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Twilight Sky Photometry and Polarimetry: The Problem of Multiple Scattering at the Twilight Time

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Abstract—This work is devoted to the study of solar light that experiences multiple scattering in the atmosphere at the twilight time, from the setting of the sun to nightfall. The work is based on polarimetric twilight sky observations at 3560 Å that were conducted in the summer of 1997 at the Astronomical Observatory at Odessa University. These data were used to determine the fraction of multiple-scattered light in the total sky background for various points of the sky, various depths of the sun under the horizon, and various polarization directions. A critical analysis is performed of some methods previously employed to take into account multiple scattering in twilight observations. The altitude distribution of small-sized atmospheric aerosol particles in the stratosphere is also examined.

INTRODUCTION

Taking account of solar light that experiences multiple scattering in the Earth's atmosphere is one of the basic problems in the study of the atmosphere by photometric analysis of the twilight sky. As early as 1923, Fesenkov called attention to the essential role of multiple scattering in his first work [1] devoted to the analysis of twilight phenomena. However, as was correctly noted by Rozenberg [2], the extreme complexity of constructing a theory of multiple scattering forced many authors to disregard this scattering or introduce various, sometimes fairly crude assumptions concerning its properties. A comparative analysis of a great number of works made by Rozenberg [2] revealed an extremely wide range of results—from the possibility of completely neglecting multiple scattering to its essential predominance over single-scattered light. Obviously, the ratio of single- to multiple-scattered light directly determines the efficiency of the twilight method of atmospheric study, in which multiple scattering is a peculiar kind of "noise" that must be subtracted from the total sky background.

The main object of investigation in this work is the multiple-scattered component of the twilight sky and its photometric and polarimetric properties during the twilight time (from sunset to the time when the twilight glow is completely lost in the night-sky background).

PROPERTIES OF SINGLE AND MULTIPLE SCATTERING

Consider the scheme of formation of single- and multiple-scattered light at the twilight time and its fundamental properties. We will only be interested in points in the solar vertical. Their brightnesses are denoted by J and j, respectively. The scheme of appearance of both components at the sunrise and sunset times is shown in Fig. 1. The brightness of the single-scattered component for a fixed wavelength is given by the integral

$$J = \mathrm{const}\int_0^\infty e^{-\tau_1(H_L, z, h)} n(H_{SC}(H_L, z, h)) \times D(H_{SC}, \gamma)\sec(z-h) e^{-\tau_2(H_L, z, h)} dH_L, \quad (1)$$

where integration is performed over H_L, the minimum altitude of the solar ray above the Earth's surface; H_{SC} is the altitude of the point of light scattering; z is the zenith distance for an observed point of the sky (which is positive in the glow region and negative in the opposite region of the sky); h is the depth of the sun under the horizon; n is the number density of particles at the altitude H_{SC}; D is the scattering function (indicatrix); γ is the scattering angle; τ_1 and τ_2 are the optical depths along the ray path before and after the scattering event, respectively. The quantity τ_2, with a small correction, is

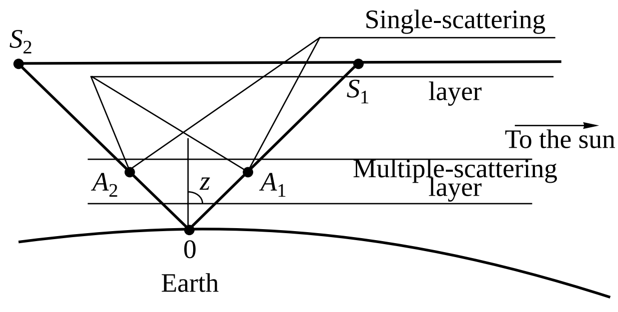

Fig. 1.

equal to the vertical optical depth of the atmosphere multiplied by sec$z$.

The "twilight ray" model is very convenient in some cases. The essence of this model is that solar rays passing near the Earth's surface experience strong absorption, while rays passing at great heights are scattered very weakly in the upper, rarefied atmospheric layers. As a result, the main part of the single-scattered component is formed in the so-called "twilight layer," which has a comparatively small thickness and does not depend on the depth of the sun under the horizon and on the zenith distance of the observed point. The minimum altitude of the twilight layer above the ground grows comparatively slowly with the sun's depth. Taking this fact into account, the integral in formula (1) can be replaced by the integrand at a certain point $H_{L0}(h)$ multiplied by the effective thickness of the layer, which is included in the constant. In this case, the effective scattering altitude $H_{SC0}(z, h)$ will correspond to every observed point.

