Polarized light scattering properties of *Emiliania huxleyi* coccoliths and coccospheres

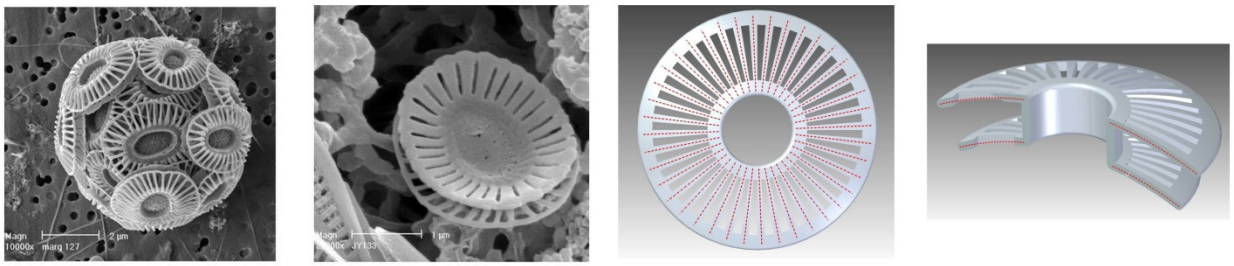
G.R. Fournier[1], G. Neukermans[2]

1- DRDC Valcartier Research Laboratory, Québec, Québec G3J1X5, Canada
2- Sorbonne Université, Centre National de la Recherche Scientifique (CNRS), Laboratoire d'Océanographie de Villefranche (LOV), F-06230 Villefranche-sur-Mer, France

It has been recently suggested that a significant amount of information about coccolithophore blooms could be retrieved by analysis of their light polarization properties. In recent optical modeling work we have shown that light backscattering from Emiliania huxleyi coccoliths is dominated by the reflection from their calcite surfaces. Here, we extend our model to include the polarization signal of backscattered light from E. huxleyi liths. Previous investigations using exact numerical Discrete Dipole Approximation models have assumed a single uniform average index of refraction for the multi crystalline calcite material of the liths while in reality calcite is strongly birefringent. We show that this structured birefringence induces significant depolarization effects which are spatially distributed over the surface of the liths. These effects are completely unaccounted for in exact codes. Using the optic axis structure of liths we have developed an approximate model that allows us to evaluate the effect of this internal depolarization on the overall polarized backscattering of E. huxleyi coccoliths and quantify the difference with the backscattering depolarization computed for a material with a single orientation averaged index.

Previous investigations using exact numerical Discrete Dipole Approximation models have assumed a random orientation of the multi crystalline calcite material of the coccoliths of Emiliana huxleyi and used a single uniform average index of refraction to model this. In reality the spatial distribution of the optical axis of the coccoliths is highly structured in a radial pattern. This structure results in a significant measured depolarization in the forward direction which is not accounted for by any model to date. As shown in Figure 1 below we model the liths, as a first approximation, as disks of bi-refringent calcite cristals with radial orientation of their optical axes.

Emiliana Huxleyi bi-refringent crystalline structure with radial orientation



coccosphere coccolith

Figure 1: the images on the right show our approximate disk model with the radial spatial orientation of the optical axes of the crystalline structure outlined in red

Since the particles are large we can separate the contributions of the diffraction, transmission and reflection terms and neglect their mutual interference terms. The resulting formulas are shown in Figure 2 below for the simple case of random crystalline axis orientation modeled by an average index of refraction. For the polarization effect of the diffracted rays that do not penetrate the material of the disk we use the simple dipole form for the Mueller Matrix. For the transmitted rays we again use the dipole form but modified by the polarization induced by the reflection loss. For the reflected rays we use the Mueller Matrix for reflecting surfaces to evaluate the resulting polarization. To obtain the final Mueller matrix the diffraction, transmission and reflection terms are added and unity normalized by integrating their sum over all angles.

