

COLORIMETRY OF THE TWILIGHT SKY FROM HORIZON SPECTRA OBTAINED FROM THE “SOYUZ-5” SPACECRAFT

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Abstract

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An analysis of visual observations of the color of the twilight sky showed (¹) that the color pattern of the twilight sky should be an indicator of the structure of the atmosphere. This qualitative conclusion lends special interest to quantitative colorimetric estimates of the color of the twilight aureole, which became possible after the first spectrophotometry of the atmosphere near the horizon carried out from the "Soyuz-2" spacecraft. The results of spectrophotometry of the twilight aureole carried out on the 6th orbit of the "Soyuz-5" spacecraft under conditions of continuous cloudiness for a solar depression angle below the horizon $\delta_{\odot} \simeq 0^{\circ}$ are discussed in (², ³).

The use of values of the monochromatic brightness I_{λ} (λ is the wavelength) and of the standard colorimetric functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, tabulated in (⁴), makes it possible to calculate the chromaticity coordinates X, Y, Z of the twilight aureole from the formulas

$$X = \frac{\int_{\Delta\lambda} I\lambda\bar{x}(\lambda) d\lambda}{\int_{\Delta\lambda} I\lambda[\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)] d\lambda}; \quad (1)$$

$$Y = \frac{\int_{\Delta\lambda} I\lambda\bar{y}(\lambda) d\lambda}{\int_{\Delta\lambda} I\lambda[\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)] d\lambda}; \quad (2)$$

$$Z = \frac{\int_{\Delta\lambda} I\lambda\bar{z}(\lambda) d\lambda}{\int_{\Delta\lambda} I\lambda[\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)] d\lambda}. \quad (3)$$

The corresponding results are presented in the form of a chromaticity diagram (Fig. 1). Of undoubted interest in this connection is a comparison of visual observations of the twilight aureole under conditions of continuous cloudiness with colorimetric experimental and theoretical data at small solar depression angles below the horizon ($\delta_{\odot} \simeq 0^{\circ}$). The importance of such a comparison is

Figure 1. Chromaticity diagram

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determined by the fact that, for small values of the angle δ_{\odot} , visual observations of the brightness and color of the twilight aureole are hindered by strong scattering of sunlight by the upper edge of the clouds.

Theoretical calculations of the colorimetric characteristics of the twilight aureole were made for several models of the vertical structure of the Earth's atmosphere and for the observing conditions from the "Soyuz-5" spacecraft. The chromaticity coordinates X, Y , and Z of the twilight aureole were computed for a purely scattering molecular atmosphere, a purely scattering molecular atmosphere in the presence of nonabsorbing aerosol particles, and a purely scattering molecular atmosphere in the presence of nonabsorbing aerosol particles and ozone. The results of calculating the corresponding chromaticity coordinates X and Y are presented in Fig. 1.

The vertical profiles of the monochromatic coefficients of molecular and aerosol scattering, as well as the vertical profile of the volume absorption coefficient by ozone, were taken according to the Elterman model of 1968 ⁽⁵⁾. Near the Earth's surface the twilight Rayleigh aureole is colored in bright, saturated reddish-orange tones, which, as ...

with increasing altitude they pass into orange, yellowish-orange, and yellow shades. A characteristic feature of the color diagram of the twilight halo of a purely scattering molecular atmosphere is the presence of a broad whitish band of increased brightness between the yellowish and light-blue colors. Similar results were obtained earlier in (6).

The twilight halo of a purely scattering molecular atmosphere, in the presence of aerosol particles directly at the Earth's surface, is colored

Fig. 1. Chromaticity coordinates X and Y of the twilight halo for various models of the Earth's atmosphere (spacecraft orbital altitude $h \sim 252$ km; angle of the Sun's descent below the horizon $\delta_{\odot} \sim 0^{\circ}$; viewing azimuth direction $\varphi = 8^{\circ}$).

a —molecular atmosphere; b —molecular atmosphere and aerosols; v —molecular atmosphere, aerosols, and ozone; g —experimental data ("Soyuz-5," 6th orbit, continuous cloud cover); a, b, v —single scattering, Elterman model, 1968.

red. However, in general, the chromaticity diagram of the molecular atmosphere reproduces all the basic colors of the twilight halo in the presence of nonabsorbing aerosol particles.