This method has already been used repeatedly, for example, by Divari [3], but in contrast to his work, we use the value of H_{L0} corresponding to the average contribution to the integral in place of the H_{L0} value corresponding to the maximum of the integrand. Owing to the asymmetry of the twilight layer, these values differ by several kilometers.

Since the scattering occurs mostly at significant altitudes (above 10 km), we can disregard refraction. Let us consider in greater detail the case $h = 0$ (sun at the horizon). In this case (if the points close to the horizon are disregarded), $H_{SC0} = H_{L0}$, and equation (1) takes the simplified form

$$J = \mathrm{const}e^{-\tau_1(H_{L0},\, z)}n(H_{L0})D\left(H_{L0}, \frac{\pi}{2} - z\right) \times \sec z e^{-\tau_2(H_{L0},\, z)} = D\left(H_{L0}, \frac{\pi}{2} - z\right)f(z). \quad (2)$$

It should be noted that for $h > 0$, the altitude of the twilight layer increases, $H_{SC0}(z)$ becomes z-dependent, and, as the sun descends under the horizon, this dependence becomes progressively steeper: the scattering in the glow region occurs in a lower place than in the opposite part of the sky.

We denote by $J_\perp$ ($J_\parallel$) the brightness of the single-scattered component in the polarization plane perpendicular (parallel) to the scattering plane. It is evident that equation (1) also holds for these quantities, with substitution of the polarization indicatrices $D_\perp$ and $D_\parallel$, respectively. The quantities $j_\perp$ and $j_\parallel$ are introduced in a similar manner.

In place of the polarization coefficient, we will use in this work a more suitable quantity: the polarization ratio K, which is equal to the ratio of the sky brightnesses for polarization directions parallel and perpendicular to the scattering plane. The degree of polarization p is connected with K by the simple relation $p = (1 - K)/(1 + K)$. For nonpolarized light, K is obviously equal to unity.

The scattering indicatrices D are the sums of air (Rayleigh) and aerosol indicatrices. From the Kabann–Rayleigh scattering matrix [2], one can readily obtain (accurate to a constant) the air scattering indicatrices:

$$D_\perp(\gamma) = 1 + \alpha; \qquad D_\parallel = \cos^2\gamma + \alpha, \quad (3)$$

where α is 1/2 of the depolarization parameter in the Kabann–Rayleigh matrix. In accordance with [2], we assume $\alpha = 0.03$. As for the aerosol indicatrices, it is only known that, in contrast to the air indicatrices, they are asymmetric with respect to $\gamma = \pi/2$, exhibiting an excess at small scattering angles.

Multiple scattering (as well as the scattering of light reflected from the Earth's surface), like single scattering, also takes place in a certain layer, located, however, at much lower altitudes, in the near-Earth atmospheric layers. Fesenkov [4] even called this component the "tropospheric component." Its mean altitude varies at an extremely slow rate with the depth of the sun under the horizon. Variation with zenith distance of the observed point is also insignificant. These facts form the basis for the assumption (which has been used repeatedly [4, 5]) that the logarithmic derivatives at the symmetric points of the solar vertical for each h value are equal to each other:

$$\frac{d\ln j(z, h)}{dh} = \frac{d\ln j(-z, h)}{dh}. \quad (4)$$

However, because the mean altitude of multiple scattering does vary, this equality cannot be integrated over a wide range of the sun's depths under the horizon (which is actually done in [5]), as will be shown below.

The effects related to the multiple scattering altitudes will disappear if we write equation (4) for two polarization directions and subtract one equation from another. We can then integrate the resulting equation, which will lead us to an expression relating the polarization ratios q of multiple scattering at the symmetric points of the solar vertical:

$$q(z, h) = \theta(z)q(-z, h). \quad (5)$$

As we shall see later, the parameter θ for any z is close to unity, and equation (5) describes the property of symmetry of multiple scattering, which is quite natural if we take into account the similar polarization properties of the scattering of light at adjacent angles.

