Effect of the particle-size distribution on the backscattering ratio in seawater

Osvaldo Ulloa, Shubha Sathyendranath, and Trevor Platt

Mie theory is used to model the backscattering ratio (the ratio of the backscattering coefficient to the total scattering coefficient) of marine particles with the assumption that they follow a Junge-type size distribution. Results show that the backscattering ratio is very sensitive to the presence of submicrometer particles and depends strongly on the shape of the size distribution. However, it is not affected significantly by absorption and does not vary with wavelength over the visible range. The implications for modeling of backscattering and ocean color in terms of phytoplankton pigment concentration are discussed.

1. Introduction

For many problems in optical oceanography, the portion of the light that is scattered in the backward direction with respect to the direction of the incident light is of primary importance. For example, the diffuse reflectance R (or ocean color) has been shown[1,2] to be related to the ratio of the (total) backscattering coefficient b_b to the (total) absorption coefficient a $[R = f(b_b/a)]$. Theoretical and laboratory studies[3,4] indicate that microorganisms, particularly phytoplankton and heterotrophic bacteria, could account for most of the total scattering in case 1 waters, i.e., in waters where phytoplankton and their derived products may be considered to be the main components determining the optical properties of seawater.[2] However, these studies[3,4] show that microorganisms can account for only a small fraction of the backscattering and suggest that most of the backscattering would be due to high concentrations of submicrometer detrital particles of organic origin, a suggestion contained also in early models of light scattering by marine particles.[5–8] But the existence of such particles in large numbers has only been demonstrated recently.[9,10] Furthermore, their optical properties have not been measured so far. It may be expected that, because of their small size and high backscattering efficiency, these particles if present would be major contributors to the backscattering coefficient, but not to the total scattering or absorption coefficients.

The backscattering coefficient is an inherent optical property[11] and can be partitioned according to

$$b_b = b_{\mathrm{bw}} + b_{\mathrm{bp}}, \tag{1}$$

where b_{bw} is the backscattering coefficient of pure seawater and b_{bp} is the backscattering coefficient of particles. In current bio-optical models (e.g., Refs. 12–14), b_{bp} is commonly modeled as

$$b_{\mathrm{bp}} = \tilde{b}_{\mathrm{bp}} \times b_p, \tag{2}$$

where $\tilde{b}_{\mathrm{bp}}$ $(= b_{\mathrm{bp}}/b_p)$ is the particle backscattering ratio and b_p is the scattering coefficient of particles.

The coefficient b_p in Eq. (2) is often modeled as a nonlinear function of the phytoplankton pigment concentration, a decision that is based on empirical evidence,[15] whereas $\tilde{b}_{\mathrm{bp}}$ is assumed to be constant[12] or to covary inversely with the phytoplankton pigment concentration.[13,14] With either of these two assumptions, the backscattering coefficient becomes a function of the pigment concentration; it has been shown that such parameterizations of backscattering in models of reflectance R are able to reproduce observations fairly well. Because phytoplankton is known to contribute significantly to the total scattering coefficient, a relation between b_p and pigments is expected. However, it is not evident why the backscattering ratio, hence the backscattering coefficient, should covary with pigments, particularly if submi-

---

The authors are with the Biological Oceanography Division, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2, Canada. O. Ulloa and S. Sathyendranath are also with the Department of Oceanography, Dalhousie University, Halifax, Nova Scotia B3H 4J1, Canada.

Received 28 September 1993; revised manuscript received 19 April 1994.
0003-6935/94/307070-08$06.00/0.

crometer detrital particles and not phytoplankton are responsible for most of the backscattering.

Some optical properties of marine particles have been studied extensively through the use of Mie theory (e.g., Refs. 3–8). The backscattering ratio has also been studied through the use of Mie theory, but, to our knowledge, only for the case of monodispersions or polydispersions with normal or log-normal size distributions,[16,17] i.e., for the case of a particular class of particles (e.g., phytoplankton) rather than for the total particle suspension. In this study we use Mie theory to study scattering by marine particles, but our emphasis is on changes in the backscattering ratio (rather than on changes in either the scattering coefficient or the backscattering coefficient[3,4]) for particles that follow a power-law (or Junge-type) size distribution. In particular, we examine how changes in the size distribution affect the backscattering ratio. We show that the backscattering ratio is affected by the presence of submicrometer particles (Section 3) and that its magnitude varies strongly with the value of the exponent that determines the shape of the size distribution (Sections 4 and 5). Finally, in Section 7 we examine the implications of these results for modeling the backscattering coefficient and ocean color in terms of the phytoplankton pigment concentration.

2. Backscattering Ratio for Polydispersions

The backscattering ratio $\tilde{b}_{\mathrm{bp}}$ for a collection of particles is given by

$$\tilde{b}_{\mathrm{bp}} = \frac{\int_0^\infty Q_{b_b}(m, x) x^2 f(x) \mathrm{d}x}{\int_0^\infty Q_b(m, x) x^2 f(x) \mathrm{d}x}, \tag{3}$$

where Q_b and Q_{b_b} are the efficiency factors[18] for scattering and backscattering, respectively; $f(x)$ is the probability density function, such that the particle size distribution is $F(x) = Nf(x)$, where N is the total number of particles per unit volume and $\int_0^\infty f(x)\mathrm{d}x = 1$. Also, x is the dimensionless optical size (or size parameter[18]) given by

$$x = \frac{\pi D n_w}{\lambda}, \tag{4}$$

where D is the diameter of the particles, n_w is the refractive index of the medium (i.e., seawater), and λ is the wavelength of light in vacuum. The refractive index of the particles is specified by a complex number

$$m = n - in', \tag{5}$$

where the real part n corresponds to the ratio of the phase velocity of light in the medium to the phase velocity of light inside the particle and the imaginary part n' describes the decrease in electric field strength or the decay of the energy flux.