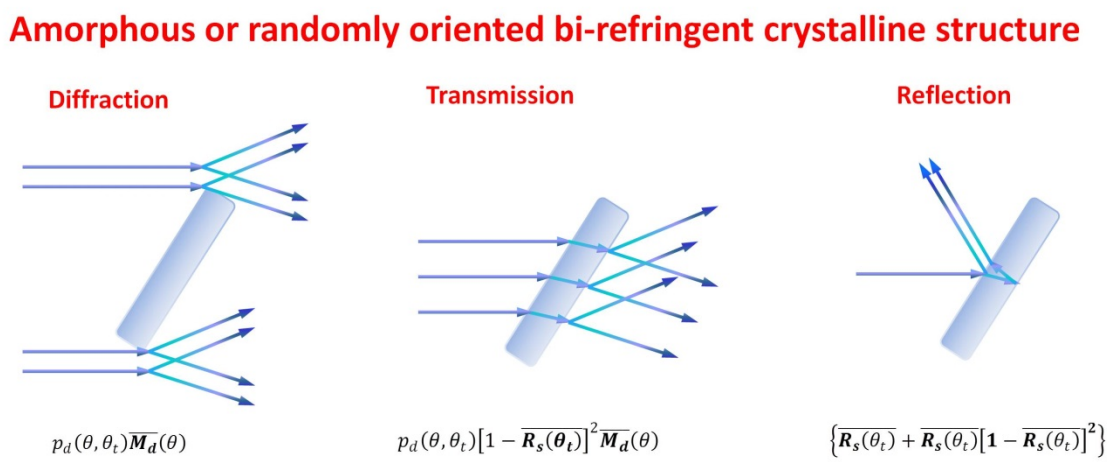


Figure2: diagram of the model separation of the diffraction, transmission and reflection terms. The diffraction phase function is given by $p_d(\theta,\theta_t)$. The dipole Mueller matrix scattering pattern is given by $\overline{\boldsymbol{M_d}}(\theta)$. The surface reflection Mueller matrix is denoted by $\overline{\boldsymbol{R_s}}(\theta_t)$.

In the case of a radial distribution of optical axes model we use the same overall approach as for the random orientation model but with one very significant difference. We account for the polarization rotation induced by the transmission through the birefringent disk which acts as a classic phase shifting plate. This polarization rotation effect is denoted by the flame colored arrows in Figure 3 below. For reference the phase shift Mueller matrix is given by the following term:

$$\Delta\varphi = (n_0 - n_e)\frac{2\,\pi\,L(\tau_d,\theta_t)}{\lambda}$$

$$\delta_t(\tau_d,\theta_t) = \cos\Delta\varphi$$

In the expression above n_0 and n_e are the ordinary and extraordinary indices of refraction of calcite. $L(t_d, \vartheta_t)$ is the ray path length through a disk of thickness t_d tilted at an angle ϑ_t. $\Delta\varphi$ is the polarization phase difference induced by the difference in indices in the directions along and perpendicular to the optical axis.

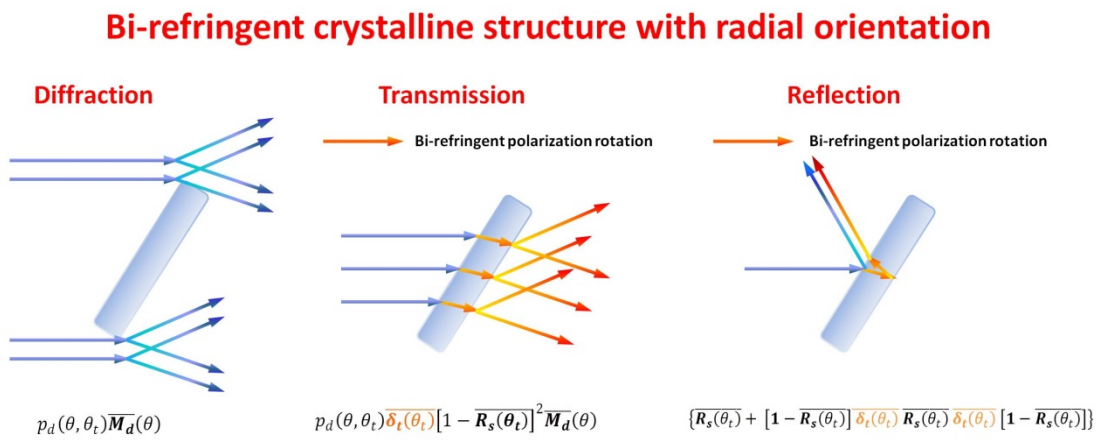


Figure3: diagram of the model separation of the diffraction, transmission and reflection terms. The diffraction phase function is given by $p_d(\theta,\theta_t)$. The dipole Mueller matrix scattering pattern is given by $\overline{\boldsymbol{M_d}}(\theta)$. The surface reflection Mueller matrix is denoted by $\overline{\boldsymbol{R_s}}(\theta_t)$. The depolarization due to the phase change term is denoted by $\overline{\delta_t}(\theta_t)$. The scattered rays that have been depolarized by the phase plate effect are shown in orange.

The graphs on the opposite page in Figure 4 show a side by side comparison of the Mueller matrix elements for disks with a randomly oriented optical axis and for disk with a radial optical axis structure. The randomly oriented case (blue curve) was compared with exact results (yellow curve) from a full T-matrix code [4]. The first element shown is the total phase function $\mathbf{M_{1,1}}$ while the subsequent elements are those of the relative Mueller matrix $\mathbf{m_{i,j}}$ (The elements are the elements of the full Mueller matrix $\mathbf{M_{i,j}}$ divided by $\mathbf{M_{1,1}}$**).** The depolarization effects due to the radial structure of the optical axes is most evident for the $\mathbf{m_{2,2}}$ and the $\mathbf{m_{4,4}}$ elements.

The main conclusion of the present work is that it is imperative that the structural distribution of the optical axes of any calcite coccolith be explicitly accounted for in polarized scattering studies. More seriously this implies that all the modeling results obtained with exact codes that assume a random crystalline orientation are seriously in error. Future models both analytic and numerical need to account explicitly for the structure of the optical axes of the coccoliths. We are pursuing and extending the analytic approach outlined above but exact numerical codes are urgently required as an accuracy check.