OBSERVATIONS

Photometric and polarimetric observations of the twilight sky were conducted in July–August 1997 at the Astronomical Observatory of Odessa University, located at Mayaki village. The sky brightness was measured for different positions of the analyzer axis in a wide range of the sun's depths under the horizon: from –2° (sun above the horizon) to 20°. The measurements

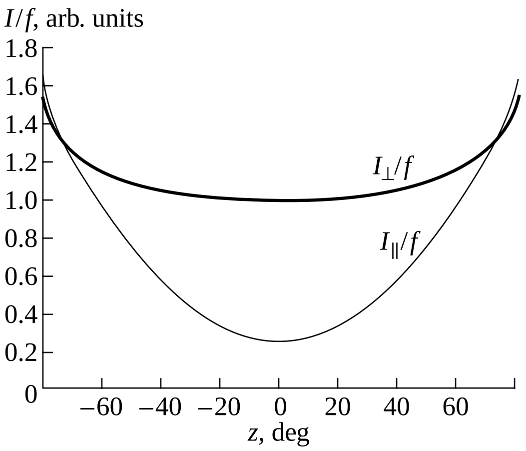

Fig. 2.

were made with an autoscanning twilight photometer [6] in the solar vertical in the range of zenith distances from –70° to +70°. The wavelength of measurements (3560 Å) lies in the ultraviolet spectral region and does not fall in the region of selective absorption of atmospheric gases, including ozone. The principal light absorption and scattering mechanism at this wavelength is Rayleigh scattering, to which scattering by particles of atmospheric aerosol may be added.

For each night of observation, the vertical optical depth of the atmosphere was determined by Bouguer's method. On account of the comparative closeness of the results obtained on different days of observation (a total of three), all graphs and diagrams presented here are given for a single observation: the evening twilight of July 31, 1997.

The observational data were used to construct the z-dependence of complete sky brightness at different polarization directions, $I_\perp$ and $I_\parallel$, at the sunset and sunrise times, i.e., for $h = 0$. Figure 2 shows the graphs of these functions divided by the function f, i.e., the sky brightnesses corrected for absorption of single-scattered light (in arbitrary units):

$$\frac{I_{\perp(\parallel)}}{f(z)} = D_{\perp(\parallel)}\left(\frac{\pi}{2} - z\right) + \frac{j_{\perp(\parallel)}}{f(z)}. \qquad (6)$$

For both directions of the polarization axis, this dependence is virtually symmetric with respect to the point $z = 0$ for all observation dates. Since the multiple-scattered component should have a significant excess in the glow region (at point A_1 in Fig. 1, the sun is at a higher altitude above the horizon than at point A_2) and the j/f ratio cannot have an essential excess in the antisolar region, we can conclude that the function D near the altitude H_{L0} at $\lambda = 3560$ Å and for $h = 0$ turns out to be nearly symmetric relative to the angle $\gamma = \pi/2$, and, therefore, small-sized particles of atmospheric aerosol are lacking at these altitudes.

Figure 3 shows the polarization ratio K of the twilight sky for different zenith distances as a function of h. Even these dependences enable one, in principle, to determine at which depths of the sun under the horizon the single scattering is completely lost against the background of the multiple scattering. This occurs at $h \sim 10°$, because, at greater depths, the polarization ratios at the symmetric points of the solar vertical become almost identical; i.e., property (5) with $\theta = 1$, typical of multiple scattering, holds. The phenomenon of inverse polarization of the multiple scattering ($K > 1$) away from the zenith is noteworthy. The reasons for its appearance will be discussed below.

The appearance of a single-scattered component, having a high asymmetry at large h with an excess in the glow region (due to the variance of effective scattering heights), leads to breaking of the K symmetry. K becomes lower at positive z because single-scattered light is more strongly polarized than multiple-scattered light.

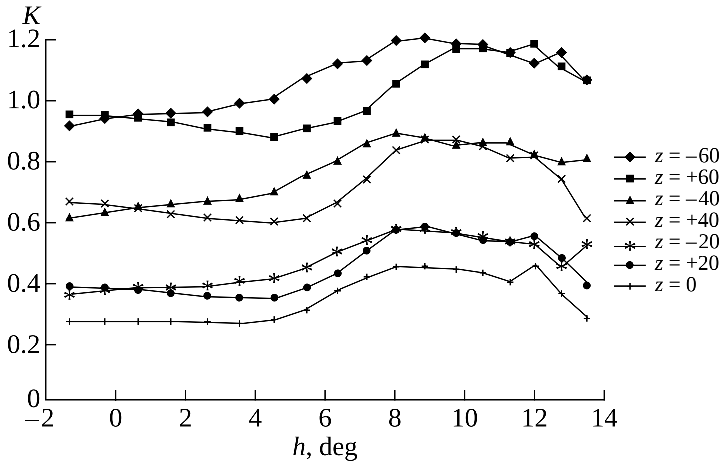

Fig. 3.

