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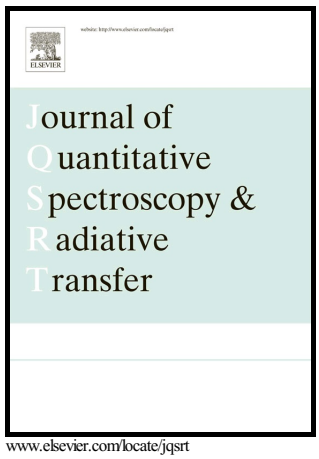

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Note

Optics of water microdroplets with soot inclusions: exact versus approximate results

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Abstract

We use the recently generalized version of the multi-sphere superposition *T*-matrix method (STMM) to compute the scattering and absorption properties of microscopic water droplets contaminated by black carbon. The soot material is assumed to be randomly distributed throughout the droplet interior in the form of numerous small spherical inclusions. Our numerically-exact STMM results are compared with approximate ones obtained using the Maxwell-Garnett effective-medium approximation (MGA) and the Monte Carlo ray-tracing approximation (MCRTA). We show that the popular MGA can be used to calculate the droplet optical cross sections, single-scattering albedo, and asymmetry parameter provided that the soot inclusions are quasi-uniformly distributed throughout the droplet interior, but can fail in computations of the elements of the scattering matrix depending on the volume fraction of soot inclusions. The integral radiative characteristics computed with the MCRTA can deviate more significantly from their exact STMM counterparts, while accurate MCRTA computations of the phase function require droplet size parameters substantially exceeding 60.

Keywords:
Cloud droplets
Soot inclusions
Electromagnetic scattering
Superposition *T*-matrix method
Ray-tracing method
Effective-medium approximation

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1. Introduction

It is widely recognized that black carbon (or soot) aerosols can act as cloud condensation nuclei and serve as cloud-droplet pollutants [1–3]. Internal contamination of cloud droplets by soot may cause substantial changes in the optical and radiative properties of liquid-water clouds (see, e.g., [4–6] and references therein). Numerically-accurate calculations of electromagnetic scattering and absorption by cloud droplets with multiple absorbing inclusions have represented a challenging problem because direct computer solutions of the macroscopic Maxwell equations for such complex and relatively large particles have been impracticable until quite recently [7,8]. As a consequence, various approximate approaches have had to be used. For example, calculations of the atmospheric energy budget have relied heavily on heuristic effective-medium approximations (EMAs) [5,6,9,10] as a means of taking into account the optical effects of internal mixing. The EMAs are based on modeling complex heterogeneous particles as being homogeneous and having a refractive index computed with one of the phenomenological mixing rules such as the Lorentz–Lorenz, Bruggeman, and Maxwell-Garnett mixing formulas [9]. Another approximate approach frequently used to calculate single-scattering properties of large cloud, snow, and soil particles containing numerous inclusions is the Monte Carlo ray-tracing approximation (MCRTA) which treats the inclusions as point-like scatterers described by the Lorenz–Mie theory (e.g., [11–15]). However, the accuracy and range of applicability of such approximate methodologies have been poorly known.

The concept of a *T* matrix was introduced by Waterman in 1971 [16] and has been widely used in studies of electromagnetic scattering and absorption by morphologically complex particles [17–24]. The most recent version of the multi-sphere superposition *T*-matrix method (STMM) developed by Mackowski [25] has extended the formulation to arbitrary configurations of spherical domains wherein any of the spheres can be located at points that are either internal or external to the other spheres. As a result, the method became applicable to the case of internal mixing (according to the definition in [26]). Unlike the approximate methodologies, the STMM is a direct computer solver of the frequency-domain macroscopic Maxwell equations and renders solutions that are both numerically exact and highly efficient. Furthermore, the STMM program can now be run on distributed-memory computer clusters as well as on serial platforms. The parallel-computing option enables accurate calculations of absorption and scattering characteristics of internal mixtures containing tens of thousands of inclusions [27–29] as well as exquisite ensemble averaging [30]. Quite expectedly, however, the numerical effort becomes prohibitive and the number of inclusions has to be reduced when the host size parameter increases and approaches ~100.