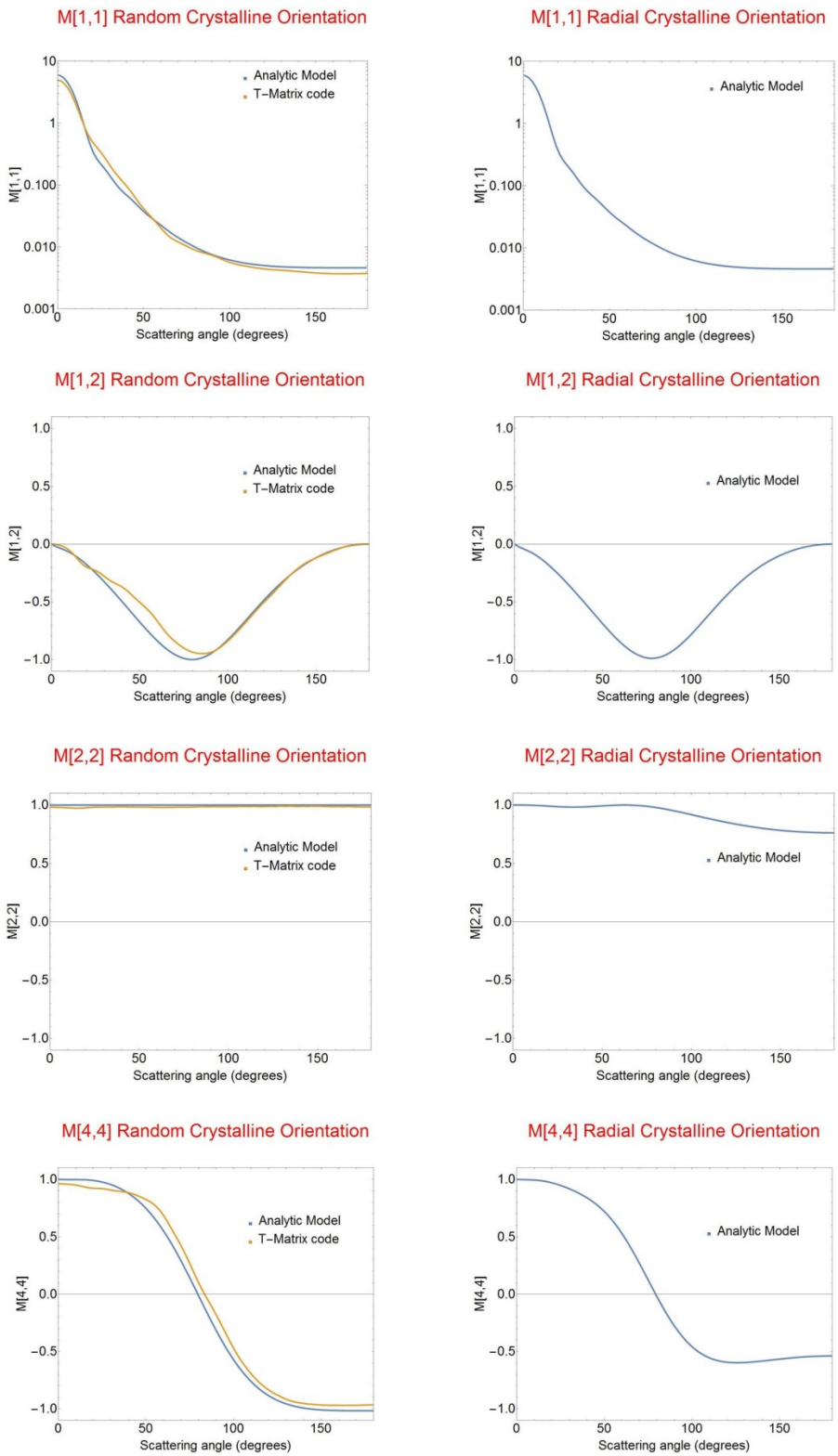


Figure 4: comparative graphs of the Mueller matrix elements for a random orientation of the optical axes and the radial structured orientation of the optical axes found in real *Emiliana huxleyi* coccoliths.

References:

1. Zhai, P.-W., Hu, Y., Trepte, C. R., Winker, D. M., Josset, D. B., Lucker, P. L., et al. (2013). Inherent optical properties of the coccolithophore: Emiliania huxleyi. *Opt. Express* 21, 17625. doi:10.1364/OE.21.017625.
2. Young, J., Geisen, M., Cros, L., Kleijne, A., Sprengel, C., Probert, I., et al. (2003). A guide to extant coccolithophore taxonomy. *J. Nannoplankt. Res. Spec. Issue*.
3. Guay, C. K. H., Bishop, J. K. B. (2002). A rapid birefringence method for measuring suspended CaCO3 concentrations in seawater. *Deep-Sea Research I* 49, 197.
4. Mischenko, M. I., Travis, L.D. (1998) Capabilities and limitations of a current FORTRAN implementation of the T-matrix method for randomly oriented, rotationally symmetric scatterers. *J. Quant. Spectrosc. Radiat. Transfer* 60, No. 3, 309.