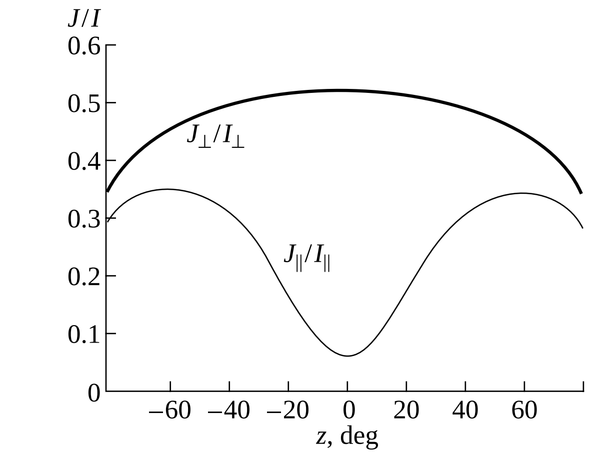

Fig. 4.

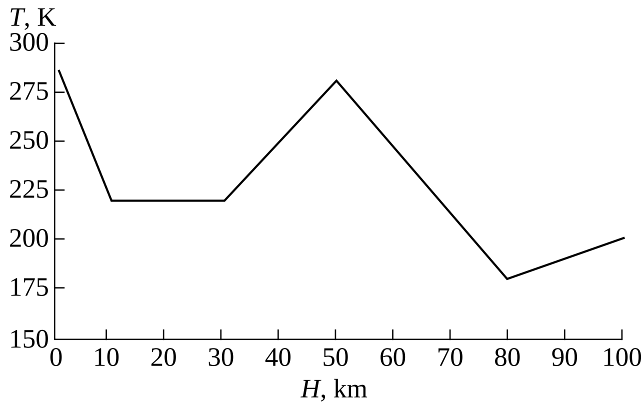

Fig. 5.

The asymmetry of the single scattering disappears (after dividing by the function $f(z)$) at $h = 0$ because there is no atmospheric aerosol at the corresponding altitudes. However, as can be seen from Fig. 3, the polarization ratios at symmetric points coincide at $h = 1°$. This effect cannot be accounted for by atmospheric refraction, since at altitudes of 20–30 km, where the scattering occurs, refraction does not exceed a few arc minutes. It is caused rather by the small asymmetry of multiple scattering, with an excess in the glow region as noted above, which does not disappear even after dividing by the function $f(z)$.

Table

Date (1997)	$J_\perp/I_\perp$	$J_\parallel/I_\parallel$	J/I
July 30, morning	0.572	0.056	0.441
July 31, evening	0.521	0.058	0.413
August 1, morning	0.492	0.053	0.388

Near $h = 0$, we notice a change of the polarization ratio due to change in the angle of single scattering. When combined with change in the $J_\perp/j_\perp$ ratio, this effect leads to an increase of K with a depth of the sun under the horizon at negative z and to a decrease of K with depth at positive z. The method of separating the single-scattered and multiple-scattered components is based on this effect.

In this method, separation is first accomplished for $h = 0$ and $z = 0$, then for $h = 0$ and any z, and, finally, for any h and any z.

Let us consider the case $z = h = 0$. Let A be the fraction of single-scattered light in the total sky brightness for the perpendicular polarization direction, and Q and q be the polarization ratios for single-scattered and multiple-scattered light, respectively. It can be shown that the total polarization ratio is

$$K = AQ + (1-A)q. \quad (7)$$

We take the mixed derivative of K with respect to z and h and express it in terms of the derivatives of A, Q, and q:

$$\frac{d^2K}{dzdh} = A\frac{d^2(Q-q)}{dzdh} + \frac{dA}{dz}\frac{d(Q-q)}{dh} + \frac{dA}{dh}\frac{d(Q-q)}{dz} + (Q-q)\frac{d^2A}{dzdh} + \frac{d^2q}{dzdh}. \quad (8)$$

