ON THE POSSIBILITY OF DETERMINING MICROPHYSICAL PARAMETERS OF THE NOCTILUCENT AND MESOSPHERIC CLOUDS BASED ON THE DATA OF REMOTE CREPUSCULAR SOUNDING FROM SPACE

A. Pikhl and R. Ryym

Institute of Astrophysics and Physics of the Atmosphere
of the Academy of Sciences of Estonia, Tyravere
Received April 24, 1992

Determination of microphysical parameters, such as the mean radius and the standard deviation of the distribution function of scatterers is considered based on the data of remote sounding of the horizon from space under dusky conditions. It has been found that the color index is the optimum measurable value. Simultaneous measurements of two color indices make it possible to estimate the particle radius and variance of the particle dimensions. In the region of small and intermediate particles ($0.01 < \overline{r} < 0.08$ μm) *the color index is more sensitive to the variations of the half–width of the distribution function and is relatively weakly dependent on the mean radius of scatterers.*

For the first time the method of crepuscular sounding of the horizon was proposed by Rozenberg[1] and by Rozenberg and Tereshkova,[2] while its detailed mathematical description can be found in the papers by Kondrat'ev, Buznikov, and Pokrovskii.[3,4] This method is most suitable for investigation of the noctilucent and mesospheric clouds (NC and MC), since under dusky conditions these clouds are seen for an observer in space as a bright layer on a darker background. Data of optical sounding of the NC and MC can be used for determining physical parameters of particles, moreover, only the single–scattering approximation can be used in calculations.

In the single–scattering approximation of the theory of radiation transfer the relationship between the components of the Stocks vector of scattered radiation and microphysical parameters of scattering particles has the form

$$\frac{4\pi I_\lambda^j}{c_\lambda}\exp(T_\lambda) \equiv A_\lambda^j(\gamma) = N S_\lambda\, g_\lambda^j\, S(\gamma)\ . \qquad (1)$$

Here I_λ^j, $j = 1, 2$ are the components of the Stocks vector measured by an observer so that $I_\lambda = I_\lambda^1 + I_\lambda^2$ is the intensity, $P_\lambda = (I_\lambda^1 - I_\lambda^2)/(I_\lambda^1 + I_\lambda^2)$ is the degree of polarization, c_λ is the spectral solar constant, N is the number of particles in the column of a unit cross section along the line of sight, S_λ is the scattering cross section of a particle, g_λ^j are the components of the scattering phase matrix such that the sum $g_\lambda^1(\gamma) + g_\lambda^2(\gamma) = g_\lambda(\gamma)$ is the scattering phase function, and γ is the scattering angle. The value T_λ stands for the effective optical thickness of the atmosphere from the Sun to the scattering particles of the NO and is given by formula

$$\exp(-T_\lambda) = \frac{1}{L}\int \exp[-\tau(l)]\ \mathrm{d}l\ , \qquad (2)$$

where the integration is performed over the line of sight, $\tau(l)$ is the optical thickness of the layer from the Sun to the point with the coordinate l, L is the cloud size along the line of sight.

If the components L_λ^j (or certain linear combinations of them) and the optical thickness T_λ are known then Eq. (1) can be used for determining the value standing in the right side of this equation, and as a result, the microphysical parameters of scatterers can be estimated. Thus, a reliable modeling of the effective optical thickness T_λ is the first and most critical step in the interpretation of the crepuscular sounding data obtained from space. We have estimated the optical thickness T_λ based on the model calculations, in which the refraction and the finiteness of the angular diameter of the Sun were taken into account. In Fig. 1 the results of such a calculation for three wavelenghts are presented as a function of the azimuthal angle of the line of sight and of the angle of submergence of the Sun below the horizon. Three cases are considered: first, the atmosphere without refraction; second, the atmosphere with refraction but with the Sun being considered as a point source; and, finally, the atmosphere with refraction and with the finite angular diameter of the Sun. The aerosol and Rayleigh scattering as well as the extinction were calculated with the use of the model from Ref. 5, while the absorption by the ozone with the use of the model from Ref. 6.

From these model calculations (see Fig. 1) the following conclusions can be drawn:

First, in the UV region of spectrum ($\lambda = 0.3$ μm) the method of crepuscular sounding of the NC and MC from space is applicable in the cases of small values of the angles of submergence of the Sun below the horizon ($\alpha < 3°$). In the cases of larger angles the solar radiation is absorbed totally by the lower dense atmosphere and by the ozone layer, and, as a result, the refraction only slightly affects the formation of T_λ (at $T_\lambda \le 1$).