Given the availability of this improved version of the STMM methodology, the main objective of this Note is to model typical effects of multiple quasi-randomly distributed absorptive inclusions on the scattering and absorption properties of microscopic spherical water droplets. We then compare the numerically-exact STMM results with those computed with the Maxwell-Garnett EMA and the MCRTA in order to evaluate and quantify the corresponding errors in the integral radiometric characteristics and scattering-matrix elements. We expect that doing so will provide guidance to researchers in deciding whether to use either approximate approach in specific applications depending on the acceptable level of numerical uncertainty.

2. Numerical results and discussion

A recent study has revealed that for the same cumulative amount of an absorptive foreign material, the absorption is maximized when the material is distributed quasi-uniformly

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throughout the droplet interior in the form of numerous small inclusions [31]. Another reason to focus on this model of heterogeneous water droplets is that it appears to be the only internal-mixing scenario that can potentially make applicable the EMA concept and the MCRTA [27–32].

To model this type of heterogeneity, we place an increasing number (N = 10, 25, 50, 100, 200, 300, 400, 500, and 600) of spherical soot inclusions quasi-randomly inside a spherical host water droplet, as illustrated in Fig. 1. The positions of the soot inclusion cannot be completely random since these particles are not allowed to overlap. However, assigning the inclusion coordinates using a random-number generator and then averaging over the uniform orientation distribution of the resulting heterogeneous droplet yields in effect a scattering object with a random and statistically uniform distribution of inclusions. All soot inclusions are assumed to be identical, with their size parameter fixed at $k_1 r = 1$, where $k_1 = 2\pi/\lambda$ is the wave number in the infinite nonabsorbing medium surrounding the droplet and $r = 0.1$ μm is radius of the inclusions. The wavelength λ is fixed at $\pi/5$ μm ≈ 0.6283 μm, thereby implying that $k_1 = 10$. The soot refractive index, 1.95+0.79i, is chosen according to the recommendation in [33], while the host refractive index, 1.33, is representative of liquid water at visible and near-infrared wavelengths.

Note that the size spectrum of black-carbon aerosols serving as cloud condensation nuclei is wide and sometimes can span several orders of magnitude [34,35]. The inclusion sizes affect the overall light scattering and absorption of heterogeneous particles [13,28,29]. Ideally one would need to assume that these embedded particulates are polydisperse and randomly distributed inside a water droplet. However, instead of estimating the actual radiative impact by soot-contaminated cloud droplets, the main goal of this study is to examine the applicability of approximate theories such as the Maxwell-Garnett EMA and the MCRTA in computations of scattering and absorption characteristics of heterogeneous water–soot mixtures by comparing their outputs with numerically-exact STMM results. Moreover, the black-carbon radius of 0.1 μm is a representative value consistent with both models and observations [36,37].

The integral radiometric characteristics typically used to describe the single-scattering and absorption properties of atmospheric particulates include the ensemble-averaged extinction, C_{ext}, scattering, C_{sca}, and absorption, $C_{\text{abs}} = C_{\text{ext}} - C_{\text{sca}}$, cross sections; the single-scattering albedo $\varpi = C_{\text{sca}}/C_{\text{ext}}$; and the asymmetry parameter g [19,38]. The angular distribution and the polarization state of the singly scattered light are nominally described in terms of the normalized Stokes scattering matrix

$$\tilde{\mathbf{F}}(\Theta) = \begin{bmatrix} a_1(\Theta) & b_1(\Theta) & 0 & 0 \\ b_1(\Theta) & a_2(\Theta) & 0 & 0 \\ 0 & 0 & a_3(\Theta) & b_2(\Theta) \\ 0 & 0 & -b_2(\Theta) & a_4(\Theta) \end{bmatrix}, \tag{1}$$

where $\Theta \in [0°, 180°]$ is the scattering angle (i.e., the angle between the incidence and scattering directions) [19,38]. Note that the specific block-diagonal structure of the scattering matrix (1) has been confirmed by all the STMM results discussed below. The (1, 1) element of the scattering matrix is the conventional phase function normalized according to

$$\frac{1}{2}\int_0^{\pi} \mathrm{d}\Theta \sin\Theta \; a_1(\Theta) = 1, \tag{2}$$

while the asymmetry parameter is defined according to

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$$g = \frac{1}{2}\int_0^{\pi} \mathrm{d}\Theta \sin\Theta \cos\Theta \; a_1(\Theta). \tag{3}$$

