows that the phase function of the natural dust particles can be adequately modeled using a wide aspect-ratio distribution of spheroidal gains, although natural dust particles are, of course, not perfect spheroids.

On the other hand, in order to retrieve the aerosol properties, such as optical thickness and effective radius, single scattering albedo, ect., most current and proposed satellite remote sensing of tropospheric aerosols relies upon radiance measurement that are interpreted using algorithms that determine the best fitting to precalculated scattered sunlight for one or more "standard" aerosol models, but this can pose a severe uniqueness problems [5]. Experience and theory have demonstrated that the measurements of polarization as well as the radiance can resolve such a uniqueness problem [5]. Moreover, measurements of the linear and circular depolarization ratios at the backscattering direction are also a powerful remote sensing technique for characterizing the microphysics of nonspherical aerosol particles, and for spherical particles both ratios are equal to zero. On the other hand, for nonspherical scatterers, both the linear and circular depolarization ratios can substantially deviate from zero, thus can be considered the indicators of particle nonsphericity [6, 7].

Based on these two questions, we modeled the dust-like aerosols using shape distributions of polydisperse, randomly oriented spheroids with refractive indices and size distributions representative of naturally occurring dust aerosols, and we evaluated the depolarization and polarization characteristics of light scattering by dust-like aerosols using the T-matrix method. The T-matrix is a powerful exact technique for computing light scattering by nonspherical particles based on numerically solving Maxwell's equations. The approach was initially proposed by Waterman [8], and it has been proved to be highly efficient for computing light scattering by nonspherical particles. This method has been substantially improved and now allows computations for randomly oriented particles with size parameters well exceeding 100 [9]. It is applicable to any particle shape [10]. Mishchenko provided a comprehensive bibliographic database on computational light scattering using the T-matrix method since the inception of the technique in 1965 through 2009 [11–13], and some T-matrix Fortran codes are also publicly available on the World Wide Web at http://www.giss.nasa.gov/staff/mmishchenko/t_matrix.html by Mishchenko [9].

2. THEORY AND DEFINITIONS

The polarization state of a beam of light is traditionally described by a vector $\mathbf{I} = (I, Q, U, V)^T$ composed of four Stokes parameters (T means transpose) [14–23]. The first Stokes parameter, I, is the intensity, while the other three parameters describe the polarization state of the beam. The Stokes parameters are always defined with respect to a reference plane, e.g., with respect to the meridional plane of the beam in a spherical coordinate system. The scattering of light by a particle can be described by a 4×4 scattering matrix. The scattering matrix is a function of the directions of light incidence and scattering and transforms the Stokes parameters I_0, Q_0, U_0, V_0 of the incidence light into those of the scattered light.

$$\mathbf{I}^{sca} = \mathbf{F}\mathbf{I}^{inc} \tag{1}$$

where $\mathbf{I}^{sca}$ and $\mathbf{I}^{inc}$ are the scattered and incident Stokes parameters, respectively.

Electromagnetic scattering most typically produces light with polarization characteristics different from those of the incidence beam. If the incident beam is unpolarized, the scattered light generally has at least one nonzero Stokes parameter other than intensity, and this phenomenon is often called polarization. When the incident beam is fully linearly ($I = Q$, $U = V = 0$) or circularly ($I = V$, $Q = U = 0$) polarized, the scattered light may become partially polarized or even totally unpolarized, and this phenomenon is called depolarization [24, 25].

Consider single scattering by a small-volume element composed of a collection of sparsely distributed, independently scattering particles. If the particles comprising the small-volume element are randomly oriented and have a plane of symmetry, the scattering matrix has the well-known simplified block-diagonal structure [24],

$$\mathbf{F}(\theta) = \begin{bmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{bmatrix}, \tag{2}$$

and it has only six independent elements. So, the Stokes vector of the scattered light is given by

$$\mathbf{I}^{sca} = \begin{bmatrix} F_{11}I^{inc} + F_{12}Q^{inc} \\ F_{12}I^{inc} + F_{22}Q^{inc} \\ F_{33}U^{inc} + F_{34}V^{inc} \\ -F_{34}U^{inc} + F_{44}V^{inc} \end{bmatrix} \tag{3}$$

From (3), even if the incident beam is unpolarized, i.e., $\mathbf{I}^{inc} = (I, 0, 0, 0)^T$ the scattered beam has a nonzero Stokes parameter, unless the (1, 2) element of the scattering matrix is equal to zero.

