# ASYMMETRY OF THE ATMOSPHERIC INDICATRIX OF SCATTERING OF LIGHT

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# "ASYMMETRY OF THE ATMOSPHERIC INDICATRIX OF SCATTERING OF LIGHT"

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As was shown by myself, the familiar formula of sky brightness derived from assumption of scattering of only the first order and absence of influence of the atmosphere's illumination by the underlying surface fully represents observations of the brightness of the day sky according to the almucantar of the Sun, at least in the case of absence of a snow blanket. This formula is the following:

$$B = -E^0_\odot \frac{\sigma}{k} f(\vartheta)\, m p^m \ln p \quad \text{or} \qquad B = E^0_\odot \sigma f(\vartheta)\, m p^m \quad (1)$$

Here B is the brightness of the sky at angular distance ~~theta~~ delta $\vartheta$ from the Sun; $E^0_\odot$ is the illumination by the Sun on an area perpendicular to radiation outside the atmosphere; m is the atmospheric mass in the direction toward the Sun or toward the observed point of the sky, which is without effect for the almucantar of the Sun; p is the coefficient of the atmosphere's transparancy: $\frac{\sigma}{k} = 1 : 2\pi \int_0^\pi f(\vartheta) \sin\vartheta \, d\vartheta$; $f(\vartheta)$ is the indicatrix of scattering of light ~~of~~ $f(\vartheta) = \mu$ is the flow of scattered light in a unity solid-angle under the angle of scattering $\vartheta$ (strength of the scattered light).

Let us determine on the basis of observed material $\frac{\sigma}{k} f(\vartheta) = \frac{\mu}{k}$, the ratio of the strength of scattered light under angle $\vartheta$ of scatter to the entire flow of scattered light. In as much as the indicatrix of scattering normalized is in such manner that for $\vartheta = 90^\circ$ we have $f(\vartheta) = 1$, then for this $\vartheta$ we have that $\mu/k = \sigma/k$; namely, the ratio of the coefficient of scattering to the coefficient of attenuation of light (in the case of absence of pure absorption). The values of $\mu/k$ characterize the scattering ability of the atmosphere.

The brightness of a clear day sky, and also of an area with known albedo set perpendicularly to solar radiation, was observed by myself, using a visual photometer of V.G.Fesenkov's design supplied with blue, green, and red Shott filters (effective wavelengths of the system: eye-filter were respectively 476, 546, and 625 mu). The observations were performed mostly in South Kazakhstan at various altitudes above sealevel.

Because the formula (1) fully represents observations, we have

$$\mu = \frac{B}{E_\odot}\,\frac{1}{m} \qquad (2)$$

in as much as $E_\odot = E_\odot^0 p^m$, holds true where $E_\odot$ is the illumination from the Sun on an area perpendicular to radiation at the site of observation. The coefficient of attentuation due to scattering is given by:

$$k = 2\pi\int_0^{\pi} \mu_\vartheta \sin\vartheta\, d \qquad (3)$$

We have from observations the ratios of sky brightness, for various $\vartheta$, to solar illumination $B/E_\odot$, and also m, which were determined from Bemporad's table. Table 1 gives the values of $\mu/k$ averaged for each observation site separately for all three filters and also the number of observations. The values of $\mu/k$ may be represented in the form $\mu/k = a/16\pi$ by analogy with the Rayleigh scattering, for which we have $\mu/k = 3/16\pi$ for $\vartheta = 90^\circ$. Table 1 gives the values of the numerator a.

From Table 1 we may draw the conclusion that on the average the values of $\mu/k$ do not depend on the altitude of the observation site in the lower aerosol layer of the atmosphere.

Table 2 gives the same values of a, taken as the average of all values of a given in Table 1, for each wavelength and separately with the mean-square errors. In addition, for sake of comparison, the a values are given for the Rayleigh and spherical indicatrices of scattering.

Table 3 gives the same values of a as do Table 1 and 2 for days with maximum and minimum observed elongation of the indicatrix of scattering for $\lambda = 546$ mu. In addition, deviations of the first indicatrix from the second for various $\vartheta$ is given in percents.