In the case of heterogeneous water droplets, the orientation-averaged values of the above optical characteristics are calculated by running the STMM program developed in [25]. To suppress the scattering resonances typical of monodisperse objects [19,38], all scattering and absorption characteristics are further averaged over three discrete host size parameters, k_1R = 59, 60, and 61. These size-parameter values correspond to droplet radii R = 5.9, 6, and 6.1 μm which lie in the range of observed effective radii of cloud droplets in the terrestrial atmosphere, perhaps somewhat on the smaller side [39,40]. The quasi-random positions of the soot inclusions are generated separately for each host size parameter. Note that as the number of the inclusions increases from 10 to 600 inside a 6-μm droplet, the corresponding volume fraction of the soot material grows from 4.63×10^{-5} to 2.78×10^{-3}.

The solid curves in Fig. 2 show the orientation- and size-averaged elements of the Stokes scattering matrix as functions of the scattering angle for N = 100 and 600. For comparison, the dotted curves depict the corresponding Lorenz–Mie results for homogeneous droplets with refractive indices calculated using the Maxwell-Garnett approximation (MGA) for the respective volume fractions of soot in the k_1R = 60 droplet. In this case the water droplets are assumed to be polydisperse and characterized by a very narrow power law size distribution [19,41] with an effective size parameter of 60 and an effective variance of 0.001.

The STMM results in Fig. 2 show that as the number of absorbing inclusions increases, the phase functions of the soot-contaminated droplets become progressively smooth and shallow at side-scattering angles, while the characteristic rainbow and glory features weaken. Furthermore, the deviation of the ratio $a_2(\Theta)/a_1(\Theta)$ from unity increases and exhibits strong backscattering depolarization qualitatively attributable to the growing contribution of "multiple internal scattering".

Although the phase functions rendered by the MGA are qualitatively similar to their STMM counterparts, substantial quantitative differences are quite obvious. For example, at the exact backscattering direction, the $a_1(180°)$ difference between the STMM and MGA results exceeds a factor of three in the case of the droplets with 100 soot inclusions (see the left-hand panel of Fig. 3). The corresponding phase-function differences at side-scattering angles for N = 600 exceed a factor of two. The differences in the ratios $a_j(\Theta)/a_1(\Theta)$ and $\pm\, b_j(\Theta)/a_1(\Theta)$ can partly be attributed to the use of different size distributions in the STMM and MGA computations, but in some cases they obviously have a component caused by the very use of an approximate scattering methodology. Most importantly, whenever the MGA is applied to a spherical host it reproduces the two fundamental Lorenz–Mie identities,

$$\frac{a_2(\Theta)}{a_1(\Theta)} \equiv 1 \text{ and } \frac{a_3(\Theta)}{a_4(\Theta)} \equiv 1. \tag{4}$$

However, Fig. 2 reveals a substantial violation of the first identity by the numerically-exact STMM results. The violation of the second identity, as illustrated by the right-hand panel of Fig. 3, is equally pronounced. These results confirm once again an essential limitedness of the concept of effective refractive index.

Fig. 4 compares the phase functions computed for the water microdroplets with an increasing number of soot inclusions using the STMM and the MCRTA. The latter is a simple

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and efficient heuristic method combining ray-optics and radiative-transfer concepts. It permits the treatment of light scattering and absorption by arbitrarily shaped host particles containing small, randomly positioned, widely separated inclusions and is expected to be applicable to host particles with sizes much greater than the wavelength of the incident radiation. In an *ad hoc* fashion, the ray-tracing program takes care of individual reflection and refraction events at the outer boundary of the host particle, while the Monte Carlo procedure essentially simulates the summation of the so-called ladder diagrams appearing in the microphysical theory of radiative transfer [38,42]. This model is detailed in [11,12,43–45] and is implemented in the form of a computer program publicly available at http://tools.tropos.de. This specific program is based on the so-called scalar approximation of radiative transfer [42] and hence can be used to compute only the $(1, 1)$ element of the scattering matrix (i.e., the phase function).