0235-6880/92/07 461-04 $02.00

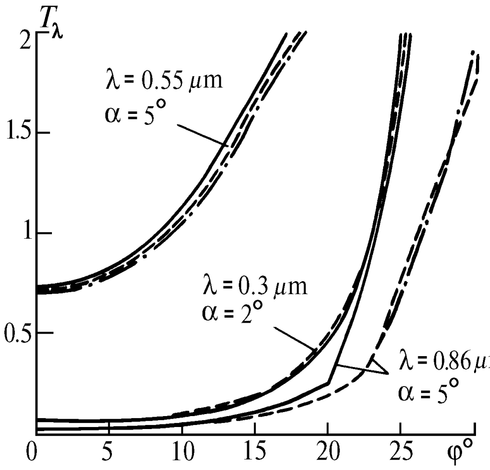

FIG. 1. The dependence of the optical thickness T_λ on the azimuthal angle of the line of sight φ and the angle α of submergence of the Sun below the horizon. The models: the atmosphere without refraction (solid lines); the atmosphere with the refraction and the Sun is assumed to be the point source (dashed lines); and, the atmosphere with the refraction and the solar diameter is taken to be finite (dashed–dotted lines).

Second, in the visible wavelength region ($\lambda = 0.55$ μm) the method can be used at the angles of submergence varying within the limits $0° < \alpha < 5°$. The refraction and the finite angular dimensions of the Sun slightly affect on the value of T_λ.

Third, in the IR wavelength region the method is applicable at the angles of submergence below the horizon down to 6–7°. The dimensions of the visible part of the solar limb have only small effect on T_λ, at the same time, the refraction should be taken into account.

Fourth, a reliable reconstruction of the microphysical parameters of the NC and MC is possible at $T_\lambda \le 1$ because at $T_\lambda > 1$ the reconstruction quality will strongly depend on the model of the lower atmosphere, and, in addition, the use of the single scattering approximation becomes too problematic.

When I_λ^j and T_λ are known Eq. (1) can be used for determining the microphysical parameters of scattering particles. For the NC consisting of ice particles, which are extremely small, and have approximately spherical shape, the mean radius $\bar{r}$ and the standard deviation $d = \sqrt{D}$ (D is the variance) of particle size are the most important microphysical characteristics of the scatterers. Therefore, Eq. (1) can be written in the form

$$A_\lambda^j(\gamma) = N\, S_\lambda(\bar{r}, d)\, g_\lambda^j(\gamma, \bar{r}, d)\,, \tag{3}$$

where the cross section $S_\lambda(\bar{r}, d)$ and the scattering matrix $g_\lambda^j(\gamma, \bar{r}, d)$ are the known functions of $\bar{r}$ and d, whose values may be calculated based on the Mie theory.[7] In this paper S_λ and g_λ^j were simulated with the use of the lognormal particle size distribution, however the obtained results are also valid for distributions close to the normal one and with the same values of $\bar{r}$ and d, because the optical properties of a polydisperse ensemble is almost insensitive to fine structure features of the distribution function shape.

We use the model of the NC, in which the values of $A_\lambda^j(\gamma)$ are the functions of three parameters, i.e., N, $\bar{r}$, and d, and as a result, it is neccessary to perform at least three independent measurements of the components of vector A in order to find these parameters. In practice it is advisable first to determine $\bar{r}$ and d with the use of two independent values of dimensionless combinations of the type $A_{\lambda_1}^{j_1}(\gamma_1)/A_{\lambda_2}^{j_2}(\gamma_2)$ and then to determine N from Eq. (3) provided that $\bar{r}$ and d are already known. Either the color index determined by the ratio of the radiation intensities at two specified wavelengths propagating along the direction (γ)

$$C_{\lambda_1\lambda_2}(\gamma) \equiv \frac{A_{\lambda_1}^1(\gamma) + A_{\lambda_1}^2(\gamma)}{A_{\lambda_2}^1(\gamma) + A_{\lambda_2}^2(\gamma_2)} = \frac{S_{\lambda_1}(\bar{r}, d)\, g_{\lambda_1}(\gamma, (\bar{r}, d))}{S_{\lambda_2}(\bar{r}, d)\, g_{\lambda_2}(\gamma, (\bar{r}, d))}\,, \tag{4}$$

or the degree of polarization

$$P_\lambda(\gamma) \equiv \frac{A_\lambda^1(\gamma) + A_\lambda^2(\gamma)}{A_\lambda^1(\gamma) + A_\lambda^2(\gamma)} = \frac{g_\lambda^1(\gamma, \bar{r}, d) - g_\lambda^2(g, \bar{r}, d)}{g_\lambda^1(\gamma, \bar{r}, d) + g_\lambda^2(\gamma, \bar{r}, d)} \tag{5}$$

may be used as such dimensionless combinations. In the problems of remote sounding the asymmetry parameter which is determined by the ratio of intensities of the radiation scattered along two different directions is also used rather frequently. However, under conditions of the crepuscular sounding from space the layer of the NC is rarely so much uniform that the number of particles N along the line of sight could be assumed constant for different directions. For this reason the asymmetry parameter cannot be used in this case.