For backscattering by a small-volume element comprising arbitrary particles in random orientation, the scattering matrix has the simple form [24]

$$\mathbf{F} = \begin{bmatrix} F_{11} & 0 & 0 & F_{14} \\ 0 & F_{22} & 0 & 0 \\ 0 & 0 & -F_{22} & 0 \\ F_{41} & 0 & 0 & F_{44} \end{bmatrix} \tag{4}$$

where $|F_{22}| \leq F_{11}$, $|F_{44}| \leq F_{11}$, and $|F_{41}| = |F_{14}| \leq F_{11}$.

The backscattering matrix is further simplified for a small volume element comprising randomly oriented particles having a plane of symmetry, such as ellipsoid, and/or particles and their mirror particles in equal numbers and in random orientation. In these cases, $F_{14} = F_{41} = 0$. So, in this paper, we have

$$\mathbf{F}(\pi) = \mathrm{diag}\left[F_{11}(\pi), F_{22}(\pi), -F_{22}(\pi), F_{11}(\pi) - 2F_{22}(\pi)\right] \tag{5}$$

In this paper, we discuss the linear and circular backscattering depolarization ratios for the dust-like aerosols. If the incident beam is 100% linearly polarized, parallel to the scattering plane, its Stokes parameters can be written as $\mathbf{I}^{inc} = I^{inc}(1 \quad 1 \quad 0 \quad 0)^T$. The linear depolarization ratio, i.e., the ratio of the flux of the cross-polarized component of the backscattered light relative to that of the copolarized component, can now be written as [24]

$$\delta_L = \frac{I^{sca} - Q^{sca}}{I^{sca} + Q^{sca}} = \frac{F_{11}(\pi) - F_{22}(\pi)}{F_{11}(\pi) + F_{22}(\pi)} \tag{6}$$

Similarly, we can consider a fully circularly polarized incident beam with Stokes parameters $\mathbf{I}^{inc} = I^{inc}(1 \quad 0 \quad 0 \quad 1)^T$ to obtain the circular backscattering depolarization ratio, δ_c, which is the ratio of the same-helicity component of the backscattered flux relative to that of the opposite-helicity component. The result for randomly oriented particles is [24]

$$\delta_C = \frac{I^{sca} + V^{sca}}{I^{sca} - V^{sca}} = \frac{F_{11}(\pi) + F_{44}(\pi)}{F_{11}(\pi) - F_{44}(\pi)} = \frac{F_{11}(\pi) - F_{22}(\pi)}{F_{22}(\pi)} \tag{7}$$

From (6) and (7), we can see that spherically symmetric particles produce zero depolarization since in this case $F_{11}(\pi) = F_{22}(\pi)$. For particles without spherical symmetry, the equality does not generally hold, and such particles can depolarize backscattered light. This explains why the linear and circular depolarization ratios can be direct indicators of particle nonsphericity.

In this paper, we use a shape mixture of randomly oriented polydisperse spheroids to model natural sand and dust particles. In averaging the light scattering characteristics over particle sizes, we must use an aerosol size distribution. We use the standard model of the accumulation mode of dust-like aerosols adopted in the MISR (multi-angle image spectro-radiometer, which is part of the NASA's Earth Observing System) aerosol retrieval algorithm [26].

$$n(r) = \frac{C_1}{r} \exp\left[-\frac{(\ln r - \ln r_g)^2}{2\ln^2 \sigma_g}\right] \tag{8}$$

where r is the radius, and $r_g = 0.4\,\mu\mathrm{m}$, $\sigma_g = 2.51$. The constant C_1 is chosen such that $n(r)$ satisfies the normalization condition

$$\int\limits_{r_{\min}}^{r_{\max}} n(r)dr = 1 \tag{9}$$

with $r_{\min} = 0.05\,\mu\mathrm{m}$ and $r_{\max} = 2\,\mu\mathrm{m}$. It is important to emphasize that in this paper, we characterize the size of a spheroid using the radius of the equal-volume sphere. Thus we compare scattering and absorption properties of spherical and nonspherical particles with the same volume.

