ENHANCED BACKSCATTERING OF POLARIZED LIGHT: EFFECT OF REGOLITH PARTICLE SHAPE ON OPPOSITION BRIGHTNESS PEAK EXHIBITED BY SOME SOLAR SYSTEM BODIES.

J. M. Dlugach[1] and M.I.Mishchenko[2], [1]Main Astronomical Observatory of the National Academy of Sciences of Ukraine, Zabolotny str. 27, 03680 Kyiv, Ukraine, dl@mao.kiev.ua, [2]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA, crmim@giss.nasa.gov.

1. Introduction

Photometric phase curves obtained for some atmospphereless bodies of the Solar system show a steep increase in brightness near the phase angle $\alpha = 0^0$. Evidently, several physical mechanisms may be involved in the formation of such a brightening. In particular, it was suggested that for a wide class of astronomical objects, coherent backscattering of light can play a role in producing this phenomenon (see,e.g., [1-4]). Because coherent backscattering from descrete random media is known to give rise to an opposition peak that has a distinct triangular shape near the opposition and half-width of few tenths of a degree, it is worthwhile to apply this mechanism to interpret the astronomical observations. In our papers [5-7], we have shown that coherent backscattering of sunlight from regolith layers composed of submicrometer-sized **spherical** grains can explain the opposition effect exhibited by Saturn's A- and B-rings, Galilean satellite Europa, bright asteroids 44 Nysa and 64 Angelina, and some regions on the Martian surface. But, it is interesting and important to examine how the characteristics of coherent backscattering can be affected by particle nonsphericity, which is the purpose of this work. We present and analyze the results of our computations performed for semi-infinite homogeneous regolith slabs composed of polydisperse, randomly oriented oblate spheroids with varying degree of asphericity.

2. Basic formula

Let the scattering medium be a plane-parallel slab composed of randomly distributed, independently scattering particles. This slab is illuminated by a parallel beam of light incident in the direction (θ_0, φ_0=0), and **S** is the Stokes reflection matrix for exactly the backscattering direction (θ, π). We will also specify the direction of incidence by the couplet $\{\mu \geq 0, \varphi = 0\}$, where $\mu = -\cos\theta$. For a macroscopically isotropic and mirror-symmetric scattering medium, the matrix **S** has the block-diagonal form [8],

$$\mathbf{S}=\begin{bmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{bmatrix} \qquad (1)$$

In accordance with the microscopic theory of coherent backscattering [9], the matrix **S** can be decomposed as

$$\boldsymbol{S} = \boldsymbol{S}^1 + \boldsymbol{S}^{\mathbf{M}} + \boldsymbol{S}^{\mathrm{C}} \qquad (2)$$

Where $\boldsymbol{S}^1$ is the contribution of the first-order scattering, $\boldsymbol{S}^{\mathbf{M}}$ is the diffuse multiple-scattering contribution composed of all the ladder diagrams of orders $n \geq 2$, and $\boldsymbol{S}^{\mathrm{C}}$ is the cumulative contribution of all the cyclical diagrams. The matrices $\boldsymbol{S}^1$ and $\boldsymbol{S}^{\mathbf{M}}$ can be found by solving the vector form of the Ambarzumian's nonlinear integral equation [10]. Then the matrix $\boldsymbol{S}^{\mathrm{C}}$ can be obtained from the exact relations [11]. The backscattering enhancement factor (the amplitude of the opposition spike) ς for exactly backscattering direction defined as the ratio of the total backscattered intensity to the incoherent (diffuse) intensity is given by:

$$\varsigma = (I_{\text{diffuse}} + I_{\text{coherent}})/\, I_{\text{diffuse}} \,. \qquad (3)$$

For the case of unpolarised incident light, the amplitude of the opposition effect is as follows [11]:

$$\zeta = \frac{S_{11}^1 + S_{11}^M + 0.5(S_{11}^M + S_{22}^M - S_{33}^M + S_{44}^L)}{S_{11}^1 + S_{11}^M} \qquad (4)$$

To determine the elements of the matrix $\boldsymbol{S}^{\mathbf{M}}$, one must first calculate the elements of the normalized Stokes scattering matrix for the particles forming the medium. In this study, we have used the method that was developed in [12] and is based on Waterman's *T*-matrix approach [13]. Then the elements S_{11}^M, S_{22}^M, S_{33}^M and S_{44}^M were computed by means of a numerical solution of Ambarzumian's nonlinear integral equation as described in [10].

3. Numerical results and discussion

To model the potential effect of particle nonsphericity on the amplitude of the opposition spike ς, we have chosen randomly oriented oblate spheroids distributed over surface-equivalent-sphere radii *r* according to the power law. The shape of a spheroid is fully described by just one parameter, the aspect ratio *E* (i.e., the ratio of the larger to the smaller spheroid axes), along with a designation of either prolate or oblate.

We have performed computations of the amplitude of the opposition spike ς for a semi-infinite homogeneous slab composed of spheroids with the real part of the refractive index $m_R = 1.2$, 1.4, and 1.6, the imaginary part of the refractive index $m_I = 0$ and 0.01, a range of values of the effective size parameter $x_{eff} = 2\pi r_{eff}/\lambda_1$ (λ_1 is the wavelength of the incident radiation in the surrounding medium), and aspect ratios $1 \le E \le 2$. The effective variance of the size distribution v_{eff} was fixed at 0.1. In our opinion such wide region of adopted parameters gives possibility to analyse possible influence of nonsphericity for a number of various submicrometer-sized grains covering the surface layers of different Solar system bodies at a wide spectral interval (from UV up to IR).