From analysis of all tables it it as a rule that the more the indicatrix of scattering is elongated "forwards," the more it is compressed "back." For $\vartheta = 60$ and $90^\circ$ the deviations from average even of individual values of $\mu/k$ lie within limits of accuracy of observations or nearly in these limits (the relative error of $\mu/k$ depends on m and is 3 to 5%). However, while for $\vartheta = 60^\circ$ these deviations have no systematic behavior with variation of elongation of the indicatrix, scattering for $\vartheta = 90^\circ$ such systematic behavior, although not great, is already noticeable; namely, as a rule, $\mu/k$ for this $\vartheta$ decreases with increasing elongation of the indicatrix of scattering. Therefore in the real atmosphere the ratio of the coefficient of scattering to the coefficient of attenuation of light $\sigma/k$ ($\mu/k$ for $\vartheta = 90^\circ$) of the same wave length varies little. For the investigated part of the spectrum, $\sigma/k$ decreases slightly with increasing wave length, keeping close to the Rayleigh value.

From the tables presented we may draw the conclusion that with increasing wavelength $\lambda$ the elongation of the indicatrix of scattering increases "forwards" and decreases "backwards." This confirms the familiar phenomenon of broadening of the solar corona with increasing $\lambda$. Let us determine the asymmetry of the indicatrix of scattering for all three wavelengths. For this purpose let us find the ratio $\mu_1/\mu_2$ of strength of scattered light "forwards" and "backwards" for symetrical angles of scattering. Let us take $\vartheta$: 1) 20 and 160°; 2) 40 and 140°; 3) 60 and 120°. For these three combinations of ~~theta~~ $\vartheta$ we obtain on the basis of observations the mean value of $\mu_1/\mu_2$ as presented in Table 4.

These values of $\mu_1/\mu_2$ are plotted on a graph as a function of $\lambda$ (see circles on Figure 1). Individual values of $\mu_1/\mu_2$ give points that are rather dispersed, but the mean values, as seen from the figure, are placed well on straight lines, which intersect near $\lambda = 300$ mu, $\mu_1/\mu_2 = 1$. Therefore, if such an extrapolation may be accepted, near $\lambda = 300$ mu the asymmetry of the indicatrix of scattering vanishes, and for $\lambda < 300$ mu the negative effect of Mie should occur. Such a conclusion is contrary to the theory of Mie, from which it follows that with increasing $2\pi\rho/\lambda$, where $\rho$ is the radius of the scattering particle, the asymmetry of the indicatrix of scattering increases. For $\rho$ constant the asymmetry of the indicatrix should increase with decreasing wavelength. Observations of the brightness of the sky provide a contrary result.

If from the strength of the scattered light we separate for each $\vartheta$ a component due to air molecules, the remainder will

will correspond to the aerosol component. The asymmetry of aerosol indicatrix of scattering is more sharply expressed than the total (molecules + aerosols) and also decreases with wavelength. Figure 1 gives $\mu_1/\mu_2$ in the case of aerosols for $\vartheta$: 1) 40 and 140°, and 2) 60 and 120° (see crosses). Individual values of $\mu_1/\mu_2$ for the aerosol component show a still more conspicuous scattering of points ~~than for the aerosol component show a still more conspicuous scattering of points~~ than for the total, because of a considerable relative error. However, the mean values of $\mu_1/\mu_2$ for the two combinations indicated are arranged well on straight lines, as seen from the figure. The values of $\mu_1/\mu_2$ are not plotted for $\vartheta$ = 20 and 160°, because in this case the mean values are obtained only from two individual values and therefore are widely scattered. However, as seen from Table 5, where $\mu_1/\mu_2$ are given for aerosol, the values of $\mu_{26}/\mu_{1}60^{\circ}$ also increase with increasing wavelength.

In order to defy contradictions with respect to the influence of scattering of higher orders, Table 6 shows $\mu_1/\mu_2$ observed during days having various turbidity of the atmosphere, but select in such a way that atmoshphere's transparency should be the same for the various wavelengths.