3. RESULTS AND DISCUSSION

3.1. The Elements of the Normalized Scattering Matrix

Figures 1 and 2 show the elements of scattering matrix computed at two wavelengths corresponding to channels on the MISR instrument (λ = 443 and 865 nm) [9] for polydisperse sphere, for polydisperse randomly oriented spheroids of a single shape and for equiprobable shape mixtures of spheroids with the aspect ratios ranging from 0.6 to 2.0 in steps of 0.05. In these computations, we have used the size distribution for the standard model of the accumulation mode of dust-like aerosols given by Equation (8), and refractive indices $1.53 + 0.0085i$ at 443 nm and $1.53 + 0.0012i$ at 865 nm. It is seen that the phase function averaged over a wide aspect-ratio distribution of spheroids is smooth, featureless and nearly flat at side-scattering

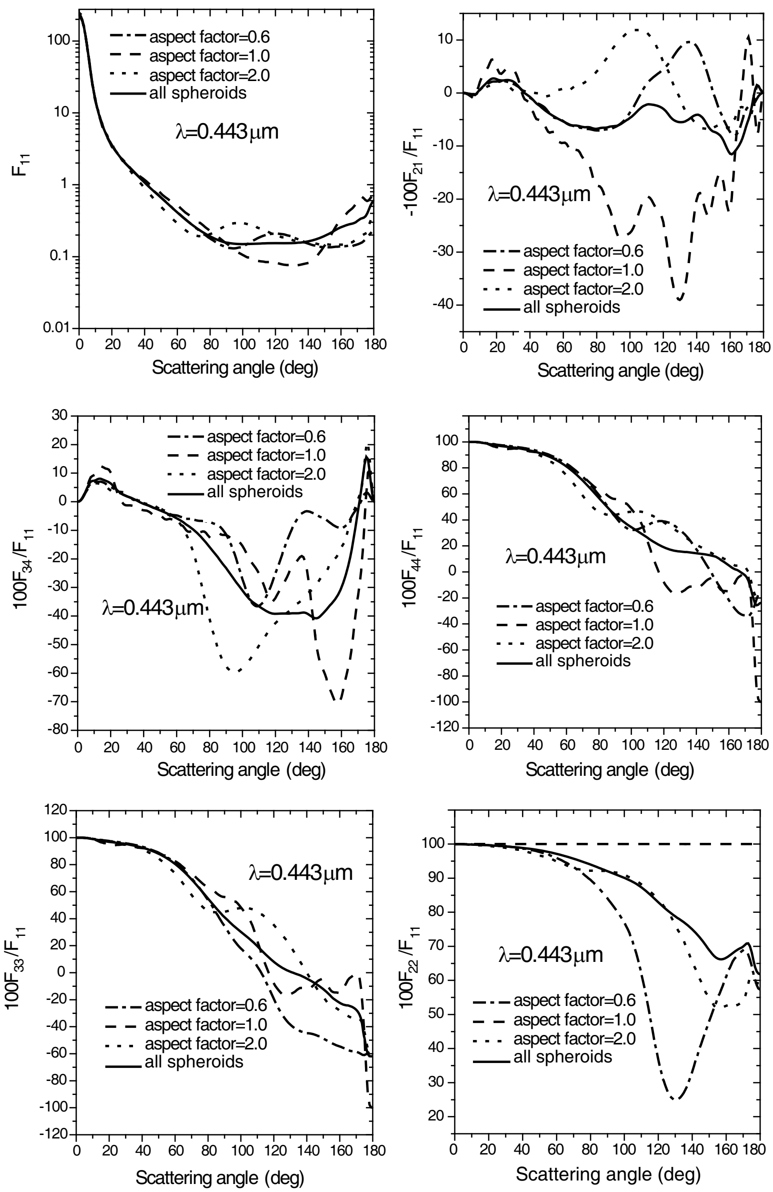

Figure 1. Elements of the normalized Stokes scattering matrix for polydisperse and equiprobable shape mixtures of randomly oriented spheroids at 0.443 μm.