We have simulated the color indices $C_{\lambda_1\lambda_2}(30°)$ and $C_{\lambda_3\lambda_4}(30°)$ and the degrees of polarization $P_{\lambda_1}(30°)$ and $P_{\lambda_2}(30°)$ as functions of $\bar{r}$ and d for $\lambda_1 = 0.3$ μm, $\lambda_2 = 0.55$ μm. $\lambda_3 = 1.0$ μm, and $\lambda_4 = 2.25$ μm. In simulation the condition $d \le \bar{r}$ was satisfied because large values of variance are not characteristic of physical distributions. Dependence of the color index $C_{\lambda_1\lambda_2}(30°)$ on the parameters $\bar{r}$ and d is shown in Fig. 2. The dependence shown in this figure is quite typical of the color indices.

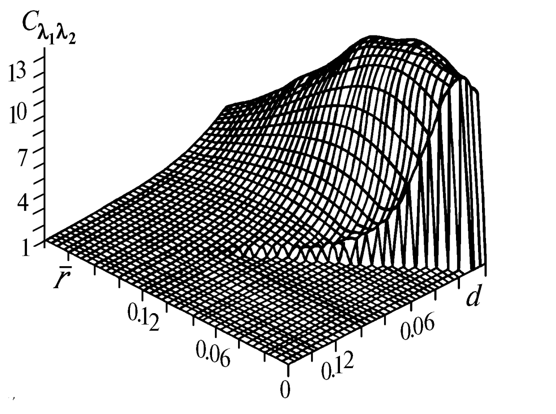

FIG. 2. The color index $C_{\lambda_1\lambda_2}(\gamma)$ as a function of the parameters $\bar{r}$ and d for $\lambda_1 = 0.3$ μm, $\lambda_2 = 0.55$ μm, and $\gamma = 30°$.

For determining unambiguously the values $\bar{r}$ and d from two independent values of the color indices $C_{\lambda_1\lambda_2}(\gamma)$ and $C_{\lambda_3\lambda_4}(\gamma)$ the corresponding surfaces need not to coincide or to lie very close. This requirement is equivalent to the condition that the isolines $C_{\lambda_1\lambda_2}(\gamma)$ and $C_{\lambda_3\lambda_4}(\gamma)$ in the plane $(\bar{r}, d)$ are neither coinciding nor parallel. The shape of isolines $C_{\lambda_1\lambda_2}(30°)$ and $C_{\lambda_3\lambda_4}(30°)$ is depicted in Fig. 3. Based on this figure one can draw the following conclusions:

– In the region of small particles ($\bar{r} < 0.08$ μm) the color index is primarily determined by the width of the distribution function and is practically independent of the mean radius of particles.

– At $\bar{r} > 0.08$ μm simultaneous measurements of $C_{\lambda_1\lambda_2}$ and $C_{\lambda_3\lambda_4}$ make the determination of the mean radius and the standard deviation of the particle dimensions sufficiently reliable and accurate within the measurement error.

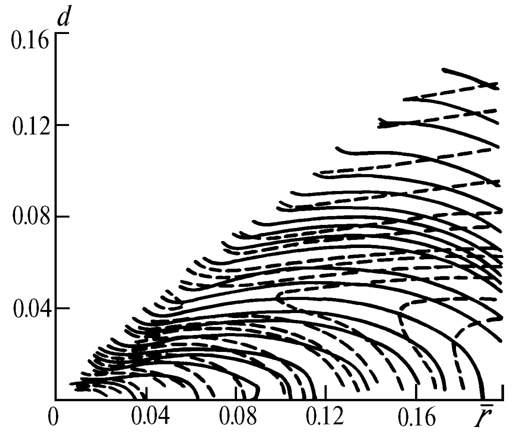

FIG. 3. The isolines of the color indices $C_{\lambda_1\lambda_2}(\gamma)$ and $C_{\lambda_3\lambda_4}(\gamma)$ in the plane $(\bar{r}, d)$ for $\lambda_1 = 0.3$ μm, $\lambda_2 = 0.55$ μm, $\lambda_3 = 1.0$ μm, and $\lambda_4 = 2.25$ μm. The solid lines refer to $C_{\lambda_1\lambda_2}$.

