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Abstract

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ON CHANGES IN THE COLOR OF THE TWILIGHT SKY

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In order to determine the cause of changes in the color of the twilight sky, we carried out photoelectric measurements of the distribution of light energy of the twilight sky at the zenith and compared the results obtained with theoretical calculations.

The observations were made on the Kamenskoe Plateau, $\varphi = 43^\circ.2$ N, $\lambda = 76^\circ 56'$E, $H = 1450$ m above sea level, during the period from 9 X to 1 XI 1956, using a photoelectric photometer constructed by V. I. Moroz (1), and 7 interference filters centered at the following wavelengths: 367; 369; 405; 437; 554; 580 and 593 mμ. The observed brightness values were expressed in absolute units, erg/cm$^2\cdot$ sec $\cdot$ Å from 1 square degree of sky, by tying them to stars with conversion to a star of class G_2.

The brightness of the twilight sky was computed taking into account only first-order scattering for a spherical atmosphere with the density distribution given in (2), without allowance for refraction. The sky brightness I was determined by the formula

$$I = I_0 \sigma (1 + \cos^2 \Phi)\, d\omega \int_0^\infty \rho_h e^{-\beta x - \alpha x_1 - \tau_h}\, dh,$$

where I_0 is the energy of solar radiation incident on 1 cm^2 at the boundary of the earth' s atmosphere; σ is the scattering coefficient of pure air; Φ is the scattering angle; $d\omega$ is the solid angle cut out on the sky (in our case 1 square degree); ρ_h is the density of the atmosphere at height h above the earth' s surface; β is the absorption coefficient of pure air; α is the absorption coefficient of ozone;

$$x = \frac{1}{n(0)} \int_0^\infty n(h)\, ds; \qquad x_1 = \int_0^\infty m(h)\, ds; \qquad \tau_h = \frac{\beta}{n(0)} \int_0^\infty n(h)\, dh;$$

$n(h)$ and $n(0)$ are the numbers of air particles at height h km and at 0, respectively; $m(h)$ is the ozone concentration at height h; ds is an element of path along the direction of the solar ray in the earth's atmosphere; dh is an element of

Fig. 1

Figure 1: Fig. 1

the path along the vertical. The integrals in the expressions for I, x, x_1, and τ_h were evaluated numerically. For this purpose the atmosphere was divided into concentric layers with thicknesses from 1 to 50 km, according to the required accuracy. The values of the coefficients β and α and the distribution of ozone with height were taken, respectively, from works $(^{3,4,5})$.

A comparison of the computed brightness values with the observed ones shows that the intensity of the observed twilight glow at all wavelengths of the visible part of the spectrum is rather close to the intensity of first-order scattered radiation only in the interval of solar depressions from 0 to 6°.5. At greater solar depressions, the observed intensities exceed by several orders of magnitude the computed intensities of first-order scattering, as is seen in Fig. 1, where for $\lambda = 440$ mμ the observed brightnesses of the twilight sky at the zenith (crosses) are compared with the theoretical ones, computed taking into account only first-order scattering.

(solid line). A similar picture also holds for other wavelengths. This result agrees with the result of Hulburt $^{(6)}$, who compared calculated values of the brightness of the twilight sky with values obtained from observations at Sacramento Peak (USA).

Fig. 1

As can be seen from Fig. 1, beginning with $g_\odot = 8°.5$, allowing for scattering of only the first order gives brightnesses even smaller than the brightness of the night sky when the Sun is depressed to $g_\odot = 18°$. Thus, it may be assumed that, for solar depressions greater than 8°.5, first-order scattering plays a negligibly small role in the total radiation flux of the sky at the zenith in all regions of the visible spectrum.

To characterize the color of the twilight sky one may use, as Zidentopf did $^{(7,8)}$, the color temperature, although it would be better to use the reciprocal values of the color temperatures. As was to be expected, in the spectral region under study the observed energy distribution cannot be represented by a single temperature value. Therefore the observed spectral region was divided into two parts: the first from 370 to 440 mμ and the second from 440 to 600 mμ. The color temperature was determined by comparing the observed energy distribution with the Planck distribution calculated for a series of temperatures. The mean values of the color temperatures for the two spectral regions are presented in Table 1 (in thousands of °K).

Table 1

Region	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°
370–440 mμ	11	11	11	11	11	12	13	12	13	13	12	12	12	14	14
440–600 mμ	9	10	16	21	24	24	27	34	37	31	17	9	7	6	5

As can be seen from the table, the color temperature for the spectral region 440–600 mμ changes depending on the depression of the Sun below the horizon, reaching a maximum value when the Sun is depressed by about 10°. In the blue part of the spectrum (the interval 370–440 mμ) these changes are almost absent. Thus, it may be assumed that the changes in the color of the twilight sky in the spectral region studied are due mainly to the region 440–600 mμ, i.e., to the region of the Chappuis absorption band of ozone, which is in agreement with the results of works (6,9). This same result is confirmed by direct comparison of the observed energy distribution with the calculated one.