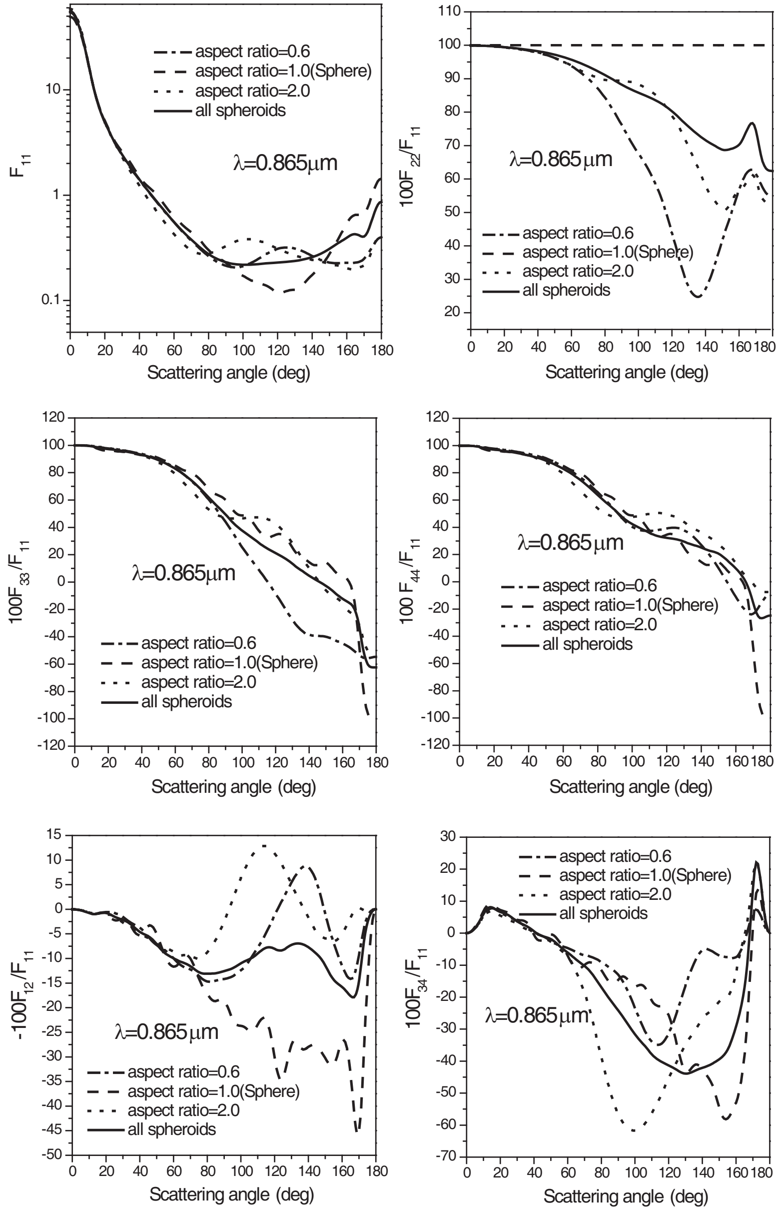

Figure 2. Elements of the normalized Stokes scattering matrix for polydisperse and equiprobable shape mixtures of randomly oriented spheroids at 0.865 μm.

angles. Importantly, it closely resembles those typically measured for natural dust aerosols [2, 27, 28]. We thus conclude that phase function of natural dust-like aerosols can be fairly well modeled by using a wide aspect-ratio distribution of spheroidal particles. The comparison of the elements of scattering matrix with those for volume-equivalent polydisperse spherical particles indicates that the scattering properties of natural dust aerosols may be significantly different from those of equivalent spheres.

