WEAK PHOTON LOCALIZATION AND OPPOSITION PHENOMENA IN PLANETARY ASTROPHYSICS

M. Mishchenko and N. Zakharova

NASA Goddard Institute for Space Studies
2880 Broadway, New York, NY 10025, USA
e-mail: crmim@giss.nasa.gov

Coherent backscattering of light by discrete random media, otherwise known as weak photon localization, is a remarkable optical phenomenon caused by constructive interference of waves propagating along the same light-scattering paths but in opposite directions. This paper briefly reviews manifestations of coherent backscattering and the use of this phenomenon as a remote sensing tool.

INTRODUCTION

Coherent backscattering is a remarkable phenomenon caused by constructive interference of waves propagating along reciprocal multiple-scattering paths in a discrete random medium [2, 7]. A well-known manifestation of coherent backscattering is an intensity peak centered at exactly the backscattering direction. The magnitude of the peak relative to the incoherent background depends on the polarization states of the incident and reflected beams and can be as large as a factor of 2 when the scattering particles are spherically symmetric, the incident beam is circularly polarized, and the intensity of the reflected beam is measured in the same-helicity channel [9]. Another manifestation of coherent backscattering can be observed when the incident beam is unpolarized. In this case the backscattering intensity peak is accompanied by a sharp asymmetric peak of negative polarization with a minimum centered at a very small phase angle (the angle between the reflected beam and the backscattering direction) [10]. This phenomenon has been called the polarization opposition effect [10] and has the same physical origin as the so-called spatial anisotropy of the backscattering intensity peak in the case of a linearly polarized incident beam [21].

It has been suggested that coherent backscattering could be a contributor to some effects observed for Solar System bodies in visible light and at radiowave frequencies [15, 17, 19]. However, accurate theoretical computations of weak localization are difficult and have been used in analyses of observational data in only a handful of publications. In this paper we briefly review the exact theory of coherent backscattering and its remote sensing applications.

THEORY

To explain the physical origin of weak photon localization, let us consider a layer composed of discrete, randomly positioned scattering particles and illuminated by a parallel beam of light incident in the direction $\hat{n}_{ill}$ (Fig. 1). The observer measures the intensity of light reflected by the layer in the direction $\hat{n}_{obs}$. The reflected signal is contributed to by waves scattered along various paths inside the layer involving different combinations of particles. Let us consider two conjugate scattering paths shown in Fig. 1 by solid and dashed lines. These paths go through the same group of N particles, denoted by their positions $\mathbf{r}_1$, $\mathbf{r}_2$, ..., $\mathbf{r}_N$, but in opposite directions. The waves scattered along the two conjugate paths interfere, the interference being constructive or destructive depending on the phase difference $\mathrm{k}(\mathbf{r}_N - \mathbf{r}_1)(\hat{n}_{ill} + \hat{n}_{obs})$, where k is the wave number in the surrounding medium. If the observation direction is far from the exact backscattering direction given by $-\hat{n}_{ill}$, then the waves scattered along conjugate paths involving different groups of particles interfere in different ways, and the average effect of interference is zero due to the randomness of particle positions. Consequently, the observer measures some average, incoherent intensity well described by the classical radiative transfer theory. However, at exactly the backscattering direction ($\hat{n}_{obs} = -\hat{n}_{ill}$), the phase difference between conjugate paths involving any group of particles is identically equal to zero and the interference is always constructive, thereby resulting in a coherent backscattering intensity peak [2]. Kuga and Ishimaru [6] were the first to measure this effect in a controlled laboratory experiment, although it may have been unknowingly observed by Lyot [8] in the form of the so-called coherent polarization opposition effect [10, 14].

