Coherent backscattering by a finite medium of particles

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We study coherent backscattering of light by a spherical random medium of spherical particles. Tentatively, the multiple-scattering theory composed of radiative transfer and coherent backscattering (RT-C) reproduces the exact electromagnetic solution available from the superposition T-matrix method for a specific microscopic medium. RT-C has promising future prospects, as it is capable of extending the electromagnetic solutions from microscopic to macroscopic scales.

INTRODUCTION

Atmosphereless solar-system objects exhibit two ubiquitous light-scattering phenomena at small solar phase angles (Sun-object-observer angle α): first, the opposition effect in the intensity of scattered sunlight; and, second, the negative degree of linear polarization $(I_\perp - I_\parallel)/(I_\perp + I_\parallel)$, where $I_\parallel$ and $I_\perp$ denote the intensity components parallel and perpendicular to the scattering plane defined by the Sun, the object, and the observer.

In order to compute multiple scattering by a complex random medium of spherical scatterers, a radiative-transfer coherent-backscattering method (RT-C) has been presented in [1, 2]. In continuation of the studies in [3], we apply RT-C to the computation of the scattering properties for a specific spherical medium of spherical particles already treated using the superposition T-matrix method in [4]. We close by discussing the results and future prospects of RT-C.

RADIATIVE TRANSFER WITH COHERENT BACKSCATTERING

Our RT-C method is based on Monte Carlo ray tracing [1, 2], where coherent backscattering is computed alongside radiative transfer (RT) with the help of the reciprocity relation of electromagnetic scattering in the exact backscattering geometry. Typical for Monte Carlo ray-tracing methods, it is fairly straightforward to extend RT-C to differing geometries of the random medium.

RESULTS AND DISCUSSION

We have carried out multiple-scattering computations for finite, spherical random media of spherical particles using RT-C, concentrating on a specific case studied earlier by Mishchenko et al. [4] using the superposition T-matrix method. The size parameter of the constituent spherical particles is $x = 2$ and the volume density of the medium is $v = 6.25\%$ (this corresponds to the value of 7.3% documented in [4]). Two cases have been studied in detail: first, the complex refractive index of the constituent particles is $m = 1.31$ and the radius of the spherical medium is $kR = 40$, where k is the wave number and R is the radius

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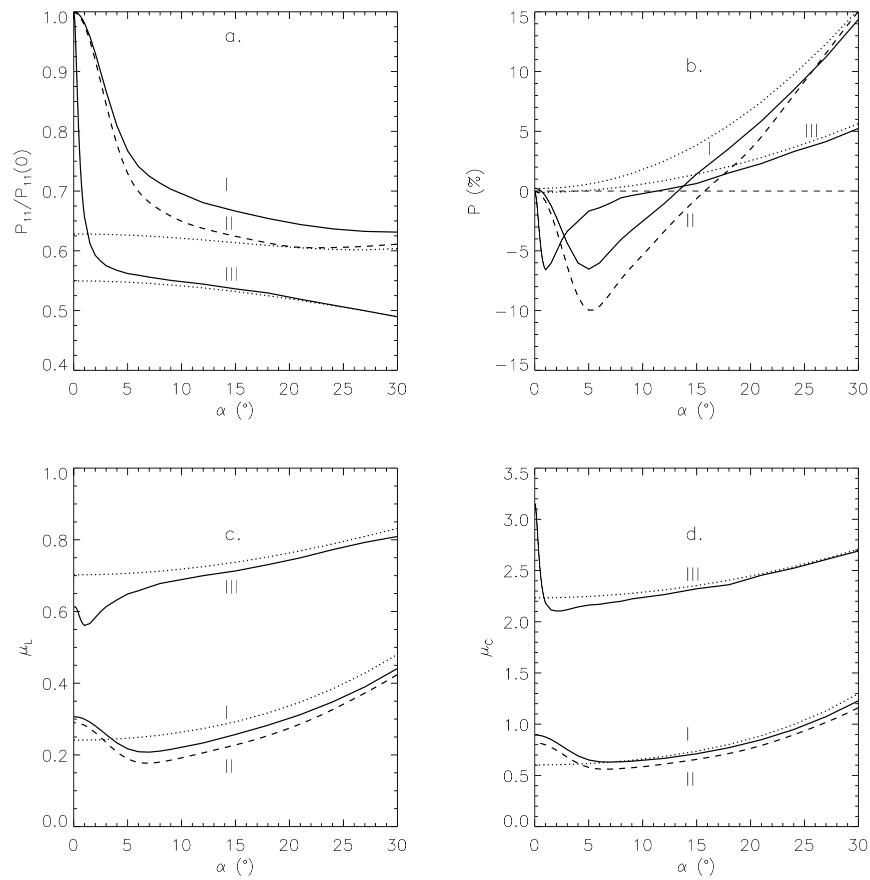

Figure 1. Multiple scattering by spherical media with volume densities $v = 6.25\%$ and varying size parameters kR (k is the wave number) composed of spherical particles with size parameters $x = 2$: a. normalized scattering phase function $P_{11}/P_{11}(0)$; b. degree of linear polarization $P = -P_{21}/P_{11}$; c. linear polarization ratio $\mu_{\rm L}$; and d. circular polarization ratio $\mu_{\rm C}$. Three sets of curves are shown: I. Radiative-transfer coherent-backscattering (RT-C; solid line) and radiative-transfer solutions (RT; dotted line; normalized with the RT-C $P_{11}(0)$ in the denominator) for $kR = 40$ and complex refractive index $m = 1.31$; II. Orientation-averaged superposition T-matrix solution for a single medium with $kR = 40$, $v = 6.25\%$, and $m = 1.31$ (dashed line); and III. RT-C and RT solutions (solid and dotted lines) for $kR \rightarrow \infty$ and $m = 1.31 + {\rm i}0.01$.

of the medium; second, $m = 1.31 + i0.01$ and $kR = 10^7$ (corresponding to $kR \to \infty$). We traced 10^5 rays in the Monte Carlo computations that required several tens of hours of single-processor computing time on a modern work station.

