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Effect of spine-like surface structures on the radiative properties of microorganism

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ABSTRACT

Many species of microorganisms possess spine-like surface structures. In this paper, we built a sphere with surface spines (SSS) model to represent such featured particles. The volume fraction of surface spines varied from 0% to 22% and the effects of the relative length, number, and radius of the spines on the radiation characteristics were studied using the discrete dipole approximation method with a complex relative refractive index of $m = 1.05 + 0.005i$. Meanwhile, the approximations by the equivalent volume sphere (EVS) and the core shell sphere (CSS) models were examined. Surface spines led to increased scattering and absorption cross sections and asymmetry parameter. The EVS model overestimated the scattering cross section and underestimated the asymmetry parameter of SSS, the relative errors of which can exceed 10%, but EVS predicted the absorption cross section well. The CSS model combined with the Maxwell-Garnett mixing rule predicted the integral radiation parameters with relative errors less than 5% in all the cases, which was also valid for relative refractive indices with an imaginary part up to 0.1 and a real part up to 1.2. The resonance peaks of the phase function and Mueller matrix elements in the back scattering directions were damped out due to the existence of surface spines for size parameters larger than 10, which could not be captured by either the EVS or the CSS models.

1. Introduction

Light scattering and absorption by particles are essential in the radiative transfer community [1] and other scientific fields like remote sensing technology [2], ocean optics [3], biomedical optics [4] and so on. Natural and artificial particles are usually complex in morphology and heterogeneous in composition. Thanks to the development of miscellaneous numerical tools including the T-matrix method [5], the discrete dipole approximation (DDA) method [6], the finite difference time domain (FDTD) method [1], to name a few, the effects of particles' non-sphericity [7,8], inhomogeneity [9–11], porosity [12], surface roughness [13,14], etc. on the radiative properties are widely investigated. However, these methods can be computationally intensive and capability-limited to deal with light scattering problems. In practical applications, highly simplified models are still applied, which may fail to interpret the scattering and absorption properties and introduce significant errors. Thus on one hand, more elaborate model particles should be involved to deepen our understanding of the light scattering process by particles, and on the other, the usefulness of simplified models should be tested and validated by comparing their

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radiative properties to those of more complex, presumably more realistic ones [15].

As an important part of the numerous kinds of particles, photosynthetic microorganisms including diatoms, green or red microalgae, cyanobacteria etc. are recently gaining more and more attention for their potential applications in CO_2 fixation, wastewater treatment, biofuel, H_2 and fertilizer production [16]. In order to design and operate the photobioreactors with optimum light availability, it is necessary to accurately predict the light transfer in the photobioreactors [16], which is governed by the radiative transfer equation (RTE). Therefore, knowledge of the radiation characteristics of the photosynthetic microorganisms is of great significance. Based on the superposition T-matrix method [17], Lee and Pilon [18] studied the absorption and scattering properties of long and randomly oriented linear chains of spheres representing filamentous cyanobacteria, and tested the approximation by infinitely long cylinders with volume-equivalent diameter. Using the same method, Heng et al. [19] investigated the radiation characteristics of bispheres, quadspheres and circular rings of spheres representing multicellular cyanobacteria, and found that their absorption, scattering cross sections and asymmetry factor can be approximated by an equivalent coated sphere with identical volume and average projected area. More generally, the radiative properties of fractal aggregates and the approximation by their equivalent coated spheres were studied [20]. In addition to the cultivation of photosynthetic microorganisms, the inherent optical properties (IOPs) of microorganisms suspended in natural waters are of great interest in areas like marine photosynthesis [21] and remote sensing of the ocean color [22]. Quirantes and Bernard [23] modeled microalgae as coated spheres or coated spheroids to account for the complex intracellular structures and found that the coated spheres could reproduce experimentally measured light scattering properties. Based on the DDA method, Gordon [24] examined the influence of shape and inhomogeneity on the IOPs by comparing the radiative properties of randomly-oriented cylindrically-shaped particles with those of equal-volume spheres and found that the spherical-based interpretation of extinction and absorption can lead to large errors. Zhai et al. [25] established a realistic nonspherical model for *Emiliania huxleyi* and studied its IOPs using DDA method. Moreover, in the area of medical diagnostics where the radiative properties of bioparticles are also of great importance, model particles for the red blood cell [26], blood platelets [27], *E. coil* cell [28], etc. have been involved to improve the measurement accuracy.