As is seen from Table 6, in the case of identical turbidity of air a greater asymmety of the indicatrix of scattering corresponds to longer wavelength. Therefore the fact of increasing asymmetry of the indicatrix of scattering with increasing wavelength should be explained by the properties of aerosols.

Table 1.

| Site of observation | Altitude h in m | ϑ in ° |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  | 10 | 20 | 60 | 90 | 120 | 140 |
| **Blue filter, $\lambda_{eff}$ = 476 mu** |  |  |  |  |  |  |  |
| City of Ivanovo, village Bogorodskoye | 150 | 10.6 | 7.64 | -- | 2.88 | 3.30 | -- |
| Desert of South Pribalkhash'ye | 400 | 9.5 | 7.41 | 3.92 | 3.06 | 3.49 | 4.111 |
| City of Alma-Ata, Botanical Garden | 850 | 18.6 | 8.73 | 3.88 | 2.80 | 3.08 | -- |
| City of Alma-Ata, Mountain Observatory | 1400 | 13.4 | 8.57 | 3.91 | 2.83 | 3.12 | 3.75 |
| City of Alma-Ata, Mount Kumbel | 3100 | 11.0 | 7.69 | 3.91 | 2.92 | 3.35 | 3.94 |
| Number of observations | -- | 19 | 21 | 19 | 21 | 19 | 14 |
| **Green filter, $\lambda_{eff}$ = 546 mu** |  |  |  |  |  |  |  |
| City of Ivanovo, village Bogorodskoye | 150 | -- | 8.67 | 3.86 | 2.82 | 3.30 | -- |
| Desert of South Pribalkhash'ye | 400 | 13.3 | 8.08 | 3.86 | 2.90 | 3.30 | 3.94 |
| City of Alma-Ata, Botnaical Garden | 850 | 24.6 | 9.56 | 3.82 | 2.81 | 2.98 | 3.41 |
| City of Alma-Ata, Mountain Observatory | 1400 | 16.5 | 8.95 | 3.88 | 2.80 | 3.02 | 3.52 |
| Shore of lake Issykkul | 1600 | 18.2 | 8.79 | 3.70 | 2.80 | 3.17 | 3.75 |
| City of Alma-Ata, Mount Kumbel | 3100 | 13.3 | 8.21 | 3.84 | 2.89 | 3.30 | 3.73 |
| Number of observations | -- | 51 | 53 | 51 | 53 | 46 | 33 |
| **Red filter, $\lambda_{eff}$ = 625 mμ** |  |  |  |  |  |  |  |
| Desert of South Pribalkhash'ye | 400 | 15.2 | 8.83 | 3.87 | 2.89 | 3.15 | 3.69 |
| City of Alma-Ata, Mountain Observatory | 1400 | 23.2 | 11.9 | 3.83 | 2.62 | 2.67 | 2.90 |
| City of Alma-Ata, Mount Kumbel | 3100 | 17.6 | 9.85 | 3.87 | 2.70 | 2.94 | 3.25 |
| Number of observations | -- | 14 | 15 | 15 | 15 | 15 | 9 |

Table 2.

| ~~theta~~ $\vartheta$ in ° | Blue filter | Green filter | Red filter | Rayleigh indicatrix | Spherical indicatrix |
|---|---|---|---|---|---|
| 10 | 12.60 ± 0.60 | 17.20 ± 0.60 | 18.70 ± 1.30 | 5.91 | 4.0 |
| 20 | 8.01 ± 0.19 | 8.71 ± 0.12 | 10.20 ± 0.30 | 5.65 | 4.0 |
| 60 | 3.90 ± 0.03 | 3.83 ± 0.02 | 3.86 ± 0.04 | 3.75 | 4.0 |
| 90 | 2.90 ± 0.03 | 2.84 ± 0.02 | 2.74 ± 0.04 | 3.00 | 4.0 |
| 120 | 3.27 ± 0.05 | 3.18 ± 0.03 | 2.92 ± 0.08 | 3.75 | 4.0 |
| 140 | 3.93 ± 0.07 | 3.67 ± 0.05 | 3.28 ± 0.13 | 4.76 | 4.0 |

Table 3.