The efficiency factors Q_b and Q_{b_b} can be computed with Mie theory, if we assume that the particles are spherical and optically homogeneous. Note that in Eq. (3), $\tilde{b}_{\mathrm{bp}}$ does not depend on the absolute number of particles present in the water or in each size class, but only on the shape of the size distribution or the relative abundance between size classes.

The size distribution of the total particle suspension (living and nonliving material) and of the pelagic organisms (living material) in aquatic ecosystems has been shown to be well represented by a power-law (or Junge–type) distribution,[19–22] for which the probability density function $f(D)$ is given by[23]

$$f(D) = KD^{-\xi}, \tag{6}$$

where

$$K = \frac{(\xi - 1)}{(D_{\min}{}^{1-\xi} - D_{\max}{}^{1-\xi})}, \tag{7}$$

$D_{\min}$ and $D_{\max}$ are the lower and upper limits of the size range under consideration, and the exponent ξ is an empirically determined coefficient. For the modeling of the optical properties of seawater, the size distributions of living and nonliving components have to be considered. However, it is not always possible to make the distinction between detritus and organisms, particularly with resistive-pulse particle counters.

For planktonic organisms, the distribution that is often studied is that of the biomass (or biovolume), and it can be shown that when the size distribution follows Eq. (6) the exponent in the normalized biomass spectrum[24] would be $(\xi - 3)$. The latter exponent has been derived theoretically from energetic principles[24] and more recently from a random-encounter model.[25] For total particle-size spectra, the observed[26] range for ξ is from ~ 3 to ~ 5, whereas for living particles[27] it is smaller, from ~ 3.7 to ~ 4.3. Note, however, that the methodology for obtaining size spectra for total particles differs from that used for living particles. For the total particles, a resistive-pulse particle counter is commonly used; for living particles, size measurements are mainly carried out by microscopy, gravimetry, or a combination of both. Furthermore, in most cases only a small segment of the total particle-size spectrum is measured. But, on the basis of the limited information available, we have assumed in our study that a Junge–type distribution with $3 \leq \xi \leq 5$ is valid for the complete size spectrum of the total particulate matter.

Here, we computed the backscattering ratio through Eq. (3) by using Eq. (6) for $f(x)$ (with the corresponding change of variable) and integrating numerically over the optical size range. The efficiency factors Q_b and Q_{b_b} were obtained from Mie theory with a computer code according to Bohren and Huffman.[28] This code does not give Q_{b_b} directly but allows it to be computed by the integration of the given Mie intensity functions over the scattering angles $\pi/2 \leq \theta \leq \pi$. Computations were carried out on a NeXT workstation, which supports the Institute of Electrical and Electronics Engineers floating-point standard. The subroutine DQAGS[29] was used for the numerical integrations in Eq. (3); the relative tolerance error was set at 0.01%.

3. Influence of Submicrometer Particles

The limits of integration in Eq. (3), particularly the lower limit, affect $\tilde{b}_{\mathrm{bp}}$ significantly, because

$$\lim_{x\to 0} f(x) = \lim_{D\to 0} f(D) = \infty. \tag{8}$$

We computed $\tilde{b}_{\mathrm{bp}}$ for different values of $x_{\min}$, or different values of $D_{\min}$ if the wavelength is fixed. Results for $\xi = 4$ are given in Fig. 1(a). They show that the backscattering ratio increases significantly with decrease in $D_{\min}$, particularly when $D_{\min} < 1$ μm, which clearly illustrates the role of submicrometer particles. When $D_{\min}$ falls below ~0.05, μm, the backscattering ratio becomes independent of $D_{\min}$, which indicates that particles with diameters lower than this value do not play any significant role in modification of the backscattering ratio. From these results, the lower limit of integration was chosen to be 0.01 μm. For the upper limit we have

$$\lim_{x\to\infty} f(x) = \lim_{D\to\infty} f(D) = 0, \tag{9}$$

and it was found that particles with $D \geq 100$ μm contribute generally < 1% to the backscattering ratio [Fig. 1(b)]. Here, $D_{\max}$ was fixed at 200 μm.