Exact computation of the coherent backscattering effect based on solving the Maxwell equations is feasible only for few-particle clusters and is complicated by several factors. First, the scattering pattern for a monodisperse cluster in a fixed orientation is always heavily burdened by multiple interference maxima and minima and by an intricate resonance structure typical of single monodisperse spheres. Second, the scattering pattern is further affected by near-field effects that result from component spheres in a closely packed cluster not being in the far-field zones of each other. Third, simple trigonometry shows that the angular width of the coherent backscattering intensity peak is of the order of $1/k\langle d\rangle = \lambda/2\pi\langle d\rangle$, where $\langle d\rangle$ is the average distance between the cluster components and λ is the wavelength in the surrounding medium. Therefore, this peak may be too broad to be reliably identified unless the cluster components are separated widely enough. However, increasing the distance between the cluster components diminishes the contribution of multiple scattering and, thus, the amplitude of the coherent backscattering peak, thereby making it difficult to detect. To smooth the effect of the first factor out and make the backscattering peak detectable, the scattering pattern must be averaged over particle sizes, cluster orientations, and distances between the components. Furthermore, the average distance between the cluster components must be much larger than the size of the components and the wavelength, but yet small enough so that the multiple-scattering contribution to the total signal be still significant.

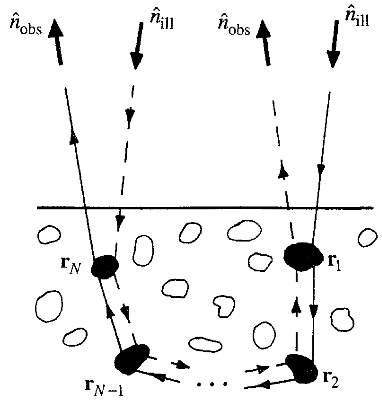

Figure 1: Schematic explanation of coherent backscattering

Ismagilov and Kravtsov [5] studied analytically the simplest case of two widely separated spheres with diameters much smaller than the wavelength, but found that the amplitude of the coherent backscattering intensity peak was extremely small because of the weakness of the multiple-scattering contribution to the total scattered signal. Mishchenko [12] applied the exact superposition T-matrix method to polydisperse, randomly oriented clusters composed of two equal wavelength-sized spheres. He computed the ratio of intensities scattered by the clusters and by two independent spheres of the same size assuming that the incident light was unpolarized. Figure 2 shows this ratio versus scattering angle (angle between the incident and scattered beams) calculated for $k\langle d\rangle = 25$, average component sphere size parameter $k\langle a\rangle = 5$, where a is the sphere radius, and relative refractive index $m = 1.2$. The curve clearly shows an enhancement of intensity with an angular width comparable to $1/k\langle d\rangle$ and an amplitude of about 1.03. Mishchenko [12] found that this feature persisted with varying $k\langle d\rangle$, $k\langle a\rangle$, and refractive index, thereby indicating that it was indeed caused by coherent backscattering.

The amplitude of the coherent backscattering peak can be significantly greater for very large collections of particles [21, 11]. Unfortunately, the exact theory of coherent backscattering for such collections is extremely complicated and has been developed only for the case of reflection of light by a semi-infinite layer composed of particles with sizes much smaller than the wavelength [1]. Mishchenko *et al.* [14] used this theory to compute the characteristics of coherent backscattering. They assumed unpolarized incident light and defined the intensity enhancement factor as the ratio of the total reflected intensity to the incoherent background value. The degree of linear polarization was defined as minus the ratio of the total reflected second Stokes parameter to the total reflected intensity. Figure 3 shows both quantities as functions of a dimensionless angular parameter q. The upper panel demonstrates the renowned intensity peak centered at exactly the opposition. The amplitude of the peak is ≈ 1.5368 and its half-width at half-maximum is ≈ 0.597. The lower panel of Fig. 3 shows that the reflected polarization is zero at opposition, which is a consequence of azimuthal symmetry in the case of normal illumination and unpolarized incident light. However, with increasing q, polarization becomes negative, rapidly grows in absolute value, and reaches its minimal value $P_{min} \approx -2.765\%$ at a reflection direction very close to opposition ($q_P \approx 1.68$). The peak of negative polarization is highly asymmetric so that the half-minimal polarization value -1.383% is first reached at $q_{P,1} \approx 0.498$, which is even smaller than the value

$q_\zeta \approx 0.597$ corresponding to the half-width at half-maximum of the backscattering intensity peak, and then at a much larger $q_{P,2} \approx 7.10$. This unusual behavior of polarization at near-backscattering angles was called in [10] the polarization opposition effect (POE).