Since $\gamma = \pi/2 - z$ at $h = 0$, the quantity dQ/dz ($z = h = 0$) vanishes. It follows from (5), with allowing for $\theta = 1$, that $dq/dz = 0$ for any h. On the other hand, the ratio $I_\perp/f$ at $h = 0$ has a minimum at the zenith; therefore, taking into account the constant value of $J_\perp/f$ [as follows from formula (3)], we have $d(j_\perp/f)/dz = 0$ and, hence, $dA/dz(h = 0) = 0$. As a result, we obtain

$$\frac{d^2K}{dzdh} = A\frac{d^2Q}{dzdh} + (Q-q)\frac{d^2A}{dzdh}. \quad (9)$$

The mixed derivative in the first term can be calculated by the direct substitution of (3) (on account of $\gamma = \pi/2 - z + h$). It turns out to be equal to $-2/(1+\alpha)$. The second term in the right-hand side of Eq. (9) also contains a mixed derivative that can be transformed as follows:

$$\frac{d^2A}{dzdh} = \frac{d^2}{dzdh}\left(\frac{J_\perp}{J_\perp + j_\perp}\right) = \frac{d}{dz}\left(\frac{(j_\perp/f)(dJ_\perp/fdh) - (J_\perp/f)(dj_\perp/fdh)}{(J_\perp/f + j_\perp/f)^2}\right), \quad (10)$$

In the last equality, we multiplied the numerator and denominator by $f^2(z)$. Since the derivatives of the functions $J_\perp/f$ and $j_\perp/f$ with respect to z vanish, the equation takes the form (because f is independent of h)

$$\frac{d^2A}{dzdh} = \frac{j_\perp f}{(J_\perp + j_\perp)^2}\frac{d^2(J_\perp/f)}{dzdh}. \qquad (11)$$

The mixed derivative of $J_\perp/f$ can be calculated by the direct substitution of integral (1) or with the help of the "twilight layer" model. Taking into account that the atmosphere at altitudes between 10 and 30 km is virtually isothermal, with a temperature $T = 220$ K, and substituting the corresponding Boltzmann distribution function into $n(H)$ we obtain, after simple calculations,

$$\frac{d^2A}{dzdh} = \left(\frac{H_{L0}}{H_{\text{atm}}} - 1\right)A(1-A), \qquad (12)$$

where $H_{\text{atm}} = 6.43$ km is the height of the uniform atmosphere corresponding to the above temperature. Because of the lack of aerosol, we can also accurately calculate the quantity H_{L0} (24.58 km). Next, we use formula (7) to express $Q - q$ in terms of K and A and, substituting (12) into (9), obtain the expression for A at $z = 0$ and $h = 0$:

$$A = -\frac{d^2K}{dzdh}\left(\frac{2}{1+\alpha} + \left(K - \frac{\alpha}{1+\alpha}\right)\left(\frac{H_{L0}}{H_{\text{atm}}} - 1\right)\right)^{-1}. \qquad (13)$$

Here, the quantity K and its mixed derivative at the point $z = h = 0$ are determined from observations. The resulting value is positive because the mixed derivative of K is less than zero.

Knowing the brightness of the single-scattered component at the zenith for $h = 0$ and for the perpendicular polarization direction, we can calculate, using (2) and (3), its value for any zenith distance and polarization direction. Figure 4 shows the z-dependence of the fraction of single-scattered light in the total sky background at the sunrise and the sunset times for two polarization directions. The table contains the fractions of single-scattered light in the total sky background at the zenith for $h = 0$ and different directions of polarization, and total radiation for all observation dates. The single scattering contribution does not exceed 50%, even for this bright phase of twilight. This conclusion, inconsistent with many existing estimates, can be considered the main result of this study.

The optical depth τ_1, appearing in integral (1), is determined chiefly by the absorption coefficient at altitudes close to H_{L0}, where aerosol is lacking. As a consequence, this depth can be calculated with the use of the gas model of the atmosphere. The optical depth τ_2, as mentioned above, is calculated from the vertical optical depth of the atmosphere. By substituting the resulting sky brightness for $z = 0$ and $h = 0$, we determine the constant in (1), which enables us to find the air (Rayleigh) part of the single-scattered component for any z and h whatsoever. However, in the general case, this quantity is equal to the overall brightness J only for