In Fig. 2 are presented curves of the energy distribution in the spectrum of the twilight sky, allowing for scattering of only the first order for a pure atmosphere (*a*), and also distribution curves obtained with allowance for ozone at its total content of 1.212 cm (*b*) and 0.400 cm (*c*). The observed brightness values are marked by crosses. As can be seen from the graphs, the observed energy distribution depends very strongly on ozone absorption in the Chappuis band. For solar depressions of 2 and 4°, the observed energy distribution proved to be closest to the energy distribution corresponding to a total ozone content of 4 mm. For depressions greater than 6°, the observed brightness values, as indicated above, cannot be represented by first-order scattering alone. Therefore at the corresponding-

of the curves of energy distribution, the observed brightnesses turn out to be considerably higher than the calculated ones.

Another characteristic of the color of the twilight sky may be the ratio of radiation intensity in two portions of the spectrum. The ratio of two monochromatic light intensities of the twilight sky changes hardly at all during the entire twilight period if they are chosen in a region of the spectrum free from ozone absorption. As an example, in Fig. 3 the circles show the values of the intensity ratio I_{367}/I_{437} for 367 and 437 mμ. A different picture occurs if one of the wavelengths belongs to the Chappuis band, as is seen from Fig. 3, where crosses mark the observed ratios I_{437}/I_{580}. In this case the ratio changes very strongly. The curve of the dependence of this ratio on the depression of the Sun has a maximum near 10°, which is in agreement with the results of I. A. Khvostikov, E. I. Magid, A. A. Shubin (10) and T. G. Megrelishvili (11), confirmed by us (12).

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

Consideration of the theoretically calculated course of this ratio shows that it is caused by ozone absorption.

Fig. 2

In Fig. 3 are presented calculated curves for the ratio of intensities I_{440}/I_{580} for pure air (a) and for an atmosphere with ozone at a total ozone content of 0.212 cm (b), 0.300 cm (c), and 0.400 cm (d). As is seen from the graph, the observed course of the intensity ratio corresponds to an ozone content of 0.400 cm, which agrees with the result presented in Fig. 2. The considered intensity ratios of twilight radiation depend to a strong degree on the ozone content, which can be used to determine the ozone content in the Earth' s atmosphere during twilight. However, the observed course of the brightness ratio of the twilight sky agrees with the calculated one only for solar depressions of 8—9°. At larger solar depressions the observed values are smaller than the calculated ones. This indicates that at solar depressions of 8—9° twilight at the zenith ceases and a transitional period from twilight to night begins. The sharp fall of the observed values of the ratios under consideration at large solar depressions is determined by the fact that under night conditions the intensity in the yellow-green region of the spectrum predominates over the intensity of the blue region of the spectrum. Under early-twilight conditions the opposite picture is observed—the intensity in the blue rays exceeds the intensity in the red. Thus, it should be considered that twilight at the zenith ends approximately at 8—9°. The period from 9 to 14° may be regarded as a transitional period from twilight to night. After 15° of solar depression, night conditions begin to become established.

Fig. 3

The observed character of the energy distribution in the spectrum of the twilight sky is due not only to the presence of ozone, but also to the general character

absorption of light in the Earth' s atmosphere. In particular, of great importance in the formation of the observed spectrum of the twilight sky are the heights of the so-called twilight rays for different wavelengths. As is seen from Fig. 4, which shows the dependence of the height of the effective twilight ray on the Sun' s depression for different wavelengths, at small solar depressions the difference in the heights of the effective twilight ray for 370 and 700 mμ reaches 20 km. Since at one and the same moment the effective twilight ray for short wavelengths lies higher than the rays for longer-wavelength radiation, the spectral distribution must be characterized by a low intensity in the extreme

Fig. 4

Figure 4: Fig. 4

blue region of the spectrum in comparison with the distribution corresponding to Rayleigh scattering.

Fig. 4. Height of twilight rays for different wavelengths as a function of the Sun’ s depression.
1 –$\lambda = 370$ mμ, 2 –440 mμ, 3 –500 mμ, 4 –580 mμ, 5 –600 mμ, 6 –650 mμ, 7 –700 mμ

Since, with increasing solar depression, the difference in the heights of the effective twilight rays decreases, as illustrated by Fig. 4, the relative intensity of the blue radiation increases, as a result of which the ratios of the intensities in the blue and yellow-green rays considered above must increase.

In analyzing the optical properties of the Earth’ s atmosphere by the twilight method, it should be taken into account that rays of different wavelengths at one and the same moment give information about different levels of the Earth’ s atmosphere. In addition, it must be borne in mind that the width of the twilight ray is different for different wavelengths. In this sense the blue rays are preferable, for which the twilight ray is considerably narrower than for the red rays.

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