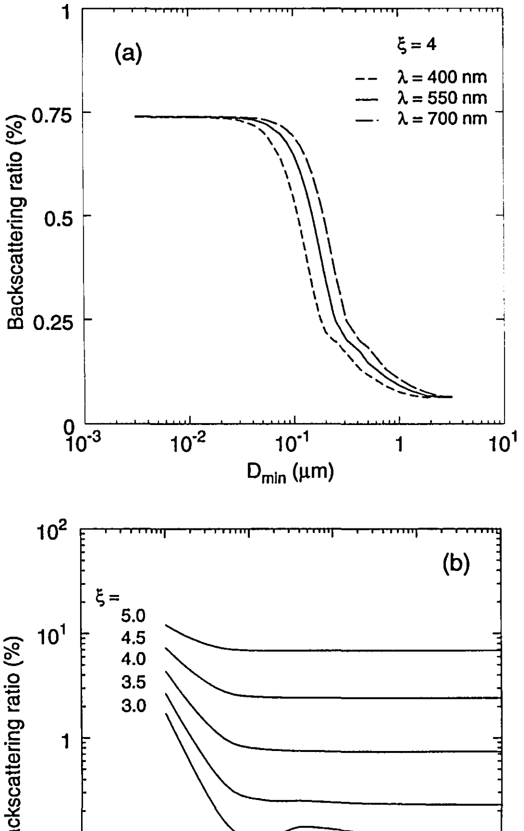

Fig. 1. (a) Effect of the lower limit in the particle-size distribution $D_{\min}$ on the particle backscattering ratio $\tilde{b}_{\mathrm{bp}}$ for $m = 1.05\text{–}0.001i$ and $D_{\max} = 200$ μm. The results are given for three wavelengths (λ) in the visible range. (b) Effect of the maximum particle diameter of the size distribution $D_{\max}$ on the particle-backscattering ratio.

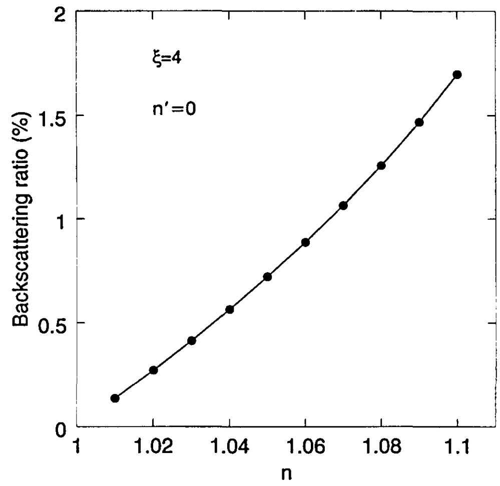

Fig. 2. Effect of the real part of the refractive index n on the backscattering ratio $\tilde{b}_{\mathrm{bp}}$.

4. Influence of the Refractive Index and the Wavelength

The particle backscattering ratio $\tilde{b}_{\mathrm{bp}}$ was computed for different values of n and n', the real and imaginary parts, respectively, of the refractive index m [Eq. (5)]. Figure 2 shows that $\tilde{b}_{\mathrm{bp}}$ increases with n. Results for monodispersions[16] have shown that the backscattering ratio for small particles ($x \lesssim 2$ or $D \lesssim 0.25$ μm at $\lambda = 550$ nm) is almost independent of the refractive index (both the real and imaginary parts), while for larger particles it is strongly dependent on n. It may therefore be surmised that the increase of $\tilde{b}_{\mathrm{bp}}$ with n seen in Fig. 2 is attributable to the relative increase in the backscattering ratio of large particles, whereas the contribution from small particles themselves remains stable.

Contrary to the cases for monodispersions or for polydispersions with a normal or log-normal distribution,[16] we found that the backscattering ratio increases with n' for a given n (Fig. 3), for $n' \gtrsim 10^{-2}$. Below this value the backscattering ratio is almost independent of n'. Even strongly absorbing particles like phytoplankton[17] will have values of $n' \leq 10^{-2}$, so that we can consider $n' = 10^{-2}$ to be an upper limit for the total particle suspension in seawater. Therefore, the variation in $\tilde{b}_{\mathrm{bp}}$ that results from absorption (i.e., from n') would be negligible for natural seawater samples. In the results presented below, the imaginary part was fixed at 10^{-3}. A

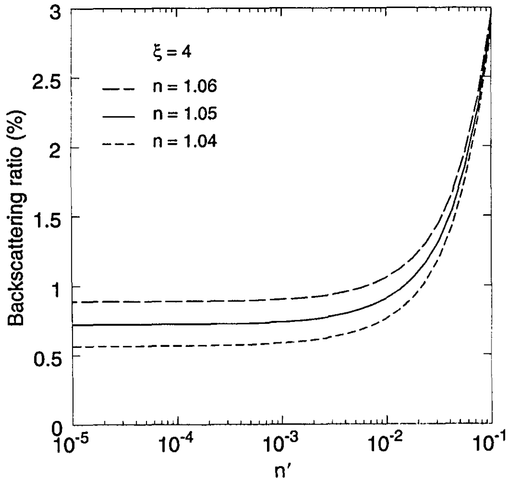

Fig. 3. Effect of the imaginary part of the refractive index n' on the backscattering ratio $\tilde{b}_{bp}$.

typical bulk value for the real part of the refractive index of the particles was chosen to be 1.05, which is typical of organic matter,[3–8] but computations were carried out for other values of n as well, for comparison.

Figure 4 shows that for particles that obey a power-law distribution the backscattering ratio does not vary with wavelength over the visible range. These results contrast with those for monodispersions,[16,17] which show that $\tilde{b}_{bp}$ can vary strongly with wavelength, depending on the size of the particles and their refractive index. They also suggest that the wavelength dependence of the particle backscattering coefficient will be similar to that of the scattering coefficient. According to Morel,[8] this dependence is $\lambda^{(3-\xi)}$ for particles with a Junge-type size distribution and exponent ξ.

