THE EFFECT OF ORIENTATION OF NONSPHERICAL SCATTERING PARTICLES ON THE ATMOSPHERIC TRANSMITTANCE

Yu.A. Lebedinskii and K.G. Predko

Branch of the Institute of Physics, Academy of Sciences of Belorus, Mogilev
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Calculation is made of the transmittance of a plane layer containing nonspherical spatially oriented scattering particles for oblique illumination based on the approximate solution of the radiative transfer equation. A qualitative analysis of the transmittance as a function of the incidence angle and of the medium parameters is presented.

In recent years progress has been made in developing applied optics of a scattering atmosphere and some other natural and artificial objects that necessitates an account of nonspherical scattering particles and their spatial orientation. Considerable advances were obtained in calculating the parameters of elementary volume and singly scattered radiation.[1-8] The calculations of multiply scattered light were carried out by either the Monte Carlo method[9] or approximated methods which were as difficult as numerical methods.[10]

The present paper is concerned with the behavior of the transmittance of the scattering atmosphere containing nonspherical spatially oriented particles with an account of the multiply scattered radiation. The approximate analytical algorithm for solving the radiative transfer equation in the medium with the parameters of the elementary volume being dependent on the direction of radiation incidence and the estimate of its precision is given in Ref. 11.

Spheroids whose shape can serve as an approximation of the shape of scattering particles of natural origin for qualitative description of the behavior of the atmospheric transmittance are chosen as a particle model. As in Ref. 11, the particles are considered to be sufficiently large to possess the preferred orientation in the atmosphere, in addition, the orientation is possible along the vertical z axis.[2] We assume that for scattering of the visible radiation on such particles the following approximation of geometric optics is valid: the extinction parameter $\varepsilon(\Omega)$ is proportional to the geometric cross section of particles in the plane perpendicular to the direction of radiation incidence. We ignore the weak dependence of the photon survival probability Λ and of the average cosine of the scattering angle $\overline{\mu}$ on $\mathbf{\Omega}$ (see Ref. 12), where $\mathbf{\Omega}$ is the unit vector of the direction.

Since the scattering phase function $X(\Omega)$ in this case is strongly forward–peaked, we use, as before, the transport approximation for the solution of the radiative transfer equation.

$$X(\Omega, \Omega') = 1 - \mu(\Omega) + 4\pi\, \overline{\mu}(\Omega)\, \delta(\Omega \cdot \Omega') . \quad (1)$$

Let the length of the vertical axis of the spheroid be L and that of the horizontal axis be M and $\Delta = L/M$. Assuming that the vertical axis of spheroids is oriented strictly along the z axis, we can write for the extinction parameter ε of the elementary volume

$$\varepsilon_0(\theta) = E_0\Delta/\left(\Delta^2\cos^2(\theta) + 1 - \cos^2(\theta)\right)^{1/2} , \quad (2)$$

where $\mathbf{\Omega} = (\theta, \varphi)$ are the spherical angles.

Since spheroids have a vertical axis of symmetry, dependence of ε on the angle φ vanishes. It should be noted that for nonspherical particles of arbitrary shape the dependence of ε on φ can be neglected because of chaotic orientation of particle axes in the horizontal plane (in the angle φ) in the atmosphere.[8] In this case to describe an oblique incidence of radiation we can also restrict ourselves to a single angle of deflection from the vertical.

In Ref. 11 it was assumed that the elementary volume was occupied with spheroids of the similar shapes (with the same values of Δ). As a rule, both oblate and prolate particles can occur in the atmosphere, e.g., in crystalline clouds.[7] Hence, in general the attenuation parameter can be written in the form

$$\varepsilon(\theta) = \int \varepsilon_0(\theta, \Delta)\, P(\Delta)\, d\Delta ,$$

where the function $P_\theta(\theta')$ is the probability density function of the angles θ' between the axis of symmetry of spheroids and the vertical. Moreover, $P_\theta(\theta')$ obviously depends on L and M. However, to qualitatively analyze the behavior of the transmittance, the preferred orientation can be ignored.

The specific calculations were carried out for a plane–parallel layer of the medium containing spheroids with two different values of Δ: Δ_1 and Δ_2. The coefficients E_1 and E_2 determine the relative content of particles with corresponding Δ. The sum $E_1 + E_2 \equiv 1$, therefore, listed in the table are only the values of E_1. The optical depth of the layer in the vertical direction is equal to H. The photon survival probability Λ amounts to 0.995.

Let us first consider the case in which $\mu_1 = \mu_2$ and unidirectional radiation is incident normally on the layer (Table I).

The four values of the transmittance in every column of Table I corresponds to the following pairs of Δ_1 and Δ_2: (0.1; 1.5), (0.1; 4.0), (0.7; 1.5), and (0.7; 4.0).

