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# Mixing rules and morphology dependence of the scatterer

Gorden Videen [a,b,*], Evgenij Zubko [c], Wenbo Sun [d], Yuriy Shkuratov [c], Alex Yuffa [a]

[a] Army Research Laboratory, Adelphi, MD 20783, USA
[b] Space Science Institute, Boulder, CO 80301, USA
[c] Institute of Astronomy, V.N. Karazin Kharkiv National University, 35 Sumskaya Street, Kharkiv 61022, Ukraine
[d] Science Systems and Applications Inc., Hampton, VA 23666, USA

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ABSTRACT

We use the discrete dipole algorithm (DDA) to calculate the light-scattering properties from arbitrarily shaped, heterogeneous agglomerated debris particles to study the performance of effective medium approximations. The homogenization of the material properties of the particle has little effect on the orientation-averaged intensity phase function. However, there are some differences in the polarization response. While the structure of the linear-polarization response is not significantly different between the homogeneous and heterogeneous cases, the amplitude of the polarization tends to show a dependence on particle heterogeneity. The Bruggeman mixing rule tends to reproduce the heterogeneous results marginally better than using the average of two distributions of the individual homogeneous components. In addition to the irregularly shaped particles, we also calculated scattering properties of equivalent-volume, homogeneous spheres. As expected, the errors due to assuming homogeneous particles are overwhelmed by those introduced by assuming the irregularly shaped particle may be replaced by an equivalent spherical particle.

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## 1. Introduction

Effective medium theories (EMTs), or mixing rules, provide a means of calculating light scattering properties of heterogeneous particles by assuming they are homogeneous. The most frequently used one is the Bruggeman mixing rule. In the context of light-scattering, mixing rules rose to prominence in the wake of the studies of morphology dependent resonances (MDRs) in the 1980s and 1990s. While very few of these early studies actually considered the effect of morphology, a number of them did consider the effect of heterogeneities on the resulting resonances [1–6]. It was impossible to verify the results theoretically at that time, but one significant experimental effort resulted in the production of a composite particle that could be measured in the microwave region [7], and whose results could also be compared with Lorenz–Mie results calculated using the Bruggeman and Maxwell–Garnett mixing rules. In the mid-1990s, models to calculate light-scattering from a sphere containing an inclusion were developed [8,9], and it became practical to make some verification of mixing rules using the approximation that a single inclusion is present [10–12]. In these studies the size of the inclusion was increased beyond that of a Rayleigh particle to address Bohren's concerns [13] about extended effective medium approximations previously proposed by Chýlek and Srivastava [14]. The primary application at the time was to address anomalous absorption observed from clouds, that was hypothesized to result from absorbing nucleating particles in water droplets, the so-called cloud-absorption anomaly [15–17].

It was not until recently that a test of mixing rules was performed using a model spherical droplet containing a

* Corresponding author. Tel.: +1 301 394 1871.
*E-mail address:* gorden.w.videen.civ@mail.mil (G. Videen).

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large number of small inclusions. Mishchenko, Liu and Mackowski use a new formulation of the superposition *T*-matrix algorithm for a spherical volume filled with a large number of inclusions [18] whose roots go back some 20 years [19,20]. More recently, Mishchenko, Dlugach, and Zakharova used this model to validate the concept of an unrestricted effective-medium approximation [21]. Unlike previous examinations, the researchers were finally equipped with efficient algorithms and the necessary computational resources to perform legitimate tests. In the spirit of the initial studies, the authors considered the effect of inclusions on resonances in their tests. While they found that the mixing rules largely failed to predict the resonance behavior, except in gross qualitative ways, i.e. they do appear to predict the direction of resonance shifts, these particular simulations do represent an extremely difficult test as the inclusions represent secondary scattering sites that scatter energy from the spherical cavity, the physics of which cannot be contained within a model of simple Lorenz–Mie theory using a mixing rule.

Within the last decade, it has become practical to use numerical techniques, like the discrete dipole approximation (DDA) to calculate the light-scattering properties from arbitrarily shaped, heterogeneous particles. Such particles include mixed-phase aerosols, ice, mineral dust, etc., and have numerous remote-sensing applications. From a practical standpoint, the use of EMTs to approximate the optical properties of such particles presents a tremendous cost-savings in computational time because the number of different material combinations of such a class of particles is infinite. In this manuscript we consider heterogeneous, irregularly shaped ice particles and perform comparisons of the resulting light-scattering properties with those of identically shaped, but homogeneous particles using two simple mixing rules.

