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Radiation characteristics and effective optical properties of dumbbell-shaped cyanobacterium *Synechocystis* sp.

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ABSTRACT

This study presents experimental measurements of the radiation characteristics of unicellular freshwater cyanobacterium *Synechocystis* sp. during their exponential growth in F medium. Their scattering phase function at 633 nm average spectral absorption and scattering cross-sections between 400 and 750 nm were measured. In addition, an inverse method was used for retrieving the spectral effective complex index of refraction of overlapping or touching bispheres and quadspheres from their absorption and scattering cross-sections. The inverse method combines a genetic algorithm and a forward model based on Lorenz–Mie theory, treating bispheres and quadspheres as projected area and volume-equivalent coated spheres. The inverse method was successfully validated with numerically predicted average absorption and scattering cross-sections of suspensions consisting of bispheres and quadspheres, with realistic size distributions, using the T-matrix method. It was able to retrieve the monomers' complex index of refraction with size parameter up to 11, relative refraction index less than 1.3, and absorption index less than 0.1. Then, the inverse method was applied to retrieve the effective spectral complex index of refraction of *Synechocystis* sp. approximated as randomly oriented aggregates consisting of two overlapping homogeneous spheres. Both the measured absorption cross-section and the retrieved absorption index featured peaks at 435 and 676 nm corresponding to chlorophyll *a*, a peak at 625 nm corresponding to phycocyanin, and a shoulder around 485 nm corresponding to carotenoids. These results can be used to optimize and control light transfer in photobioreactors. The inverse method and the equivalent coated sphere model could be applied to other optically soft particles of similar morphologies.

1. Introduction

Photosynthetic microorganisms use sunlight as their energy source and carbon dioxide as their carbon source. They can be cultivated to produce a variety of valuable products such as nutritional supplements, natural dyes, cosmetics, biofuels, and fertilizers [1,2]. In addition, they can be used to treat wastewater [2] and to reduce carbon dioxide emissions from industrial exhaust gases [3]. However, key advances in cultivation systems and biomass harvesting methods are required to improve productivity and make the technology cost effective [4].

The unicellular freshwater cyanobacterium *Synechocystis* sp. PCC 6803 has been considered for biofuel production [5]. It was the first photosynthetic organism whose entire genome was sequenced due to the

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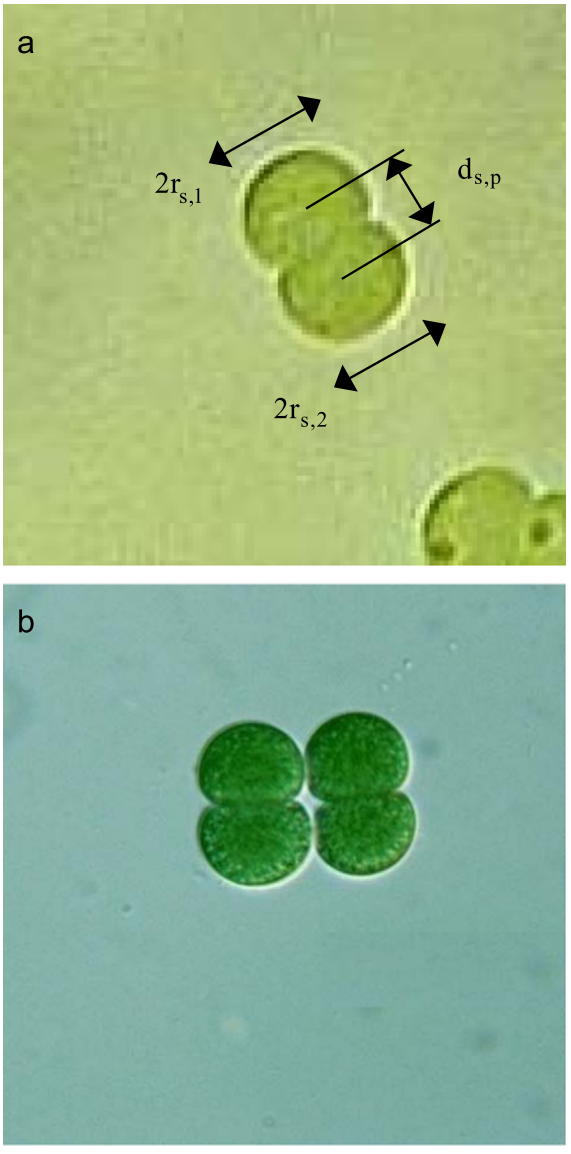