It is obvious from Fig. 4 that the MCRTA is unable to reproduce the strong backscattering enhancement traditionally called the glory. Furthermore, the sharpness and magnitude of the primary and secondary rainbows rendered by the MCRTA are grossly overestimated. The side-scattering differences between the STMM and MCRTA phase functions are also quite pronounced. One can think of several potential causes of these side- and backscattering differences, including the inadequacy of the ray-tracing concepts of reflections and refractions and the failure of the radiative-transfer concept of ladder sequences of widely separated particles [38,42]. The numerical comparisons of ray-tracing and Lorenz–Mie results in [19,41] and of radiative-transfer and STMM results in [46] suggest that the failure of the ray-tracing concepts is likely to be the more significant factor.

Fig. 5 further quantifies the accuracy of the MGA and MCRTA as a function of the number of inclusions N. Note that the extinction cross section computed by the MCRTA for a particle much larger than the wavelength is identically equal to twice the area of the particle's projection on the plane normal to the incidence direction, the diffraction on and the geometric interception of the "incident rays" by the particle's projection being equal contributors. We define the relative errors of the approximate results, in percent, as $(C_{\mathrm{approx}}/C_{\mathrm{STMM}} - 1) \times 100\%$, where C represents any parameter of interest. The relative MGA errors as a function of the number of soot inclusions fall within the ranges [–4.44%, 7.82%], [–0.98%, 0.03%], and [0.10%, 2.75%] for the absorption cross section, single-scattering albedo, and asymmetry parameter, respectively. The corresponding MCRTA ranges are [–31.43%, –18.16%], [0.10%, 2.77%], and [2.49%, 2.75%]. The errors of both sets of approximate results usually grow with the number of soot inclusions. The notable exception is the MCRTA asymmetry parameter whose significant deviation from its STMM counterpart is essentially N-independent.

The reader should recall that the soot volume fraction at N = 600 is 2.78×10^{-3}. The real degree of soot contamination in terrestrial water clouds is unlikely to reach such high values [4,47–49]. Therefore, we conclude that the popular Maxwell-Garnett mixing rule can be safely used to calculate the optical cross sections, single-scattering albedo, and symmetry parameter for the quasi-uniform internal mixing scenario. Although the average performance of the MCRTA is not as good as that of the MGA, its accuracy can be expected to improve as the host water droplets become larger.

3. Concluding remarks

Our numerically exact single-scattering STMM results show that the presence of soot in water microdroplets can have a noticeable effect on their extinction, scattering, and absorption cross sections, single scattering albedo, asymmetry parameter, and, especially, elements of the

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scattering matrix. The significant linear depolarization evident from the $a_2(\Theta)/a_1(\Theta)$ ratio is the prime manifestation of the morphological complexity of soot-contaminated droplets despite their perfectly spherical outer boundaries. Our results indicate that the Maxwell-Garnett effective-medium approximation can be safely used to calculate the integral radiative characteristics of soot-contaminated droplets but, depending on the actual volume fraction of soot, can fail in computations of the elements of the scattering matrix. Droplet size parameters ~60 are not sufficiently large for the MCRTA to yield adequately accurate phase functions. One can expect, however, that as the droplet size parameter increases the accuracy of the MCRTA can become significantly better. In general, our study testifies against indiscriminate use of the approximate methods in remote-sensing applications dealing with soot-contaminated cloud droplets.

Besides the MGA, another popular EMA is the so-called Bruggeman mixing rule [9,50]. If the volume fraction of the inclusions is substantial then the predictions of the two mixing rules can, in principle, differ. However, in the case of volume fractions as small as those considered in this Note both mixing rules yield nearly identical results despite the large refractive-index mismatch between liquid water and soot. Therefore, all conclusions reached above for the MGA are also valid for the Bruggeman mixing rule.

On a final note, we hope that our methodology of obtaining physical insight into the validity of the two approximate methods will find applications in light-scattering parameterization development. A good example would be the analysis of such important aspects of characterizing ambient aerosols as the interconnection between the effective refractive index and the effective particle mass density as well as the consistency of mixing rules used to calculate these two parameters of a multicomponent mixture via the index–density relationship [51].

Acknowledgments

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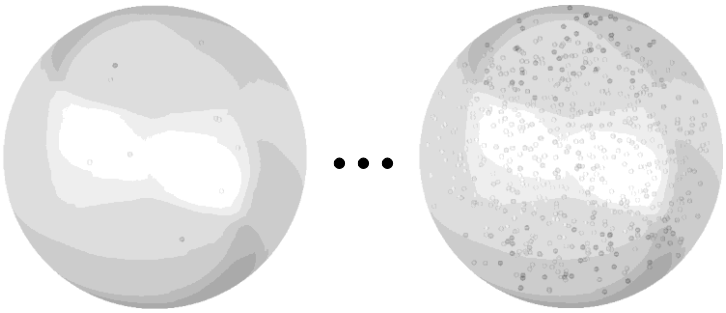

Fig. 1. Spherical water microdroplets populated with an increasing number N of spherical soot inclusions ranging from $N = 10$ to $N = 600$.