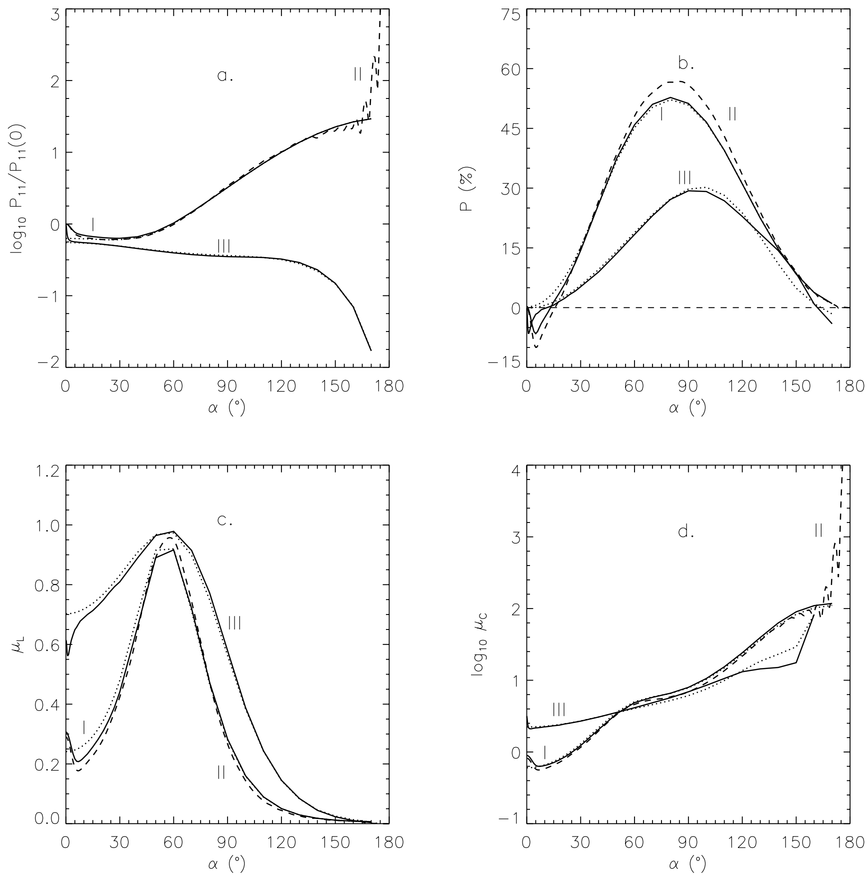

Figure 2. As in Fig. 1 for the full range of phase angles.

Figures 1 and 2 show the RT-C and RT results for the scattering phase matrix element P_{11} (the scattering phase function), degree of linear polarization for incident unpolarized light $P = -P_{21}/P_{11}$, linear polarization ratio $\mu_L = (P_{11} - P_{22})/(P_{11} + 2P_{21} + P_{22})$, and circular polarization ratio $\mu_C = (P_{11} + P_{44})/(P_{11} - P_{44})$ as a function of the phase angle α. We note that the results by Mishchenko et al. [4] are based on a single realization of a spherical medium of randomly distributed spherical particles with averaging over orientations.

Overall, RT-C succeeds in reproducing the scattering characteristics of the spherical medium with size parameter $kR = 40$ from zero phase angle to the rise of the diffraction pattern ($\alpha \approx 160°$). This is particularly remarkable as the scattering medium is microscopic in size with a moderate volume density of 6.25%. For $\alpha < 160°$, no other multiple-scattering configurations or interference mechanisms appear to be of significance equal to that of coherent backscattering.

Comparing RT-C and RT shows that, in the present case, coherent backscattering is significant even for $\alpha > 20°$. Based on additional computations, the angular widths of the coherent-backscattering phenomena are rather insensitive to the volume density because of the forward-scattering tendency of the constituent spheres. It is seen that increasing the size of the medium by more than a factor of 2×10^5 does not cause qualitative differences in the degree of polarization. There are, however, large quantitative differences between all the angular patterns for the media of $kR = 40$ and $kR \to \infty$, showing that there is considerable amount of further development work needed for the superposition T-matrix method. Different RT-C and RT levels for large phase angles $\alpha > 30°$ suggests that further work is needed to improve the numerical accuracy of the Monte-Carlo computations.

There is an extensive amount of future work needed to compare the RT-C and superposition T-matrix methods. Studies can be carried out to find the limits of applicability for RT-C in terms of volume density and medium size. For example, RT-C works for media composed of a single sphere and 500 spheres and it appears mandatory to map the applicability in between. The success of RT-C for finite media of particles calls for a corresponding treatment for compact particles. In this spirit, initial studies were carried out for the so-called exploding particle by Zubko et al. [5] using the discrete-dipole approximation (DDA). DDA can be utilized, in particular, to study the role of the near fields in scattering by aggregates where the spherical particles are in contact with one another.

RT-C is currently being applied to derive lunar single-scattering, volume-density, and surface-roughness characteristics [6]. RT-C can be optimized via parallelization of the Monte Carlo computation. In the longer term, the methods can be extended to the computation of multiple scattering by random media of nonspherical scatterers.

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