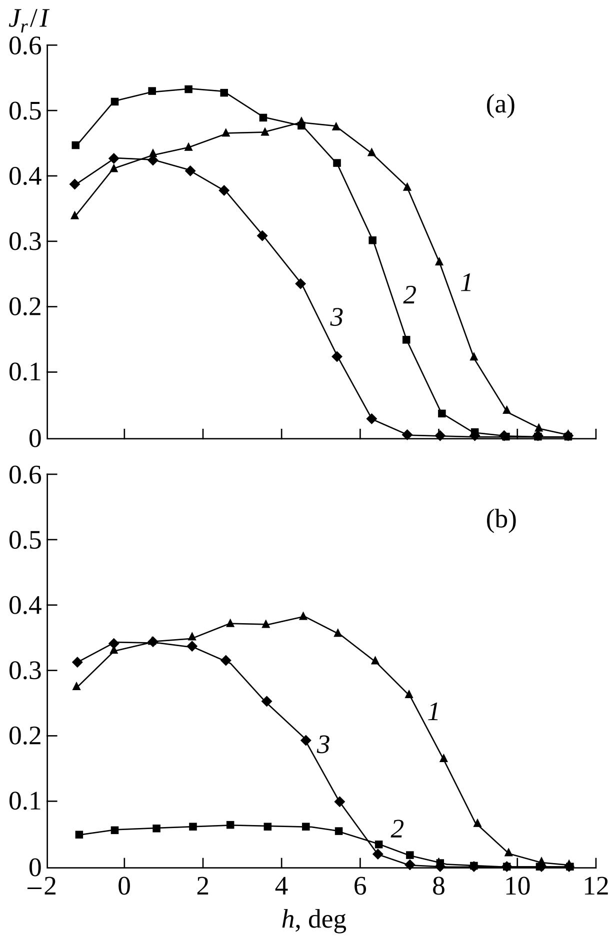

Fig. 6. Fraction of the Rayleigh scattering in the total sky brightness versus the depth of the sun under the horizon for various directions of the polarization plane: (a) perpendicular to the scattering plane, (b) parallel to the scattering plane. (*1*) $z = +60°$; (*2*) $z = 0$; (*3*) $z = -60°$.

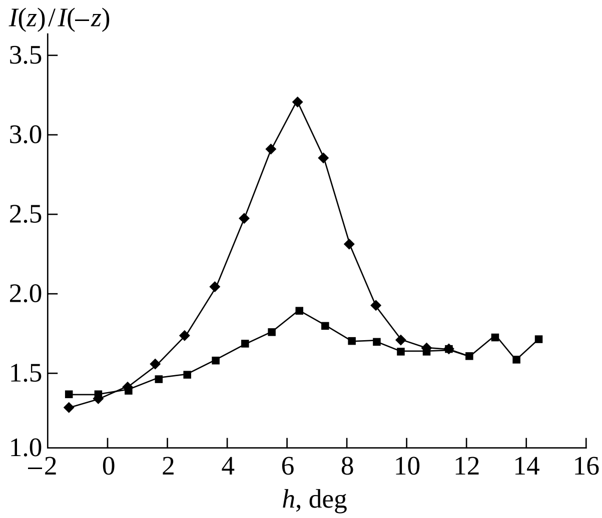

Fig. 7. Ratio of sky brightnesses at symmetric points of the solar vertical with and without allowance for Rayleigh scattering ($z = 60°$, polarization is perpendicular to the scattering plane).

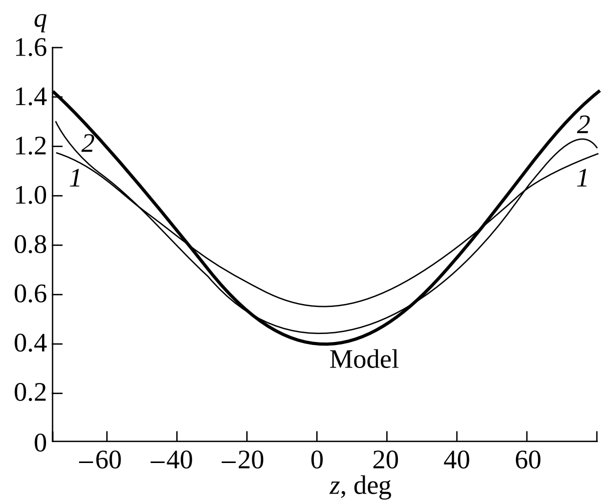

Fig. 8.

depths of the sun close to zero; when h and the effective scattering altitude are large, atmospheric aerosol may play the significant part.