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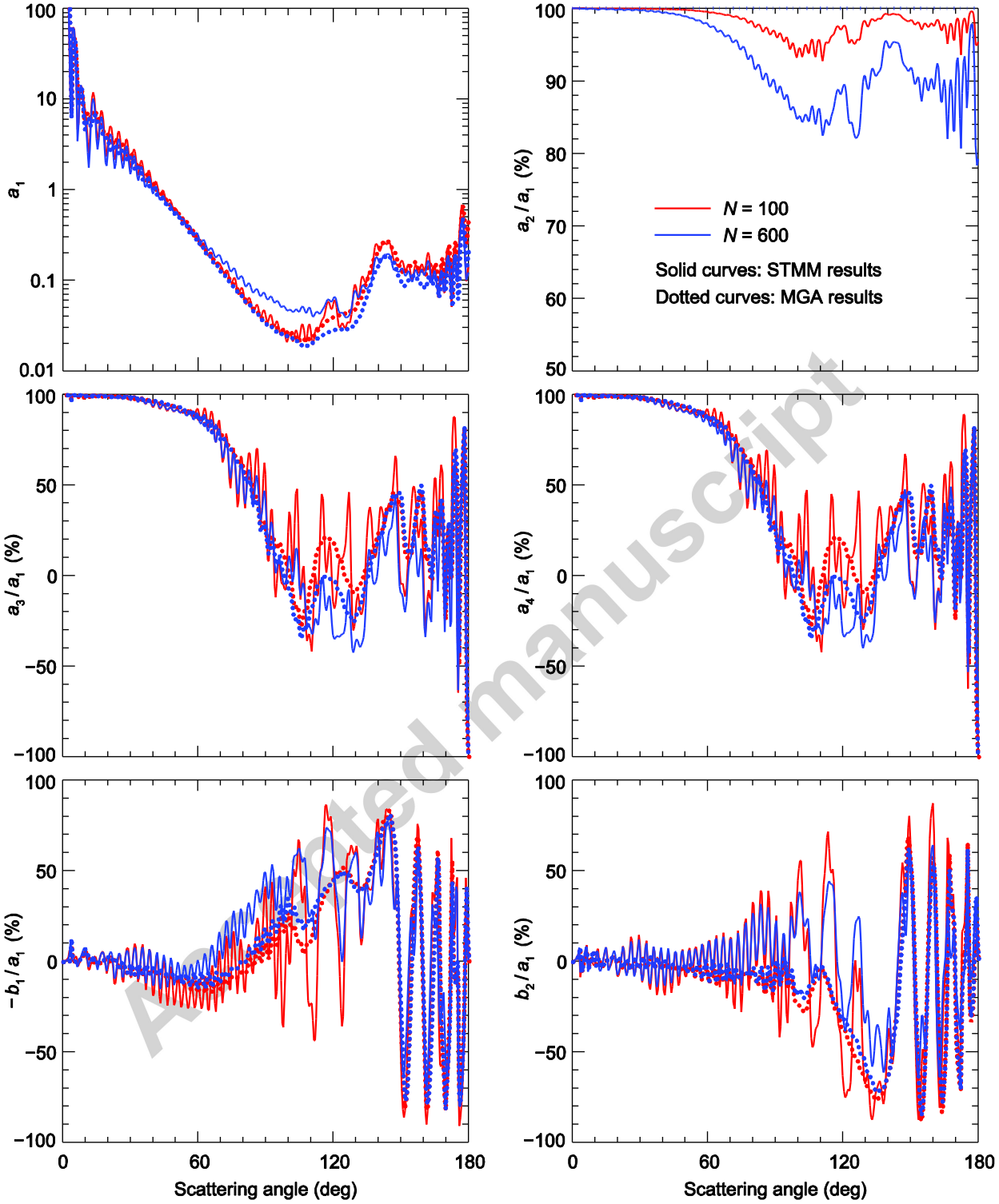

Fig. 2. Ensemble-averaged elements of the Stokes scattering matrix for soot-contaminated water microdroplets.