5. Influence of the Shape of the Size Distribution

After the limits of integration have been fixed, as discussed previously, changes in the size distribution $f(D)$ [Eq. (6)] can only occur through changes in the exponent ξ. Values of $\tilde{b}_{bp}$ were computed for the range of values reported for ξ in the literature. Results show (Fig. 5) that $\tilde{b}_{bp}$ is highly dependent on ξ and that this dependence increases with n. The strong variation of $\tilde{b}_{bp}$ with ξ suggests that differences in the backscattering ratio in natural waters can arise from changes in the shape of the size distribution of the total particle suspension. Waters with a higher ξ (a more negative slope in a log–log plot) will have higher backscattering ratios, and vice versa.

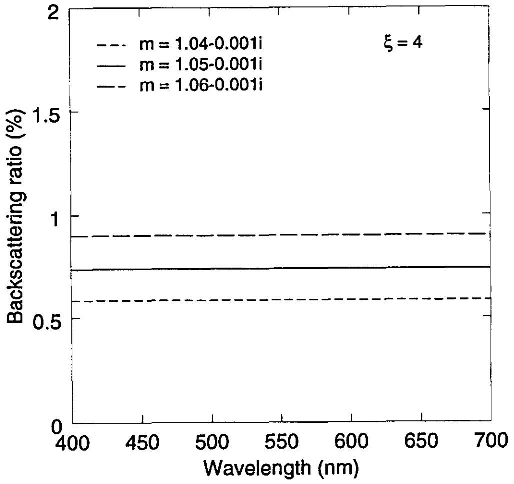

Fig. 4. The backscattering ratio $\tilde{b}_{bp}$ as a function of wavelength for particles with a Junge-type size distribution and a diameter range $0.01 \leq D \leq 200$ μm.

6. Backscattering Ratio and Pigment Concentration

In conventional bio-optical models the backscattering coefficient is modeled as a function of phytoplankton pigment concentration through the product of the backscattering ratio and the scattering coefficient [Eq. (2)]. Although the scattering coefficient has been shown to covary with pigments,[15] the backscattering ratio has ient has been little studied, and it is assumed either to be constant[12] or to covary inversely with phytoplankton pigments.[13,14] No direct empirical evidence has been presented yet to support a dependence of backscattering on pigment concentration. Here we discuss some indirect evidence based on comparisons between measured and modeled reflectance spectra.

Sathyendranath *et al.*[30] presented a model of reflectance R that considered the presence of phytoplankton, yellow substances, and nonchlorophyllous particles in seawater. They used a relation of the form[2]

$$R(\lambda) = 0.33\,\frac{b_b(\lambda)}{a(\lambda)} \tag{10}$$

to model the diffuse reflectance at a wavelength λ, where b_b is the total backscattering coefficient and a is the total absorption coefficient.

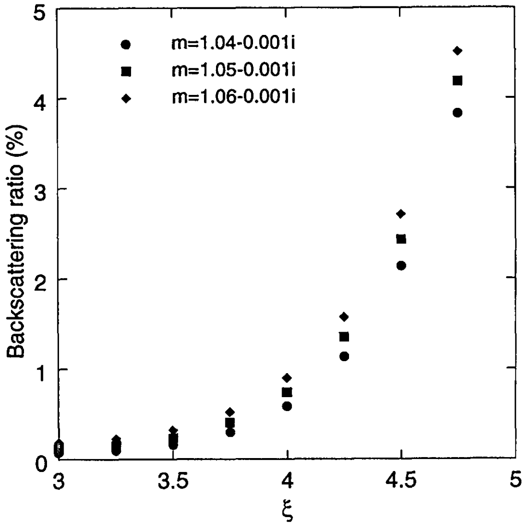

Fig. 5. Effect of the exponent ξ in the Junge-type size distribution on the backscattering ratio $\tilde{b}_{bp}$ for different values of the refractive index m.

The total absorption coefficient, in turn, is expressed as the sum of contributions from pure seawater, phytoplankton, nonchlorophyllous particles and yellow substances. The total backscattering coefficient is partitioned into contributions from pure seawater, phytoplankton, and nonchlorophyllous particles, according to

$$b_b = b_{\mathrm{bw}} + \tilde{b}_{\mathrm{bc}} b_c + \tilde{b}_{\mathrm{bx}} b_x, \tag{11}$$

where $\tilde{b}_{\mathrm{bc}}$ and $\tilde{b}_{\mathrm{bx}}$ are the backscattering ratios of phytoplankton and nonchlorophyllous particles, respectively. The magnitude of $\tilde{b}_{\mathrm{bc}}$ is assumed to be constant and equal to 0.5%, and b_c at 550 nm is assumed to be a function of the pigment concentration C, according to[15]

$$b_c[550] = 0.12C^{0.62}, \tag{12}$$

where b_c is in reciprocal meters and C is in milligrams per cubic meter. The values of b_x in Eq. (11) are obtained by subtraction of b_c and b_w from measured values of b, and the values of $\tilde{b}_{\mathrm{bx}}$ (plus the concentration of yellow substances and a parameter that specifies the wavelength dependence of the scattering coefficient) are obtained by iteration, when theoretical reflectance spectra are fitted to those that are measured.