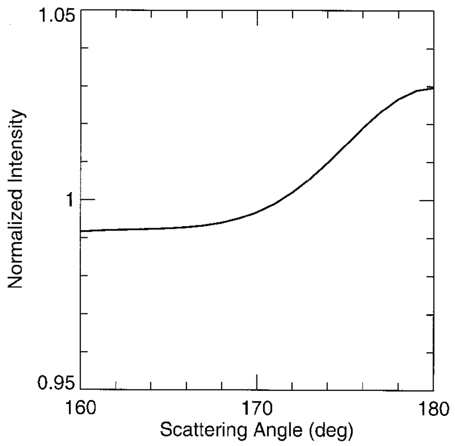

Figure 2: Coherent backscattering by polydisperse, randomly oriented two-sphere clusters

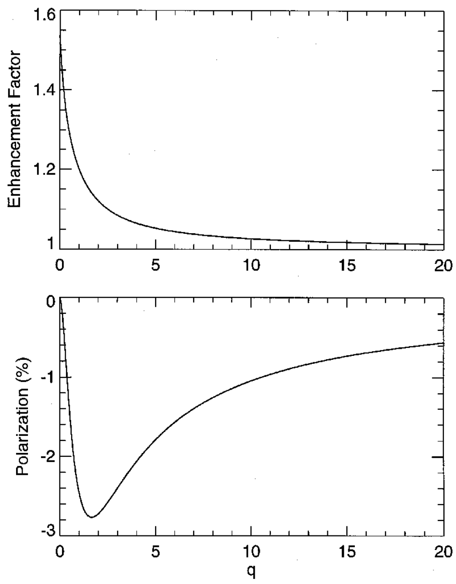

Figure 3: Theoretical angular profiles of the intensity enhancement factor and the degree of linear polarization of the reflected light for a half-space of nonabsorbing Rayleigh particles illuminated by an unpolarized beam of light incident normally to the boundary of the scattering medium

A useful exact result was obtained by Mishchenko [9], who showed that the photometric and polarization characteristics of coherent backscattering at exactly the backscattering direction as well as outside the backscattering peak can be expressed in terms of the solution of the classical radiative transfer equation. This result allows the use of realistic models of polydisperse, arbitrarily sized and arbitrarily shaped particles with any refractive indices. Other theoretical approaches are based on the so-called diffusion approximation [18] and Monte Carlo computations [20]. Because the angular width of the intensity peak caused by coherent backscattering from optically thick layers is proportional to the ratio wavelength/(photon mean free path), it is negligibly small for sparse particle collections and does not affect the results of remote sensing observations of such tenuous objects as clouds, aerosols, and precipitation. However, measurements of coherent backscattering can be a valuable characterization tool in laboratory and remote sensing studies of layers of closely spaced particles such as dense particle suspensions and natural and artificial particulate surfaces [2, 11, 15].

DISCUSSION AND APPLICATIONS

Because lasers are the most frequently used sources of illumination and usually generate linearly or circularly polarized light, explicit laboratory demonstrations of POE have been extremely rare. Apparently, the first laboratory observation of POE was made by Lyot as long ago as in 1920s [8], although the physical explanation of this phenomenon was, of course, unknown at that time. POE may have also been observed in more recent laboratory measurements by Geake and Geake [3] for fine alumina powders, although the smallest phase angle in their experiments was 2° and may be too large for definitive conclusions to be made. These measurements may suggest that POE weakens and ultimately disappears with increasing particle size, which would be consistent with the similar disappearance of the spatial anisotropy of the backscattering intensity peak in the case of a linearly polarized incident beam observed by van Albada *et al.* [21].

Sharp peaks of negative polarization at phase angles considerably less than 1 deg were observed for Saturn's rings and the Galilean satellites of Jupiter [10, 16]. Because these peaks were distinctly different from the symmetric, nearly parabolic negative polarization branch commonly observed for many Solar System bodies [3, 15], they were interpreted in terms of POE caused by coherent backscattering of sunlight by a surface layer composed primarily of microscopic ice particles [10, 16]. The fact that the same objects exhibit comparably narrow intensity peaks centered at exactly the opposition [4, 10] provides strong support for this interpretation. Weak localization is also the likely cause of the unusually strong and narrow photometric opposition effect observed for bright E type asteroids [13].

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