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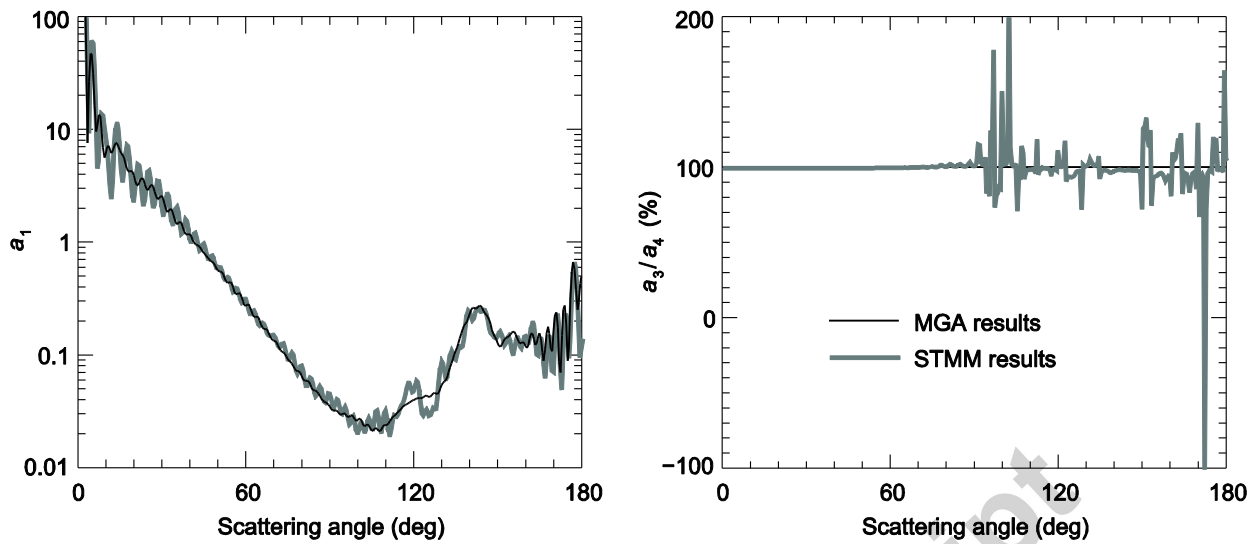

Fig. 3. The phase function and the ratio $a_3(\Theta)/a_4(\Theta)$ for water droplets with 100 soot inclusions.

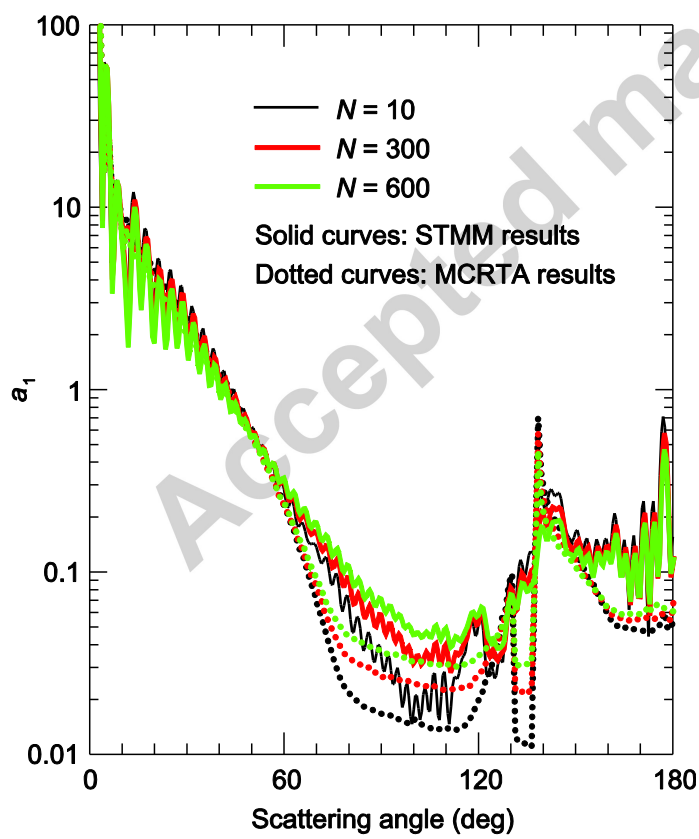

Fig. 4. Comparison of the STMM phase functions (solid curves) and their MCRTA counterparts.