We also have studied the behavior of isolines of the color indices for other series of wavelengths, i.e., $\lambda_1 = 0.3$ μm, $\lambda_2 = 0.55$ μm, $\lambda_3 = 0.55$ μm, and $\lambda_4 = 1.0$ μm. In this case the isolines were parallel in higher degree than that shown in Fig. 3, and as a result, in the case of such a set of wavelengths the reconstruction of the parameters $\bar{r}$ and d would be more ambiguous. It should be noted that decrease of a scattering angle from 30 to 10° leads to the same result, i.e., the parallelism between the isolines intensifies, while the intersections between them can be observed only in the region of small values of d.

Figure 4 shows the isolines of the color index $C_{\lambda_1\lambda_2}$ and the degree of polarization P_{λ_1}. It can be seen that almost everywhere in the figure the isolines of C and P are parallel. This means that the degree of polarization does not bear additional information that could be useful when determining particle size distribution functions of the NC and the MC using the color index.

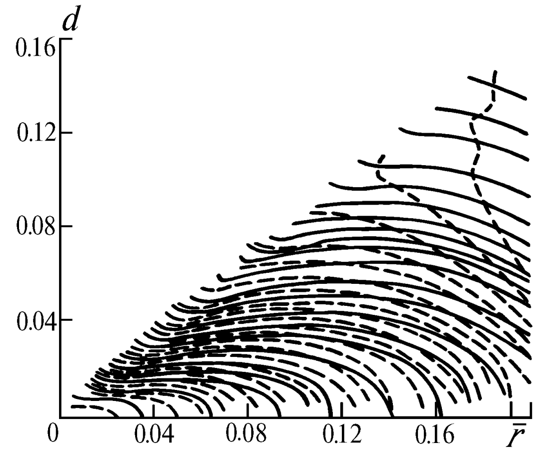

FIG. 4. The isolines of the color index $C_{\lambda_1\lambda_2}(\gamma)$ and of the degree of polarization P_{λ_1} in the plane $(\bar{r}, d)$ for $\lambda_1 = 0.3$ μm, $\lambda_2 = 0.55$ μm, and $\gamma = 30°$. The dashed lines refer to P_{λ_1}.

Summarizing the model calculations on reconstruction of the microphysical parameters, i.e., the mean radius and the standard deviation of the particles of the NC and the MC, the following conclusions can be drawn:

First, when planning experiments on the crepuscular sounding it is neccessary to take into account the fact that the optical thickness of the paths strongly depends not only on the wavelength but also on the azimuthal angle of the line of sight, and for this reason the permissible angles of the submergence of the Sun below the horizon in the UV range (0.3 μm) $\alpha \le 3°$, in the visible range (0.55 μm) $\alpha \le 5°$, and in the IR range (0.86 μm) $\alpha \le 6°$.

Second, in processing of the obtained data one should carefully take into account the extinction of solar radiation in the lower atmosphere; when the optical thickness $T_\lambda \le 1$ the refraction and the finiteness of the angular diameter of the Sun in the UV and visible wavelength regions can be ignored, while in the IR range the refraction is needed to be taken into account.

Third, the optical properties of the NC strongly depend on both the mean radius of the particles and the standard deviation d, and, therefore, interpretation of the measurement data should necessarily take into account both these parameters.

Forth, two values of the color index, one of which is measured in the UV or visible, and another in the IR, are most usefull for determining $\bar{r}$ and d.

Fifth, the employment of the degree of polarization for determining the parameters of the particle size distribution function under dusky condition is useless for two reasons:

– The isolines of the degree of polarization and the color index are parallel almost everywhere in the plane $(\bar{r}, d)$, and as a result, it is impossible to determine simultaneously these parameters of the distribution function.

– Accurate measurements of the degree of polarization from space is a complicated problem because this value is very small in the region of the solar aureole.

REFERENCES

1. G.V. Rozenberg, Dusk (Fizmatgiz, Moscow, 1963), 380 pp.
2. G.V. Rozenberg and V.V. Nikolaeva–Tereshkova, Izv. Akad. Nauk, Fiz. Atmos. Okeana **1**, No. 4, 386–394 (1965).
3. K.Ya. Kondrat'ev, A.A. Buznikov, and O.M. Pokrovskii, Dokl. Akad. Nauk SSSR **235**, No. 1, 53–56 (1977).
4. K.Ya. Kondrat'ev, ed., *The Investigation of the Environment from the Manned Space Stations* (Gidrometeoizdat, Leningrad, 1972), 399 pp.
5. *A Preliminary Cloudiness Standard Atmosphere for Radiation Computation. Radiation Commission IAMAP,* Boulder, Colorado (1984), 53 pp.
6. Z.L. Alexandrov, I.L. Karol, L.R. Rakipova, et al., *Atmospheric Ozone and Change in Global Climate* (Gidrometeoizdat, Leningrad, 1982), 168 pp.
7. D. Deirmendjian, *Electromagnetic Scattering on Spherical Polydispersions* (Elsevier, New York, 1969), 292 pp.