Fig. 1. Micrographs of (a) a free floating dumbbell-shaped *Synechocystis* sp. cell with two lobes of radius $r_{s,1}$ and $r_{s,2}$ of about 1 μm and (b) *Synechocystis* sp. immediately after cell division. Reproduced with permission from Prof. Yuuji Tsukii (Hosei University, http://protist.i.hosei.ac.jp/).

similarities between its photosynthetic apparatus and that of higher plants [6]. It is widely used as a standard in studies involving photosynthesis, environmental stress response, pigment synthesis, lipid production, and other metabolic processes [6–9]. *Synechocystis* sp. contain different photosynthetic pigments including Chlorophyll *a* (Chl *a*), phycocyanin (PCCN), as well as photosynthetic (PSC) and photoprotective (PPC) carotenoids [10]. Each type of pigments possesses its own absorption spectra enabling the microorganisms to absorb photons in the photosynthetically active radiation (PAR) region ranging from 400 to 700 nm [11]. This species has also been genetically engineered with reduced light harvesting pigments (particularly PCCN), to increase their energetic yield per cell [5]. Fig. 1a shows a micrograph of dumbbell-shaped *Synechocystis* sp. cells approximately 2 μm in length and resembling overlapping bispheres. Fig. 1b shows a micrograph of *Synechocystis* sp. immediately after fission when the cell divides into two identical daughter cells and resembling quadspheres [12].

Photosynthetic microorganisms are typically cultivated in open or closed photobioreactor (PBR) systems. The productivity of these systems is severely hampered by low light energy conversion efficiencies [13]. Indeed, incident light is rapidly attenuated in the culture due to light absorption and scattering by the microorganisms, resulting in inhomogeneous light distribution. In regions of the PBRs directly exposed to sunlight, the light intensity may be excessively high causing photoinhibition [14]. On the other hand, deeper in the PBR, light intensity may be too small to drive photosynthesis or even respiration. Both phenomena result in low photosynthetic efficiency and in a significant decrease in the overall PBR productivity. Therefore, PBR design and control must be improved so that light can be utilized as efficiently as possible. In order to do so, analytical tools modeling coupled light transfer, hydrodynamics, and growth kinetics have been developed [15–17]. In all these models, the spectral radiation characteristics of the photosynthetic microorganisms are essential input parameters.

The present study aims to measure the radiation characteristics of *Synechocystis* sp. during exponential growth. It also aims to develop an inverse method able to retrieve the effective spectral complex index of refraction of *Synechocystis* sp. and other particles with complex touching or overlapping bisphere and quadsphere morphologies from their absorption and scattering cross-sections.

2. Background

2.1. Light transfer

The spectral radiation intensity $I_\lambda(r,\hat{\mathbf{s}})$ (in W/m^2 sr nm) along the direction $\hat{\mathbf{s}}$ at location $\mathbf{r}$ and wavelength λ in homogeneous, absorbing, scattering, and non-emitting microorganism suspensions satisfies the radiative transfer equation (RTE) expressed as [18]

$$\hat{\mathbf{s}}\cdot\nabla I_\lambda(\mathbf{r},\hat{\mathbf{s}}) = -\kappa_\lambda I_\lambda(\mathbf{r},\hat{\mathbf{s}}) - \sigma_{s,\lambda} I_\lambda(\mathbf{r},\hat{\mathbf{s}}) + \frac{\sigma_{s,\lambda}}{4\pi}\int_{4\pi} I_\lambda(\mathbf{r},\hat{\mathbf{s}}_i)\Phi_{T,\lambda}(\hat{\mathbf{s}}_i,\hat{\mathbf{s}})\,\mathrm{d}\Omega_i \quad (1)$$

where κ_λ and $\sigma_{s,\lambda}$ are the effective spectral absorption and scattering coefficients of the suspension (in m^{-1}), respectively. In addition, the extinction coefficient is defined as $\beta_\lambda = \kappa_\lambda + \sigma_{s,\lambda}$. The scattering phase function $\Phi_{T,\lambda}(\hat{\mathbf{s}}_i,\hat{\mathbf{s}})$ represents the probability that light propagating in the solid angle $d\Omega_i$ along direction $\hat{\mathbf{s}}_i$ be scattered into the solid angle $d\Omega$ along direction $\hat{\mathbf{s}}$. It is normalized such that

$$\frac{1}{4\pi}\int_{4\pi}\Phi_{T,\lambda}(\hat{\mathbf{s}}_i,\hat{\mathbf{s}})\,\mathrm{d}\Omega_i = 1. \quad (2)$$

In addition, the asymmetry factor g_λ for an axisymmetric