For applications of solving radiation transfer in photobioreactors, remote sensing of microorganisms as well as the diagnosing of bioparticles, we should know as much as possible on their radiation characteristics. However, photosynthetic microorganisms or other bioparticles usually have well-defined shapes and complex internal structures. Our knowledge on their radiation characteristics is still very limited. For some species of unicellular photosynthetic microorganisms, they possess spine-like surface structures (microvilli, flagellums, etc.) as shown in Fig. 1 (a) for microalgae of *Desmodesmus spp*. and Fig. 1(b) *Golenkinia*. Fig. 1(c) demonstrated another example of such featured bioparticles: the fungal spore. As shown in Fig. 1, the length, total number and the effective radius of the spines as well as the size of the bioparticle can vary considerably depending on the species of the bioparticles. However, this feature is often neglected and a homogeneous sphere model is still widely applied in the calculation of their radiation characteristics, which raises the questions that what is the impact of this morphological feature on the radiation characteristics and if the radiation characteristics of such featured particles can be reproduced by simplified equivalent models.

Therefore the aim of this paper is to establish models to represent microorganisms with spine-like surface structures and to investigate its impact on the radiation characteristics. In addition, the approximations by the equivalent volume sphere and the core shell sphere are investigated. This work finds its motivation to facilitate the solving of the radiation transfer in the photobioreactors in cases of microorganisms with spine-like surfaces, and it can also be applied to ocean optics and bio-optics.

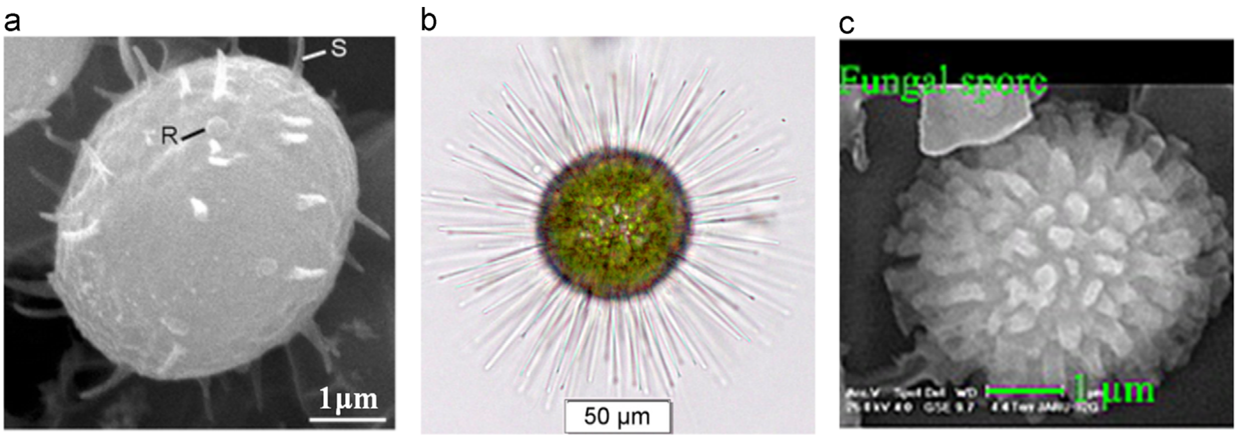

Fig. 1. Images of some bioparticle examples, (a) *Desmodesmus spp*. microalgae [29], reproduced with permission from Springer; (b) *Golenkinia*, reproduced with permission from Alan L. Baker (University of New Hampshire, http://cfb.unh.edu/phycokey/phycokey.htm); (c) Fungal spore [30], reproduced with permission from American Geophysical Union.