## 2. Heterogeneous particles

We employ the DDA to calculate the light-scattering properties of heterogeneous agglomerated debris particles.

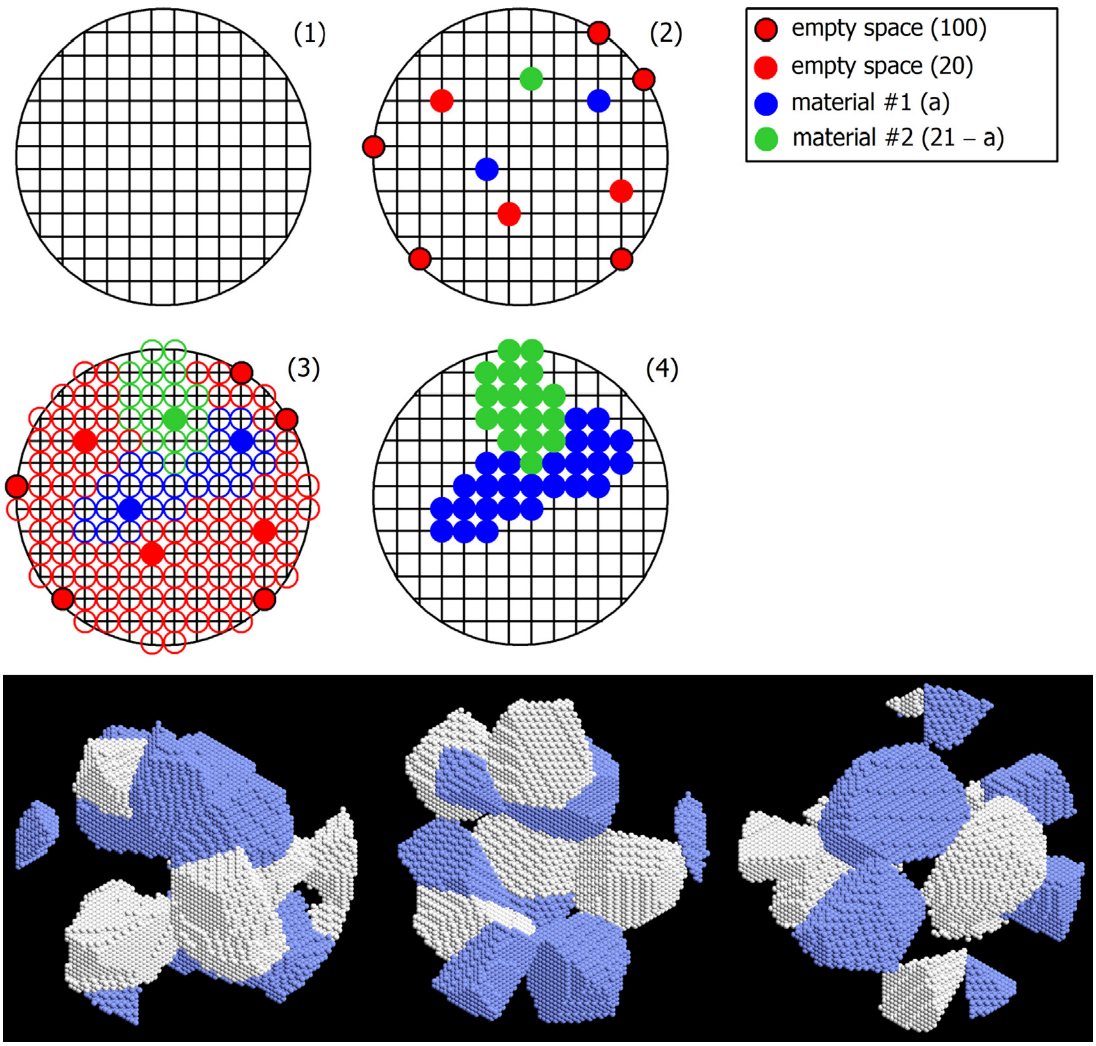


**Fig. 1.** A cartoon depicting the method for generating heterogeneous agglomerated debris particles in two dimensions (top) and three example images of agglomerated debris particles (bottom).