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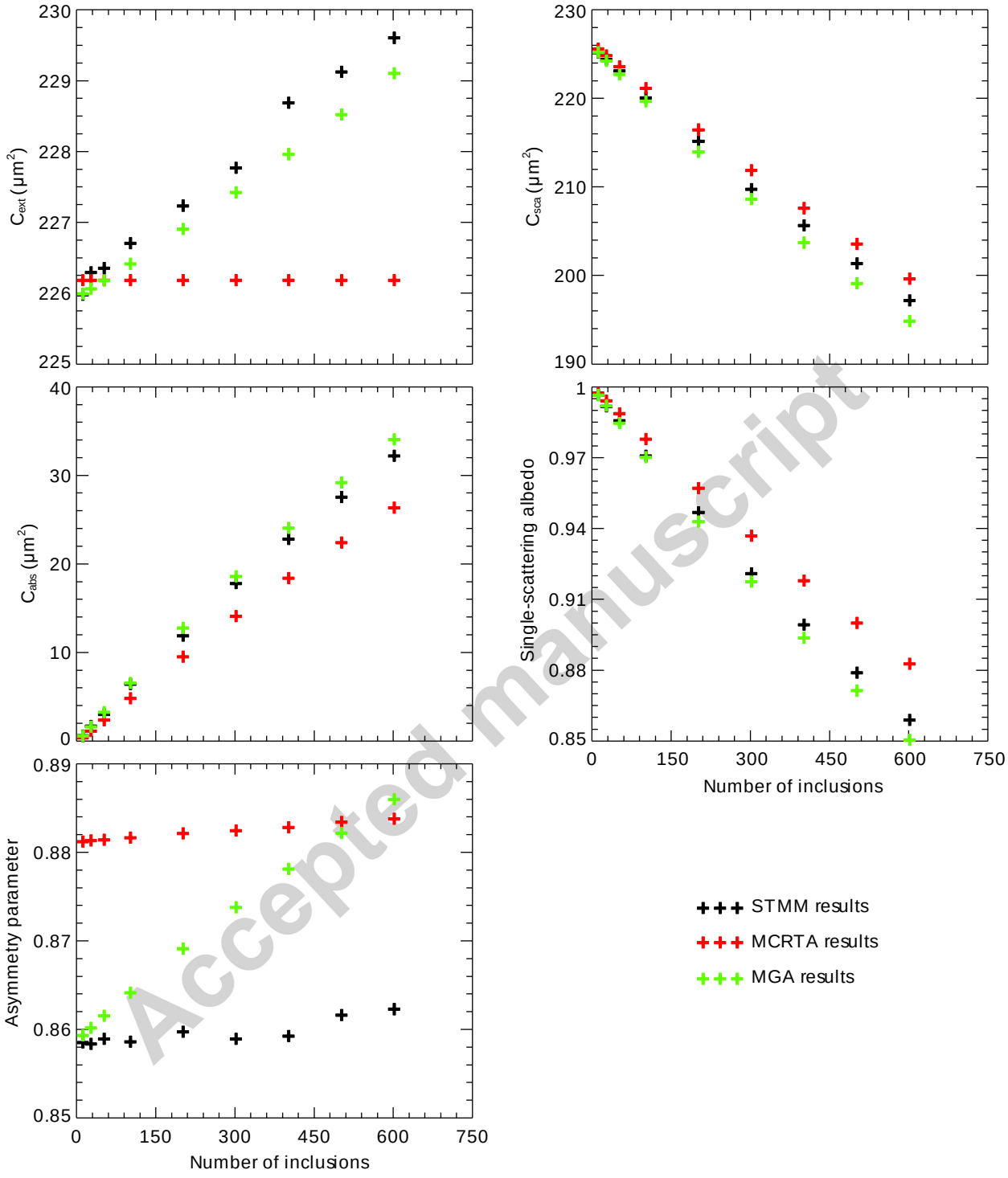

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Fig. 5. Comparison of the STMM cross sections, single scattering albedo, and asymmetry parameter with their MCRTA and MGA counterparts.