Interpretation of single-particle negative polarization at intermediate scattering angles

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We study how the internal field structure of irregular particles affects the far-field scattering characteristics by modifying the internal fields of the dipole groups that have the greatest contribution. We concentrate on the longitudinal component, i.e., the internal field component parallel to the incident wave vector. We use the discrete-dipole approximation to discretize the internal field and omit the longitudinal component from the dipoles that have the highest energy density above a preset cutoff value. We conclude that only a relatively small number of core dipoles, about 5 % of all dipoles, contribute to the non-Rayleigh-type negative polarization at intermediate scattering angles. These core dipole groups are located at the forward part of the particles. The number of core dipoles in the group becomes greater as particle asphericity increases. We find that the interference between the core dipole groups, which was studied previously for spherical particles, is preserved to a large extent for non-spherical particles. We also find that the longitudinal component has little effect on both the degree of negative polarization and the depolarization ratio near backscattering.

INTRODUCTION

Single scattering from irregular mineral particles produces negative polarization and shows a decrease in positive polarization at intermediate scattering angles [1, 2, 3]. Multiple scattering between different parts of the scattering system can also decrease the positive polarization, but no mechanism has been hypothesized for it to produce negative polarization at these scattering angles. We feel that this feature most likely has a single-scattering mechanism, as we have seen similar polarization characteristics in numerical simulations of large agglomerated debris particles. In this manuscript, we provide evidence that concentrated regions of the longitudinal component of the electric field inside scatterers are responsible for these features.

We consider single dielectric particles that are comparable to the wavelength in size. For spherical particles the incident wave always 'refracts' into the particle and produces an odd parity with respect to the central scattering plane for the longitudinal component [4]. For non-spherical particles, the refraction is distorted by the irregular surface. Refraction also can focus the incident wave on to certain parts of the particle interior. The curved surface acts like a source of internal waves, whose resulting interference can result in concentrated areas, known as hot spots [5]. We define dipoles that are located at these areas as core dipoles, and all other dipoles as non-core dipoles. In this manuscript we show that these hot spots cause a decrease in linear polarization at intermediate scattering angles. This effect is more prominent for symmetric particles, like spheres.

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In our previous studies [6, 7], we have argued that the negative polarization occurring at intermediate scattering angles for wavelength-scale spherical particles arises from constructive interference in the scattering plane between two maxima of the longitudinal component that are separated by distances on the order of half a wavelength. There is always destructive interference between the waves that form these maxima in the case where the incident field is polarized perpendicular to the scattering plane (TE) and, hence, zero contribution from the longitudinal component. However, for the parallel incident field (TM), the contribution generally varies between destructive and constructive interference depending on the scattering angle. Near the $90°$ scattering angle, the partial electromagnetic waves originated from these maxima interfere constructively and, so, their contribution to the scattered field is additionally amplified. We stress that the longitudinal component always produces negative polarization of light scattered at $90°$. This means that non-Rayleigh-type polarization characteristics arising from the longitudinal component must be related to interference inside the scatterer.

In this study, we identify regions inside the scatterers, defined as the core dipoles, that are the primary contributors to linear polarization characteristics at intermediate scattering angles, and study the effect when we omit the longitudinal component for core dipoles, non-core dipoles, and the same number of randomly chosen dipoles. We choose the brightest core dipoles based on a 30 % cutoff value from the total longitudinal energy density of all dipoles. Based on our studies, this seems to represent the most contributing dipoles. We also study the effect of interference between the waves scattered internally from the core dipoles by computing the total electric field in the YZ-plane from all dipoles along the X-axis. We also compute the total electric field from all dipoles in the XZ- and XY-planes to reveal phase differences between the maxima. We do this for both X- and Y-polarized incident fields. It should be noted that this procedure is purely a mathematical tool and not something that could be observed or measured.

MODELING

For the Gaussian-random-sphere particles, we use circumscribing-sphere size parameter $x_{cs} = 12.0$, refractive indices $m = 1.5 + \mathrm{i}0.01$, and $m = 1.5 + \mathrm{i}0.1$, the standard deviation of relative radius $\rho = 0.245$, and the power-law index of the covariance function $\nu = 4$. For the agglomerated debris particles, we use the same size and refractive indices as for the Gaussian-random-sphere particles. For all the studied particles we use ensemble averaging for the shapes using 20 different realizations of shape for each case. For the computations we use the DDA code developed by Zubko [8]. In the DDA computations we use a $64 \times 64 \times 64$ -dipole grid for the sample shapes.

RESULTS

In Fig. 1, we present the results from numerical computations using DDA averaged over 20 samples. We show the degree of polarization $P = (I_\perp - I_\parallel)/(I_\perp + I_\parallel)$ using a 30 % cutoff value for the Gaussian and debris particles. For the Gaussian particles, the effect of omitting the core dipoles is comparable to omitting the non-core dipoles in magnitude. Here we also see deviations from the exact solution at intermediate scattering angles when omitting random dipoles. Notice also that omitting the core dipoles has little effect on the negative polarization at forward scattering and backscattering directions. For the debris particles, omitting non-core dipoles has a stronger effect than omitting the core dipoles. We also studied more highly absorbing particles (not shown here), and found that increasing absorption weakens the effect of omitting for both Gaussian and debris particles. This indicates that the contribution from the longitudinal component to linear polarization at intermediate scattering angles is weakest for absorbing, highly irregular particles. We also used 10, 50, 70, and 90 % cutoff values in our studies, and found similar effects than for the 30 % cutoff case shown here.