|  | ~~theta~~ $\vartheta$ ° |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Data | 10 | 20 | 60 | 90 | 120 | 130 |
| 14 Oct 1945 | 24.60 | 9.56 | 3.82 | 2.81 | 2.98 | 3.18 |
| 12 Oct 1948 | 9.16 | 6.98 | 3.83 | 2.97 | 3.51 | 3.94 |
| Difference in % | + 169 | + 37 | + 0.3 | - 5.4 | - 15 | - 19 |

Table 4.

| Wavelength $\lambda_{eff}$ in $m\mu$ | $\frac{\mu_{20^\circ}}{\mu_{160^\circ}}$ | $\frac{\mu_{40^\circ}}{\mu_{140^\circ}}$ [sic] | $\frac{\mu_{60^\circ}}{\mu_{120^\circ}}$ |
|---|---|---|---|
| 476 | 1.60 | 1.37 | 1.20 |
| 546 | 1.82 | 1.50 | 1.27 |
| 625 | 2.09 | 1.66 | 1.34 |

Table 5.

| Wavelength $\lambda_{eff}$ in $m\mu$ | $\frac{\mu_{.0^\circ}}{\mu_{160^\circ}}$ [sic] | $\frac{\mu_{40^\circ}}{\mu_{240^\circ}}$ [sic] | $\frac{\mu_{60^\circ}}{\mu_{120^\circ}}$ |
|---|---|---|---|
| 476 | 2.92 | 2.15 | 1.54 |
| 546 | 4.02 | 2.63 | 1.70 |
| 625 | 7.86 | 3.20 | 1.90 |

indicatrix with increasing $\lambda$ should be explained by properties of the aerosols.

Table 6.

| Site of observation | Date | Wavelength $\lambda_{eff}$ in m$\mu$ | $p$ | $\frac{40^\circ}{140^\circ}$ | $\frac{.0^\circ}{120^\circ}$ [sic] |
|---|---|---|---|---|---|
| Mount Kumbel' | 9 Aug 1949 | 546 | 0.90 | 1.32 | 1.12 |
| " " | 11 Aug 1949 | 625 | 0.90 | 1.90 | 1.39 |
| Desert | 9 Oct 1948 | 625 | 0.90 | 1.67 | 1.31 |
| Mount Kumbel' | 10 Aug 1949 | 546 | 0.87 | 1.63 | 1.36 |
| Desert | 10 Oct 1948 | 546 | 0.87 | 1.29 | 1.13 |
| Mountain Observatory | 5 Sep 1946 | 546 | 0.87 | 1.51 | 1.20 |
| " " | 28 Aug 1946 | 625 | 0.87 | 2.06 | 1.51 |
| Mount Kumbel' | 9 Aug 1949 | 476 | 0.84 | 1.27 | 1.18 |
| Desert | 9 Oct' 1948 | 546 | 0.84 | 1.45 | 1.24 |

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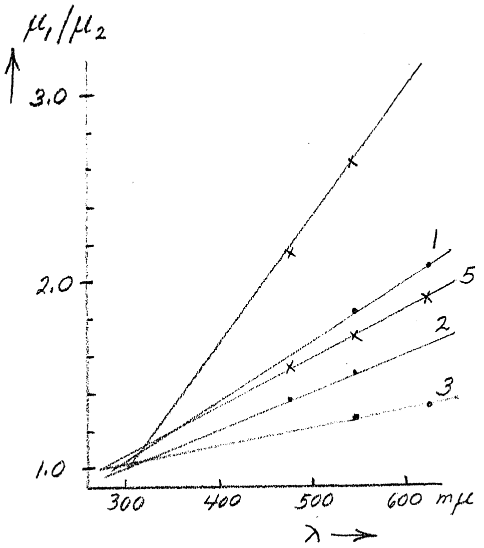

Figure 1. ⊙ - molecules + aerosols:
1 - $\mu_{20°}/\mu_{160°}$

2 - $\mu_{40°}/\mu_{140°}$

3 - $\mu_{60°}/\mu_{120°}$.

X - aerosols:
4 - $\mu_{40°}/\mu_{140°}$

5 - $\mu_{60°}/\mu_{120°}$.

- END -

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