The presence of ozone has a substantial effect on the evolution of the color of the twilight halo in the altitude range 20–30 km for wavelength $\lambda = 600$ m μ (maximum absorption in the Chappuis band). In contrast to the atmospheric models considered above, the sequence of color changes of the twilight halo

in the vertical direction in this case is as follows: red, reddish-orange, orange, yellowish-orange, yellow, whitish-

gray, light blue, blue, then again whitish, blue, and dark-blue tones. Since the monochromatic brightness curves of the twilight halo at $\delta_{\odot} \simeq 0^{\circ}$ lack noticeable depressions caused by the regular distribution of aerosol with altitude (7), the color features of the chromaticity diagram in the altitude range 20–30 km are due to ozone absorption to a greater extent than to scattering by aerosol particles.

A comparison of the absolute values of the chromaticity coefficients X and Y , calculated on the basis of experimental data and theoretical models for the angle of descent of the Sun below the horizon $\delta_{\odot} \simeq 0^{\circ}$ (the case of continuous cloud cover), indicates a discrepancy in chromaticity near the underlying surface (see Fig. 1). According to the experimental colorimetric data, the twilight halo near the horizon at $\delta_{\odot} \simeq 0^{\circ}$ is colored in purplish-red and purplish-pink tones, which then pass into purple, pale-pink, whitish, blue, and dark-blue. This color evolution closely corresponds to the color photograph of the twilight halo obtained by B. V. Volynov from the Soyuz-5 spacecraft at $\delta_{\odot} \simeq 0^{\circ}$ under conditions of continuous cloud cover (the photograph is not given because of the difficulty of reproducing color in print).

Since spectrophotometry of the twilight halo was carried out under conditions of continuous cloud cover, the deviation of the experimental colorimetric data from the theoretical data, calculated in the single-scattering approximation for a cloudless atmosphere, may be explained by unaccounted multiple scattering, by the presence of a reflecting cloud surface, or by the combined action of both factors. In the future it is highly desirable to investigate separately the influence of multiple scattering and of a reflecting surface located at different levels in the atmosphere on the color of the twilight sky observed from space.

As was shown earlier (1–3), there are discrepancies among the altitude evolutions of the color patterns of the twilight halo observed during the flights of the spacecraft *Vostok-6*, *Voskhod*, *Soyuz-5*, and *Gemini-4*. The descriptions of the color pattern of the twilight halo made by D. McDivitt and E. White on the *Gemini-4* spacecraft at $\delta_{\odot} \simeq 0.5^{\circ}$ (8) are closest to the visual colorimetric data obtained during the flight of the *Soyuz-5* spacecraft (cloudless atmosphere). The exceptions are the presence of a broad white band in the upper part of the halo (*Gemini-4*) and a dark-blue narrow band in the lower part of the halo (*Soyuz-5*). The existence of the first color feature may be due to reflection of sunlight from the upper part of the spacecraft window or to the influence of color adaptation of the cosmonaut's eye. The second feature was observed at rather large angles of the Sun's descent below the horizon and disappeared at $\delta_{\odot} \simeq 0^{\circ}$ (1). It is probably a consequence of a sufficiently powerful aerosol layer localized in the lower stratosphere at the time of the visual observations from the *Soyuz-5* spacecraft. These questions will be considered in more detail in the future. However, it can already be stated (taking into account the remarks made above) that a model of a molecular atmosphere containing aerosol and ozone (L. Elterman (5)) explains fairly well the principal qualitative features of

the color patterns of the twilight halo observed from the *Gemini-4* and *Soyuz-5* spacecraft under conditions of a cloudless atmosphere.

As was shown in (1-3), at small angles of the Sun's descent below the horizon the vertical depressions of the brightness of the twilight aerosol atmosphere are small or absent. However, it turned out that the color pattern of the twilight halo is very sensitive to the presence of such vertical inhomogeneities in the atmosphere as, for example, an ozone layer. Therefore, from the evolution of the color of the twilight halo with altitude it is possible to carry out a qualitative analysis of the vertical distribution of optically important components of the atmosphere.

As the angle of the Sun's descent below the horizon increases, the intensity of the scattered light and the saturation of the tones in the color pattern decrease. However, characteristic breaks and minima appear on the monochromatic-brightness curves; in color images (or photographs) of the twilight aureole, these are perceived as dark bands of reduced brightness. It is quite evident that, in solving inverse problems of space atmospheric optics that are important for practice, the colorimetric analysis of the optical data obtained should be combined with an analysis of the absolute values of the depressions on the monochromatic-brightness curves of the twilight aureole. There is also no doubt that a reliable solution to many problems of space atmospheric optics is possible only on the basis of broad and comprehensive experimental studies of the spectral brightness and color of the twilight aureole, carried out simultaneously under different conditions.

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CITED LITERATURE

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