Figure 6(a) shows the derived values of $\tilde{b}_{\mathrm{bx}}$ plotted against the measured pigment concentration for waters that are believed to be case 1. The observed inverse relationship between $\tilde{b}_{\mathrm{bx}}$ and pigment concentration suggests that waters with low pigment concentrations have higher backscattering ratios of nonchlorophyllous particles than do pigment-rich waters. A similar relationship holds if the total particle suspension (phytoplankton + nonchlorophyllous particles) is considered [Fig. 6(b)]. If the particles in these waters follow a Junge-type distribution, these results suggest that phytoplankton-rich waters are characterized by lower values of ξ than oligotrophic waters (compare with Fig. 5). The backscattering ratio of total particles was computed as

$$\tilde{b}_{\mathrm{bp}} = \tilde{b}_{\mathrm{bc}} \chi + \tilde{b}_{\mathrm{bx}}(1 - \chi), \tag{13}$$

where $\chi = b_c/b_p$. Linear regression of the particle backscattering ratio in percent on the logarithm of pigment concentration in milligrams per cubic meter gives

$$\tilde{b}_{\mathrm{bp}} = 0.78 - 0.42 \log_{10} C. \tag{14}$$

This expression is consistent with the models of Morel[13] and Gordon *et al.*[14]

7. Discussion

A. Influence of Small Particles

Here, the backscattering ratio for marine particles has been modeled with Mie theory. It has been shown that, if the size distribution of particles varies according to $D^{-\xi}$, the backscattering ratio is largely controlled by submicrometer particles and that its magnitude does not vary with wavelength, nor is it significantly affected by absorption. Note that it is essential to include submicrometer particles to obtain the magnitudes of backscattering ratios ($\geq 0.2\%$) that have been deduced from observations[2,31] [Fig. 1(a)]. Moreover, our results indicate that the backscattering ratio varies strongly with the parameter ξ. These results, however, are highly dependent on the assumption that the size distribution that is adopted is valid for particles smaller than 1 µm. Direct evidence for the existence of large concentrations of submicrometer particles has only recently been obtained,[9,10] but their existence has been predicted by optical models since the early 1970s.[5-8]

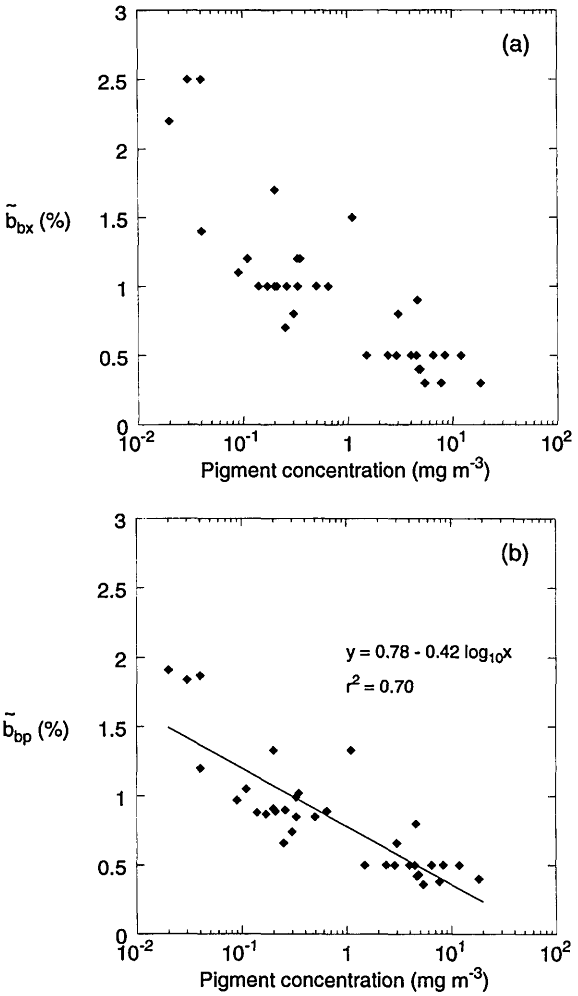

Fig. 6. (a) The backscattering ratio of nonchlorophyllous particles $\tilde{b}_{\mathrm{bx}}$ as a function of phytoplankton pigment concentration (chlorophyll *a* + phaeopigments). The $\tilde{b}_{\mathrm{bx}}$ values were derived when a model of reflectance was fitted to observed reflectance spectra.[30] (b) The backscattering ratio of total particles $\tilde{b}_{\mathrm{bp}}$ for the same data set [obtained from Eq. (13) in the text] as a function of pigment concentration. The stations plotted represent case 1 waters and correspond to the cruises of Antiprod, Discoverer, and Cineca V (Ref. 30). Stations 16, 35, 47, and 72 of the Cineca V cruise were excluded because they seem to be in case 2 waters.