As can be seen from Table I, the transmittance T, as a rule, increases with relative content of oblate particles in the medium. At larger H and smaller $\overline{\mu}$, however, the dependence of the transmittance T on the relative content of particles with different Δ becomes nonmonotonic. This can be accounted for by the fact that the angular structure of the scattered light becomes sufficiently

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diffuse at larger optical depths H and smaller $\bar{\mu}$. In this case, if at small H the main contribution to the transmittance comes from the values of ε at small angles of deflection of radiation from the vertical, then the values of ε at large angles of light incidence become also important at larger optical depths H. Therefore the decrease of T with the relative content of oblate particles at $H = 10$ and $\bar{\mu} = 0.75$ can be explained by the increasing attenuation at lager angles of incidence.

TABLE I. Behavior of the transmittance T as a function of the relative content of the particles.

H / $\bar{\mu}_1$	E_1 = 0	0.2	0.4	0.6	0.8	1.0
2	0.875	0.877	0.880	0.884	0.888	0.894
0.9	0.867	0.870	0.873	0.877	0.883	0.894
	0.875	0.877	0.878	0.879	0.881	0.882
	0.867	0.869	0.871	0.874	0.877	0.882
2	0.722	0.725	0.731	0.738	0.750	0.773
0.75	0.705	0.709	0.714	0.723	0.737	0.773
	0.722	0.725	0.727	0.730	0.734	0.739
	0.705	0.709	0.713	0.719	0.726	0.739
10	0.527	0.529	0.533	0.540	0.556	0.599
0.9	0.503	0.505	0.509	0.526	0.537	0.599
	0.527	0.531	0.535	0.539	0.545	0.551
	0.503	0.507	0.513	0.520	0.531	0.551
10	0.325	0.325	0.323	0.321	0.323	0.371
0.75	0.298	0.296	0.293	0.290	0.294	0.371
	0.325	0.330	0.336	0.343	0.351	0.360
	0.298	0.302	0.307	0.316	0.331	0.360

The dependence of T on the relative content of particles is stronger at larger H and smaller $\bar{\mu}$.

In addition to the transmittance T, an important value is $R = T/\bar{T}$, where $\bar{T}$ is the transmittance for chaotically oriented particles. As can be seen in Fig. 1, the value of R varies more significantly as a function of relative content of particles than the value of T does. Moreover, the value of R always decreases with the relative content of oblate particles.

Let us now consider the case in which $\bar{\mu}_1 \neq \bar{\mu}_2$. From formula (1) and from what has been said above it follows that in this case the total $\bar{\mu}$ is simply $\bar{\mu} = \bar{\mu}_1 E_1 + \bar{\mu}_2 E_2$. It can be seen from Table II that the transmittance T decreases as E_1 increases when $\bar{\mu}_1 > \bar{\mu}_2$ and as E_1 increases when $\bar{\mu}_1 < \bar{\mu}_2$.

TABLE II. Behavior of the transmittance T as a function of the relative content of the particles for $\Delta_1 = 0.1$ and $\Delta_2 = 4$ *at* $H = 10$.

$\bar{\mu}_2$ / $\bar{\mu}_1$	E_1 = 0	0.2	0.4	0.6	0.8	1.0
0.75 / 0.9	0.503	0.435	0.383	0.345	0.321	0.371
0.9 / 0.75	0.298	0.328	0.344	0.386	0.458	0.598

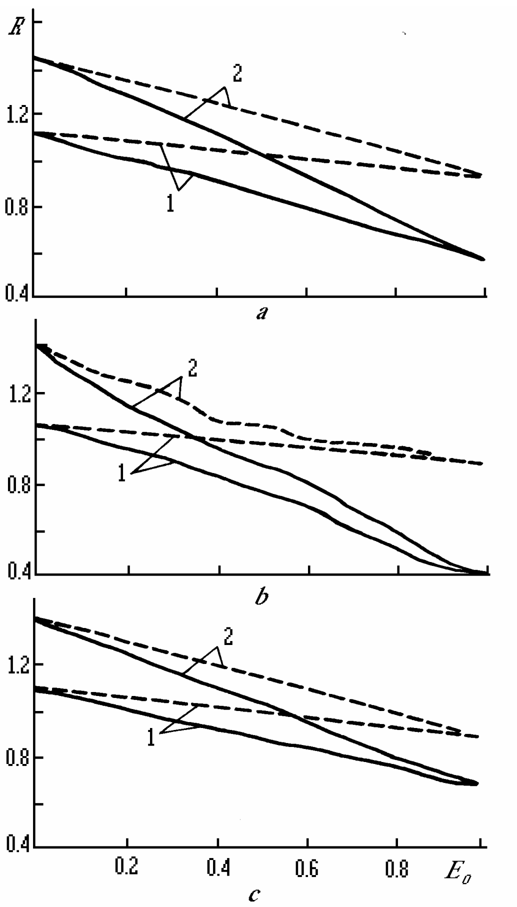

FIG. 1. The dependence of the value R on the relative content of oblate spheroids in the medium: a) $H = 10$ *and* $\bar{\mu} = 0.9$, *b)* $H = 10$ *and* $\bar{\mu} = 0.75$, *and c)* $H = 2$ *and* $\bar{\mu} = 0.75$. *1)* $\Delta_1 = 1.5$ *and 2)* $\Delta_2 = 4.0$. *Solid lines refer to* $\Delta_1 = 0.1$ *and dashed lines refer to* $\Delta_1 = 0.7$. *Direction of light incidence is normal.*