The main results of our computations are shown in the form of color diagrams of the amplitude of the opposition spike ς as a function of the effective size parameter x_{eff} and aspect ratio E for $\mu = 1$, 0.642, and 0.156. Let us first analyze the case of conservative scattering, $m_I = 0$ (Fig. 1). One can see that the calculated values of ς lie in the range of 1.3 – 1.7. In the case of $m_R = 1.2$, the amplitude of the opposition effect does not depend on the shape of particles. The dependence on the value of E increases with increasing real part of the refractive index and/or with increasing effective size parameter (i.e decreasing wavelength). But it is not a monotonous function of m_R, the aspect ratio E, and effective size parameter x_{eff}. The maximum value of this dependence is seen for E ~1.4, $m_R = 1.6$, and it does not exceed 20%.

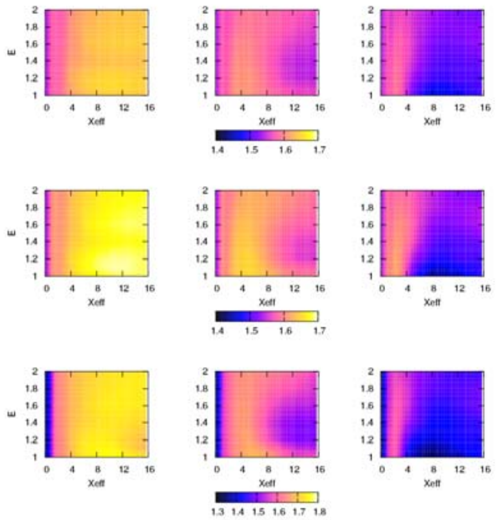

Fig. 1. Amplitude of the opposition effect versus effective equal-surface-area-sphere size parameter and aspect ratio for $m_R = 1.2$ (left-hand column), 1.4 (middle column), and 1.6 (right-hand column), and $\mu = 1$ (top row), 0.642 (middle row), and 0.156 (bottom). The imaginary part of the refractive index is fixed at $m_I = 0$.

Fig. 2 shows the result of computations of the amplitude of the opposition spike ς in a case of absorbing particles ($m_I = 0.01$). The most obvious effect of increasing absorption is a significant decrease in the values of ς and an appearance of weak dependence on particle asphericity also for $m_R = 1.2$. But also as in a case of nonabsorbing particles, the maximum difference in values of ς caused by different particle asphericity, does not exceed 20%.

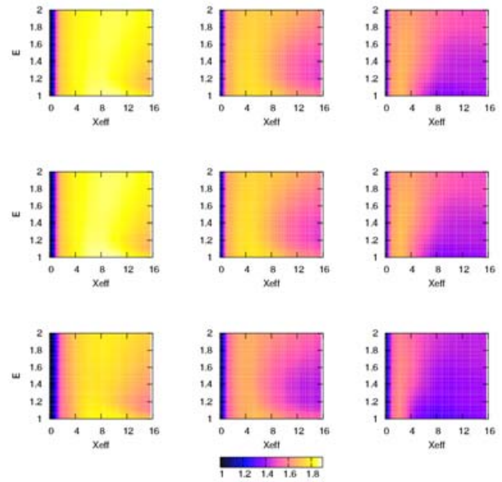

Fig. 2. As in Fig. 1, but for $m_I = 0.01$

4. Conclusions

Using the model of a semi-infinite homogeneous slab composed of randomly oriented, polydisperse oblate spheroids with varying aspect ratios, we have demonstrated that for unpolarised incident light, the amplitude of the opposition effect caused by coherent backscattering depends very weakly on particle shape.

References

[1] Kuga Y., Ishimaru A. (1984) *JOSA, A*1, 831-835. [2] O'Donnel K.A., Mendez E.R. (1987) *JOSA, A*4, 1194-1205. [3] Shkuratov Yu.G. (1988) *Kin. Fiz. Nebes.Tel, 4,* 33-39. [4] Hapke B. (1990) *Icarus, 88,* 407-417. [5] Mishchenko M.I., Dlugach J.M. (1992) *MNRAS, 254,* 15p-18p. [6] Mishchenko M.I., Dlugach J.M. (1993) *Planet. Space Sci., 41,* 173-181. [7] Dlugach Zh.M., Mishchenko M.I. (1999) *Solar System Res., 33,*472-481. [8] Mishchenko M.I. et al. (2002). *Scattering, absorption, and emission of light by small particles*. [9] Mishchenko M.I. et al. (2006) *Multiple scattering of light by particles: radiative transfer and coherent backscattering*.
[10] Mishchenko M.I. (1996) *JQSRT, 56,* 673-702. [11] Mishchenko M.I. (1992) *JOSA,* 9, 978–982. [12] Mishchenko M.I. et al. (1996) *JQSRT, 55,* 535–575. [13] Waterman P.C. (1971) *Phys. Rev.* D3, 825-839