Gordon and Brown[5] found that Kullenberg's[32] data on the volume scattering function $\beta(\theta)$ at 632.8 nm could be reproduced using a Junge–type particle size distribution, with $\xi = 4$ and a single value for the refractive index $m = 1.05–0.01i$, which is typical of organic particles. They did not have simultaneous measurements of the size distribution, but they used other particle-size data for the region[19] in which no measurements were available below 1 μm. However, to reproduce the observed backscattering $[\beta(\theta > 90°)]$ they had to extrapolate the observed size distribution into the submicrometer region. Subsequently, Brown and Gordon[6] used a two-component model (organic particles with $m = 1.01–0.01i$ and $0.1 \leq D \leq 2.5$ μm, and inorganic particles with $m = 1.15$ and $2.5 \leq D \leq 10$ μm, both with $\xi = 4$) to reproduce Kullenberg's data. Their results still showed that a large fraction of the suspended particle volume had to consist of small organic particles. Later, Brown and Gordon[7] used simultaneous measurements of the size distribution and the volume scattering function to study the problem; the lower limit in their size-measurement (Coulter Counter) data was 0.65 μm. They could reproduce the volume scattering function at 488 nm using a three-component model, with inorganic particles in the middle-size class ($1.25 \leq D \leq 3.75$ μm) and organic particles in two classes of small and large sizes ($0.65 \leq D \leq 1.25$ μm and $3.75 \leq D \leq 17.0$ μm, respectively). However, the model could not reproduce the variation of $\beta(\theta)$ with wavelength. To achieve this, they had to include smaller particles of organic origin, or inorganic particles with a much smaller value for ξ. Regarding the small organic particles, they wrote: ". . . The prediction of the existence of vast quantities of small organic particles cannot be verified at this time, since little is known about sea water organics in these small sizes."[7] Morel,[8] on the other hand, found that the average of several measured phase functions (or normalized volume scattering functions) for marine particles could be reproduced with a Junge–type distribution with $\xi = 4$, $m = 1.05$, and $0.2 \leq x \leq 100$, i.e., with the implicit assumption of the presence of submicrometer particles that followed the same distribution as the larger particles.

Recently, Morel and Ahn[3] and Stramski and Kiefer[4] showed that, if particles obey a Junge–type distribution with $\xi \approx 4$, most of the total scattering would be due to particles with $1 \lesssim D \lesssim 10$ μm, whereas most of the backscattering would be due to particles <1 μm. Although phytoplankton abundance, size ranges, and optical properties are such that they can contribute significantly to the total scattering coefficient, they could not account for the required backscattering. Furthermore, heterotrophic bacteria, which are in the submicrometer size range and are present in numbers that are at least an order of magnitude higher than phytoplankton, could account for only a certain fraction of the backscattering coefficient, but not for most of it. Both groups suggested that the possible component responsible for most of the backscattering in the ocean is very small, organic, detrital particles.

If indeed submicrometer particles are the main contributors to the backscattering in the ocean, the implications for our understanding of optical processes in the ocean are significant, as it is commonly assumed that phytoplankton determines the optical properties of seawater, and optical properties are usually modeled in terms of phytoplankton pigment concentration.[12–14] However, theoretical results, including those presented here, stress the importance of extremely small particles other than phytoplankton. Note that the lower end of detection of the resistive-pulse particle counters currently[10] used to characterize these submicrometer particles is not better than 0.32 μm, while the theoretical computations carried out here (and those discussed above) require that the abundance of small particles continues to increase as the diameter diminishes to at least 0.1 μm [Fig. 1(a)].

Examination of submicrometer particles by transmission electron microscopy and energy-dispersive spectroscopy[33] has shown that they are mainly of organic nature, that their greatest abundance occurs in the <0.12-μm size fraction, and that they follow a power-law size distribution. However, the extent to which particle sizes are altered as a result of the sample processing (e.g., as a result of dehydration) required in these techniques is not known.

The use of Mie theory to describe the backscattering ratio was based on the assumption that marine particles are spherical particles, which is not strictly the case. Theoretical analysis of the light-scattering properties of nonspherical particles[34,35] shows that their optical properties deviate from those of spheres of the same volume, particularly as the optical size (x) increases. Furthermore, the magnitude of the deviations is much greater when large-angle ($>90°$) scattering is considered.[34,35] However, for randomly oriented nonspherical particles with sizes lower than the first maximum in the scattering curve (Q_b versus x) for spheres, results[34] show that the efficiency factors and other optical properties, including the backscattering ratio,[35] are primarily dependent on the size and weakly dependent on the shape, and therefore are very close to those properties for spheres. Thus, considering that the backscattering ratio is largely controlled by submicrometer particles [Fig. 1(a)] and that the sizes of submicrometer particles of organic origin clearly lie below the first maximum in the scattering curve, we expect the errors that are introduced by assuming sphericity when computing the backscattering ratio to be much lower for the total particle suspension than for individual particles or particles with a narrow size distribution.

Rather than emphasizing the magnitudes, however, we wish to stress our conclusion that a major source of variability in the backscattering ratio would be the shape of the total particle-size distribution, parameterized here by the coefficient ξ in the Junge–type distribution. As mentioned earlier, the backscattering ratio is commonly used to estimate the backscattering coefficient from the total scattering coefficient, because a large body of experimental results exists that relates the total scattering coefficient's variation to that in the phytoplankton pigment concentration.[15] Here, the approach has been to study the dimensionless backscattering ratio for the total particle population, about which we know much less, to understand the sources of its variability and to examine whether the assumption of its dependence on pigment concentration[12,13] has any theoretical or empirical justification.