3.2. Linear and Circular Depolarization Ratios

Figure 3 shows the results of computations of the linear and circular depolarization ratios for a lognormal size distribution of polydisperse, randomly oridented spheroids with different aspect ratios. From the

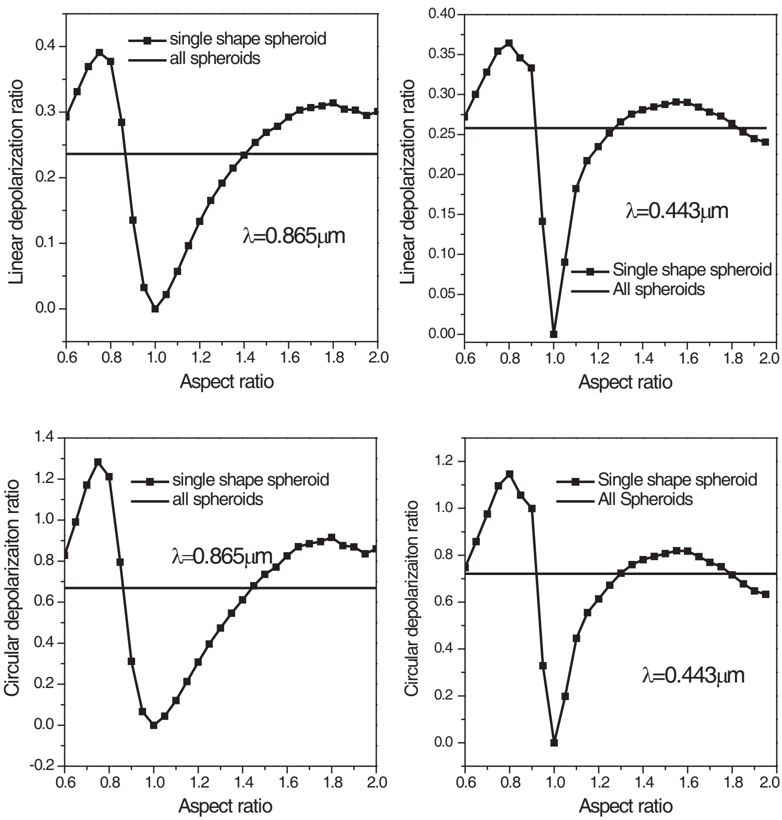

Figure 3. Linear and circular depolarization ratio versus the aspect ratio for polydisperse randomly oriented spheroids.

graph, we can see that the linear and circular depolarization ratios have a rapid increase with the increasing of the aspect ratios from 0.6 to 0.8, and they have a rapid decrease with the increasing of the aspect ratios from 0.8 to 1.0. Furthermore, minimal values for all shapes are observed at the aspect ratio equal to 1.0, i.e., spherical particles, and even spheroids with aspect ratios as small as 1.05 or 0.95 can also produce strong depolarization. This explains why the linear and circular depolarization ratios can be direct indicators of particle nonsphericity. Compared with the single shape spheroids, the depolarization ratios generated by the mixed spheroids lie between the maximum and minimum, and they intersect with the graphes at different aspect ratios. So, single shape spheroids cannot be used to model the natural dust-like aerosols. Otherwise, it will generate large errors or uniqueness solution in satellite remote sensing.

4. CONCLUSIONS

This study was motivated to provide a better model of dust-like aerosols and analyze its polarization and depolarization characteristics. Our computations have shown that phase function averaged over a wide aspect ratios distribution of spheroids is smooth, featureless, and nearly flat at side-scattering angles and closely resembles those typically measured for natural sand and dust particles. Thus, although natural dust aerosols are surely not perfect spheroids, their phase function is always the result of averaging over a multitude of different shapes and apparently can be adequately modeled using a wide aspect ratio distribution of spheroids. Finally, we computed the linear and circular depolarization ratios for polydisperse, randomly oriented spheroids with varying aspect ratios from 0.6 μm to 2.0 μm, and the results were compared with the ensemble-averaged depolarization ratio for spheroids. From the computed results, we can conclude that single shape particles cannot be used to evaluate the depolarization and polarization characteristics of natural dust aerosols.

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