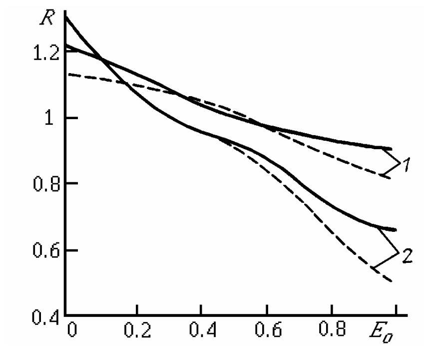

FIG. 2. The dependence of the value R on the relative content of oblate spheroids for different scattering phase functions and spheroids with different Δ. *Solid lines refer to* $\bar{\mu}_1 = 0.9$ *and* $\mu_2 = 0.75$, *dashed lines refer to* $\mu_1 = 0.9$ *and* $\bar{\mu}_2 = 0.75$. *1)* $H = 2$ *and 2)* $H = 10$. *Direction of light incidence is normal.*

As can be seen in Fig. 2, the value of R always falls down as E_1 increases.

Let us now consider the oblique illumination. Let θ be the angle of deflection of radiation from the vertical. In this case the behavior of the transmittance T, to a considerable extent, is determined by the relative content of oblate and prolate particles, i.e., by the function $\varepsilon(\theta)$. Roughly the transmittance can be assumed maximum when the direction of light incidence is close to the direction of minimum optical depth of the layer.

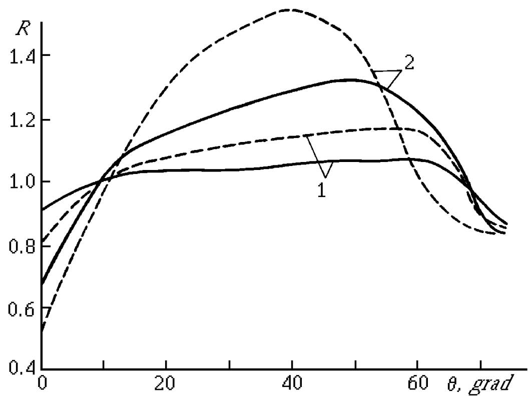

FIG. 3. The dependence of the value R on the angle of light incidence for $\Delta_1 = 0.1$, $\Delta_2 = 4.0$, $E_1 = 0.75$, *and* $E_2 = 0.25$. *Solid lines refer to* $\overline{\mu} = 0.9$ *and dashed lines refer to* $\overline{\mu} = 0.75$. *1)* $H = 2$ *and 2)* $H = 10$.

The maximum in R shifts toward larger angles of incidence due to the decrease of T at larger incidence angle. At larger optical depth H, the maximum shifts toward smaller angles. This can be accounted for by the fact that the transmittance T for chaotically oriented particles for weakly real absorption by the medium varies insignificantly as the incidence angle changes at large optical depth of the layer. The maximum shifts toward smaller angles when the scattering phase function is less forward–peaked (Fig. 3).

REFERENCES

1. S. Asano, Appl. Opt. **22**, No. 9, 1390–1396 (1983)
2. A.B. Fraser, J. Opt. Soc. Am. **69**, 1112–1118 (1979)
3. L.I. Podkamen', S.G. Guminetskii, and A.D. Arkhelyuk, Izv. Akad Nauk SSSR, Ser. FAO **12**, 1287–1292 (1986)
4. N.V. Voshchinnikov and V.G. Farafonov, Opt. Spektrosk. **85**, No. 1, 135–141 (1985).
5. L.E. Paramonov, V.N. Lopatin, and R.Ya. Sid'ko, Opt. Spektrosk. **61**, No. 3, 570–576 (1986).
6. C.F. Bohren and D.R. Huffman, *Absorption and Scattering of Light by Small Particles* (Interscience–Wirley, New York, 1986).
7. O.A. Volkovitskii, L.N. Pavlova, and A.G. Petrushin, *Optical Properties of Cristalline Clouds* (Gidrometeoizdat, Leningrad, 1984), 198 pp.
8. F.Ya. Sid'ko, V.N. Lopatin, and L.E. Paramonov, *Pol arization Properties of Biological Particle Suspensions* (Nauka, Novosibirsk, 1990), 120 pp.
9. A.R. Holt and J.W. Stepherd, J. Phys. **A12**, No. 1, 159–166 (1979).
10. K. Furutsu, J. Math. Phys., No. 4, 765–777 (1980).
11. Yu.A. Lebedinskii and K.G. Predko, Izv. Akad. Nauk SSSR, Ser. FAO, No. 9, 970–975 (1987).
12. A.G. Petrushin, Izv. Akad. Nauk SSSR, Ser. FAO, No. 12, 1293–1299 (1986).