B. Relation Between ξ and Chlorophyll

Sprules and Munawar[27] analyzed biomass size spectra from different lakes and included the results of Rodriguez and Mullin[22] for the Central Gyre in the North Pacific for comparison. Their compilation showed that ξ decreases (the slope becomes more positive) with increasing chlorophyll concentration. Kitchen, Zaneveld, and Pak[36] also found a significant negative correlation between the exponent in the total particle-size distribution and chlorophyll concentration. Their size measurements were carried out with a resistive-pulse particle counter that covered equivalent spherical diameters between 1.6 and 32 μm.

The empirical studies on living and total particles that were mentioned above suggest that an inverse relation exists between the coefficient ξ and chlorophyll concentration when comparisons are made across ecosystems. (Note that an inverse relation between ξ and pigment concentration is not necessarily true for vertical profiles.) The strong direct relationship between ξ and $\tilde{b}_{bp}$ (Fig. 5) evident in our results may then imply an inverse relation between the backscattering ratio and chlorophyll concentration. This inverse relation is also deduced when theoretical and observed reflectance spectra are compared (Figs. 6). Therefore, even if most of the backscattering is due to nonphytoplanktonic particles of very small size, the backscattering ratio would vary inversely with chlorophyll concentration because of the inverse relation between the slope of the size distribution and the chlorophyll concentration. Note, however, that no such relation has yet been shown to exist for the size range comprising submicrometer particles. An inverse relation between ξ and pigment concentration also implies that in waters with lower pigment concentrations, the backscattering coefficient should vary more strongly with wavelength than it does in pigment-rich waters. This is because the particle backscattering ratio will not vary with wavelength (Section 4) and the scattering coefficient will vary according to $\lambda^{3-\xi}$ (Ref. 8).

Recently, Kitchen and Zaneveld[37] showed that by using a model of three-layered spheres for phytoplankton they could reproduce measured volume scattering functions[31] of natural seawater samples. They obtained higher backscattering than with a model for homogeneous spheres with the same size distribution. Their computations, however, did not take into account particles with diameter <0.6 μm, and their results have not yet been reconciled with laboratory measurements,[38] which show that phytoplankton have very low backscattering efficiencies.

Optical models used for the study of ocean color by remote sensing[12–14] are based on the assumption that a relation exists between the backscattering coefficient and the phytoplankton pigment concentration. On the other hand, theoretical studies suggest that most of the backscattering would be due to submicrometer detrital particles and not to phytoplankton. Here we have offered an explanation for this apparent contradiction: An inverse relation between the backscattering ratio and phytoplankton pigment concentration is possible if there is an inverse relation between pigments and the exponent (i.e., shape) of the total particle-size distribution, which in turn is the principal control on the backscattering ratio.

The work presented in this paper was supported by the U.S. Office of Naval Research, the National Aeronautics and Space Administration, the Department of Fisheries and Oceans, Canada, and the Canadian Department of National Defence. Additional support was provided by the International Development Research Centre (Canada) to O. Ulloa and by the Natural Sciences and Engineering Research Council (Canada) through operating grants to S. Sathyendranath and T. Platt. We thank G. N. White III for technical assistance with the computations and H. R. Gordon and two unknown referees for useful comments on the manuscript. This work was carried out as part of the Canadian contribution to the Joint Global Ocean Flux Study.

References

1. H. R. Gordon, O. B. Brown, and M. M. Jacobs, "Computed relationships between the inherent and apparent optical properties of a flat homogeneous ocean," Appl. Opt. **14,** 417–427 (1975).
2. A. Morel and L. Prieur, "Analysis of variations in ocean color," Limnol. Oceanogr. **22,** 709–722 (1977).
3. A. Morel and Y.-H. Ahn, "Optics of heterotrophic nanoflagellates and ciliates: a tentative assessment of their scattering role in oceanic waters compared to those of bacteria and algal cells," J. Mar. Res. **49,** 177–202 (1991).
4. D. Stramski and D. A. Kiefer, "Light scattering by microorganisms in the open ocean," Prog. Oceanogr. **28,** 343–383 (1991).
5. H. R. Gordon and O. B. Brown, "A theoretical model of light scattering by Sargasso Sea particles," Limnol. Oceanogr. **17,** 826–832 (1972).
6. O. B. Brown and H. R. Gordon, "Two component Mie scattering models of Sargasso Sea particles," Appl. Opt. **12,** 2461–2465 (1973).
7. O. B. Brown and H. R. Gordon, "Size-refractive index distribution of clear coastal water particulates from light scattering," Appl. Opt. **13,** 2874–2881 (1974).
8. A. Morel, "Diffusion de la lumière par les eaux de mer. Résultats expérimentaux et approche théorique," in *Optics of the Sea,* AGARD Lect. Ser. **63,** 3.1.1–3.1.76 (1973).
9. I. Koike, S. Hara, T. Terauchi, and K. Kogure, "Role of submicrometer particles in the ocean," Nature (London) **345,** 242–244 (1990).
10. A. R. Longhurst, I. Koike, W. K. W. Li, J. Rodriguez, P. Dickie, P. Kepkay, F. Partensky, B. Bautista, J. Ruiz, M. Wells, and