When calculating the brightness of the air component, we used the height distribution of temperature presented in Fig. 5. The temperature in the region of the mesospheric minimum (at an altitude of 80 km) is taken from [7], with allowance made for the latitude of the observation site. The results of the calculation are shown in Fig. 6. An interesting fact is worthy of note: at the bright period of twilight, the contribution of single scattering increases with the sun's depth under the horizon for some zenith distances. As we will see below, the aerosol scattering coefficient at the given wavelength does not exceed anywhere the air coefficient, and the graphs presented in Fig. 6 enable one to estimate the role of single scattering in general. It becomes disappearingly small at effective scattering altitudes of 100–120 km, in quite a good agreement with the values adopted in [5] for the same wavelength.

To estimate the aerosol scattering coefficient, we return to formula (4) for multiple scattering. As mentioned above, this is only an approximate formula, and its integration gives rise to perceptible errors. Nevertheless, we can rewrite (4) as

$$j(z, h) = r(z, h)j(-z, h), \qquad (14)$$

where $r(z, h)$ is a slowly varying function of h that depends parametrically on z. The similar function $R(z, h)$ for single scattering exhibits quite different properties: owing to the variance of effective scattering altitudes, it rises sharply with increasing h. The total brightness ratio $R_0(z, h)$ is connected with these functions by a relation similar to (7) for the polarization ratio.

The upper curves in Fig. 7 show the dependence $R_0(h)$ for $z = 60°$. It is apparent that for $h = 6°$, the growth of R_0 changes to a decrease, and at $h = 10°$, the function $R_0(h)$ reaches a plateau, where its value is slightly higher than the value at $h = 0$. This points unambiguously to the fact that multiple scattering is completely dominant for $z = 60°$ (in the glow region!) at $h > 10°$. Correspondingly, the same situation occurs even earlier on the opposite side of the sky.

If we plot a similar dependence after subtracting the Rayleigh component from the total sky background (the lower curves in Fig. 7), we will also find a peak at $h = 6°$, though with smaller height. This gives evidence of the presence of "nonsubtracted" single-scattered light (obviously scattered by aerosol particles). Since the aerosol scattering at $z = –60°$ and $h > 4°$ is very weak for two reasons (the altitude variance and the small value of the coefficient of scattering at large angles), we can conclude that small-sized atmospheric aerosol particles appear above 40 km, and that their role in scattering and polarization of light (which was already indicated in [8] for violet rays) is insignificant. This is all that we can say in this context because the accuracy of this method is extremely low, which is due to the unknown function $r(h)$ and the high sensitivity of the method to the choice of height distribution of temperature in the atmosphere. From Fig. 7, we also see that the value of the function $r(h)$ for $h > 10°$ is higher than for $h = 0°$, which points to perceptible deviations from Eq. (4).

To summarize the review of observational data, we show in Fig. 8 the polarization ratios q for multiple-scattered light as a function of z for $h = 0°$ (*1*) and $h = 12°$ (*2*). These curves, differing only slightly from each other, satisfy Eq. (5), and agree reasonably with the model curve constructed for double scattering under the assumption that the secondary light source is a thin glowing semicircle with a gradual fall of intensity from the center (above the sun) toward the edges. The multiple scattering becomes nonpolarized at zenith distances of about 50°, and at still closer distances to the horizon, the "inverse polarization" effect takes place ($j_{\parallel} > j_{\perp}$), which is caused by the scattering of light coming from the side (relative to the solar vertical) regions of the sky sphere. The effects of increasing K at high z, as well as at $h = 8°–10°$, are precisely due to multiple scattering and are not produced by atmospheric aerosol, as Rozenberg [2] thought.

DISCUSSION

The main result of this work is the estimate of the fraction of multiple-scattered light in the total background of the twilight sky for various depths of the sun under the horizon and various zenith distances of the sky point in the solar vertical. The fraction of multiple scattering has turned out to be much higher than most of the existing estimates, in particular, the estimates published in [2] and made in [9, 10]. Most of these estimates are based on theoretical calculations of the brightness of single- and double-scattered light. As a rule, the results of these studies were as follows: the fraction of multiple scattering at the zenith at sunset is about 20% of the total sky brightness, and then it grows very slowly. Even at the time of dark twilight (h = 12° and more), single scattering, though lower in brightness than multiple scattering, remains sufficiently detectable and measurable. From these findings, Rozenberg infers that the twilight method is suitable even for studying the uppermost layers of the Earth's atmosphere (up to altitudes of 200–300 km).