In Fig. 2, we show the contributions of the internal longitudinal components on the far-field scattering intensities at 90°. For all particles, when the incident field is polarized parallel to the scattering plane (panels at the top), there is a very bright amplified area at the forward part of the particle. The area is symmetric for the sphere, becomes distorted for the Gaussian-random-sphere particle, and even divides into several areas for the debris particle. When the incident field is polarized perpendicular to the scattering plane (panels at the bottom), there is only weak amplification for all particles. In the X-polarized incident field case for the sphere (top panel on the left), the whole bright area is in phase, which can be seen as enhancement in the curve above the panel. For the Y-polarized case (bottom panel on the left), the two weak maxima have opposite phase, which can be seen as cancellation in the curve above the panel. For the X-polarized incident field case for the Gaussian particle (top panel in the middle), the bright areas are generally in phase, while for the Y-polarized case (bottom panel in the middle), there is significant cancellation. In the X-polarized case for the debris particle (top panel on the right), there are actually two bright areas, which also can be seen in the curve above the panel. However, these bright areas have opposite phases, which is seen as partial cancellation in the curve to the right from the panel. This also produces cancellation for the X-polarized incident wave. For the Y-polarized case (bottom panel on the right), the contribution of the three maxima near the front part of the particle almost completely cancel due to destructive interference. This can be seen in the curve above this panel. Overall, it is evident that the greatest contribution to negative polarization comes from the incident field polarized parallel to the scattering plane. The contribution appears to be weakened for the perpendicular incident field.

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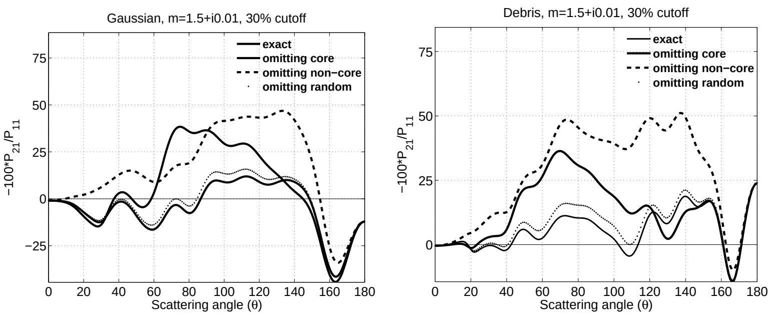

Figure 1. The degree of linear polarization for the Gaussian-random-sphere and debris particles with the exact solution (thin line), and when omitting the longitudinal component from core dipoles (thick line), non-core dipoles (dashed line), and random dipoles (dotted line). The longitudinal energy density cutoff value is 30%. The size parameter is $x_{cs} = 12$, the refractive index is $m = 1.5 + \mathrm{i}0.01$, and the standard deviation of radius for the Gaussian-random-sphere particle is $\rho = 0.245$. Notice that the results are only averaged over 20 samples.

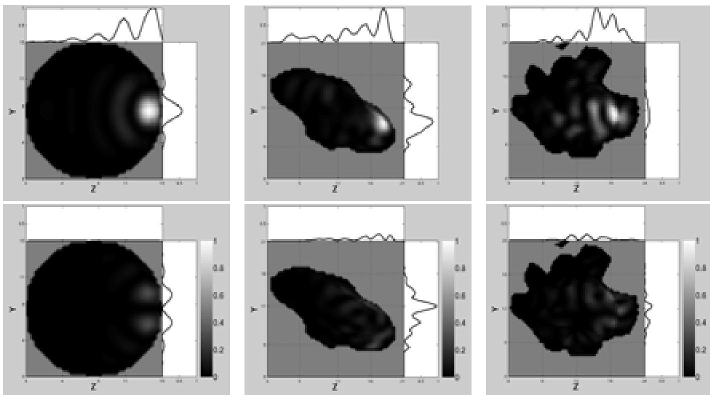

Figure 2. The far-field contribution of the longitudinal intensity component at 90° scattering angle for the spherical (panels on the left), Gaussian-random-sphere (panels in the middle), and agglomerated debris particle (panels on the right) in fixed orientation in the $Y - Z$ plane. The mapping is not a cross-section, but shows results integrated over the X dimension. On the top panels are the cases with the incident field X-polarized, and on the bottom panels Y-polarized. At the top of each panel, we show the intensity contributions integrated along both the X- and Y-axes of the particle. Similarly, at the right of each panel, we show the intensity contributions integrated along the X- and Z-axes. The refractive index is $m = 1.5 + \mathrm{i}0.01$. The incident wave is propagating from left to right.

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