D. F. Bird, "Submicron particles in northwest Atlantic shelf water," Deep-Sea Res. **39,** 1–7, (1992).

11. R. W. Preisendorfer, "Application of radiative transfer theory to light measurements in the sea," Monogr. Int. Union Geod. Geophys. Paris **10,** 11–30 (1961).
12. S. Sathyendranath and T. Platt, "The spectral irradiance field at the surfaces of the ocean: a model for application and in the interior in oceanography and remote sensing," J. Geophys. Res. **93,** 9270–9280 (1988).
13. A. Morel, "Optical modeling in the upper ocean in relation to its biogenous matter content (Case I waters)," J. Geophys. Res. **93,** 10749–10768 (1988).
14. H. R. Gordon, O. B. Brown, R. H. Evans, J. W. Brown, R. C. Smith, K. S. Baker, and D. K. Clark, "A semianalytic radiance model of ocean color," J. Geophys. Res. **93,** 10909–10924 (1988).
15. A. Morel, "In-water and remote measurements of ocean color," Boundary Layer Meterol. **18,** 177–201 (1980).
16. A. Morel and A. Bricaud, "Theoretical results concerning the optics of phytoplankton, with special reference to remote sensing applications," in *Oceanography from Space,* J. F. R. Gower, ed. (Plenum, New York, 1981), pp. 313–327.
17. A. Morel and A. Bricaud, "Inherent optical properties of algal cells including picoplankton: theoretical and experimental results," Can. Bull. Fish. Aquat. Sci. **214,** 521–559 (1986).
18. H. C. van de Hulst, *Light Scattering by Small Particles* (Wiley, New York, 1957).
19. H. Bader, "The hyperbolic distribution of particles sizes," J. Geophys. Res. **75,** 2822–2830 (1970).
20. R. W. Sheldon, A. Prakash, and W. H. Sutcliffe, Jr., "The size distribution of particles in the ocean," Limnol. Oceanogr. **17,** 327–340 (1972).
21. T. Platt, M. Lewis, and R. Geider, "Thermodynamics of the pelagic ecosystem: elelementary closure conditions for biological production in the open ocean," in *Flows of Energy and Material in Marine Ecosystems,* M. J. R. Fasham, ed. (Plenum, New York, 1984), pp. 49–84.
22. J. Rodriguez and M. Mullin, "Relation between biomass and body weight of plankton in a steady-state oceanic ecosystem," Limnol. Oceanogr. **31,** 361–370 (1986).
23. K. S. Shifrin, *Physical Optics of Ocean Water* (American Institute of Physics, New York, 1988).
24. T. Platt and K. Denman, "Organization in the pelagic ecosystem," Helgol. Wiss. Meeresunters. **30,** 575–581 (1977).
25. D. A. Kiefer and J. Berwald, "A random encounter model for the microbial planktonic community," Limnol. Oceanogr. **37,** 457–467 (1992).
26. M. Jonasz, "Particle-size distributions in the Baltic," Tellus **35B,** 346–358 (1983).
27. W. G. Sprules and M. Munawar, "Plankton size spectra in relation to ecosystem productivity, size, and perturbation," Can. J. Fish. Aquat. Sci. **43,** 1789–1794 (1986).
28. C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles* (Wiley, New York, 1983).
29. A. H. Morris, Jr., "NSWC library of mathematics subroutines," Rep. NSWC TR 90–21 (Naval Surface Warfare Center, Dahlgren, Va., 1990).
30. S. Sathyendranath, L. Prieur and A. Morel, "A three-component model of ocean colour and its application to remote sensing of phytoplankton pigments in coastal waters," Int. J. Remote Sensing **10,** 1373–1394 (1989).
31. T. J. Petzold, "Volume scattering functions for selected ocean waters," SIO Ref. 72–78, 72–79 (Scripps Institution of Oceanogrpahy, La Jolla, Calif., 1972).
32. G. Kullenberg, "Scattering of light by Sargasso Sea water," Deep-Sea Res. **15,** 423–432 (1968).
33. M. L. Wells and E. D. Goldberg, "Marine submicron particles," Mar. Chem. **40,** 5–18 (1992).
34. S. Asano and M. Sato, "Light scattering by randomly oriented spheroidal particles," Appl. Opt. **19,** 962–974 (1980).
35. A. Mugnai and W. J. Wiscombe, "Scattering from nonspherical Chebyshev particles. 1: Cross sections, single-scattering albedo, asymmetry factor, and backscattered fraction," Appl. Opt. **25,** 1235–1244 (1985).
36. J. C. Kitchen, J. R. V. Zaneveld, and H. Pak, "Effect of particle size distribution and chlorophyll content on beam attenuation spectra," Appl. Opt. **21,** 3913–3918 (1982).
37. J. C. Kitchen and J. R. V. Zaneveld, "A three-layered sphere model of optical properties of phytoplankton," Limnol. Oceanogr. **37,** 1680–1690 (1992).
38. Y.-H. Ahn, A. Bricaud, and A. Morel, "Light backscattering efficiency and related properties of some phytoplankters," Deep-Sea Res. **39,** 1835–1855 (1992).