It should be noted that most of the theoretical studies referred to the yellow–green part of the spectrum, where the role of multiple scattering may be somewhat lower than in the violet region, where our observations were carried out. It is reasonable to expect that the fraction of multiple scattering in yellow–green rays at sunset exceeds 50%, but then rapidly decreases. In this case, however, the wavelength dependence of this fraction cannot be very strong, as Rozenberg correctly notes.

What is then the reason for the substantial underestimation of the role of multiple scattering in theoretical works? In our opinion, the essence of the problem is that the authors do not take into consideration the third and higher orders of light scattering. When the sun sinks under the horizon by 12° and more, single-scattered light disappears completely, even in the glow region; therefore, at the zenith, we cannot observe double-scattered light either. Also, the mere fact of the predominance of multiple scattering during bright twilight suggests the essential role of high-order scattering. Thus, the authors of theoretical works compared only two components of twilight glow, which may both be insignificant, whereas the dominant component was disregarded.

Rozenberg's conclusions on the small value of multiple scattering are based on experimental works indicating that the h-dependences of brightness and color of the sky during bright twilight are consistent with the theoretical dependences obtained for single scattering. The unsoundness of such arguments becomes understandable if we recall that the role of multiple scattering at this period virtually does not increase (or even slightly declines) with increasing h, thereby not violating the above dependence. It is this property of multiple scattering, as well as its weak wavelength dependence, that has often been the reason for the relative correctness of the results of works where multiple scattering was ignored or underestimated. Multiple-scattered light begins to influence the sky color substantially at $h > 4°$, resulting in the sky growing blue. This well known effect has also been assigned repeatedly to the single-scattered component.

Rozenberg in his book also expressed hope that the rapid development of computational technique would allow one to create a mathematical model of double scattering. High-order scattering makes this problem much more difficult to solve, and, even now, 30 years after Rozenberg's book first appeared, the solution of the problem seems impossible.

Rozenberg's book also contains a reference to another work devoted to multiple scattering and published as early as the 1930s [11]. The author, Hulburt, attempted to estimate the brightness of multiple scattering at the zenith by representing it as the product of air density at altitudes from 15 to 40 km and the measured sky brightness in the glow region. Despite some inaccuracies committed in this work and noticed later [2], the idea by itself was absolutely correct, because the method was designed to take scattering of all orders into account. It is quite logical that Hulburt came to the conclusion that at h = 10°, single scattering is lost on the background of multiple scattering. It is this conclusion that has become the object of strong criticism in [2] and in many other works based on theoretical estimates of the contribution of multiple scattering.

Finally, we should mention the method of separating single- and multiple-scattered light components that is being developed at the Astronomical Observatory at Odessa University (its basic principles are described in [5]). The essence of this method is an extrapolation of the empirical property of multiple scattering (the constancy of the logarithmic derivative of its brightness with respect to h), which was revealed in the region of large h to the region of small h. The method is attractive in its simplicity, but, unfortunately, the multiple-scattered component does not follow this property very well, showing a significant deviation at h = 8°–9°, just where the single scattering in the mesosphere is still noticeable. In our opinion, this deviation can be accounted for by the rapid change of the contribution of double scattering against the background of higher-order scattering. As a result, the scattering coefficient turns out to be overstated, particularly at high angles, which makes the study of mesospheric aerosol difficult.

CONCLUSION

In this paper, we advance a method of investigation of the role of multiple scattering in forming twilight glow based on measurements of the brightness and the degree of polarization of the twilight sky. Ideas on the effectiveness of polarimetric observations have long been stated, and the method itself can to some extent be considered as the development of the method proposed by Fesenkov [4].

Unfortunately, the results of this study (from the viewpoint of the efficiency of the twilight method for probing the atmosphere) cannot be considered in an optimistic light. In spite of numerous arguments against taking multiple scattering into account, its role has proved to be very significant. Admittedly, some assumptions concerning the dependence of multiple scattering on the depth of the sun under the horizon and on the degree of polarization have been rather well verified, which indicates a possibility of twilight studies of the atmosphere at least at the time of bright twilight, when the depth of the sun under the horizon does not exceed 8–10°.

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