EVALUATION OF THE ATMOSPHERIC OPTICAL CHARACTERISTICS IMPACT ON THE SOLAR CORONA OBSERVATION

*Kalinka Bakalova, Vitchko Tsanev**

Solar-Terrestrial Influences Laboratory, Bulgarian Academy of Sciences, 1113 Sofia

**Institute of Electronics, Bulgarian Academy of Sciences, 1113 Sofia*

Introduction

The present study of the atmospheric optical characteristics is stimulated by the necessity to account for their influence on the spectral images of the corona taken during the total solar eclipse from 11 August 1999. Nevertheless, the approach is common to various methods of coronal observations – e.g. during eclipses or using coronographs. We are mostly interested in the optical properties of the atmosphere that determine the transfer of direct and single scattered coronal radiation during a total solar eclipse. The final aim of the present study is to determine the restrictions on observations due to the atmosphere by comparison between the direct and single scattered components in the coronal measurements under various circumstances including the direction of the beam, the solar zenith angle and the altitude of observation.

The solar corona, when there are appropriate conditions for observation, could be considered as an extended light source of dimensions up to 22 solar radii R_{Θ} [1] and a corresponding angular radius not exceeding 6^{0}. That is why the angular radius of the optical field of view is confined to 6^{0} in our computations, supposing that the optical axis of the photograph instrument is pointing to the Sun. As far as every beam bearing specific information from the corona is projected onto a particular point in the picture, the polar coordinates of this point are in one-to-one correspondence with the direction of the beam. All possible directions of observation inside the view field are defined by the polar angle θ about the optical axis and the azimuth angle φ measured in the image plane which is normal to the optical axis. Each view line has a different zenith angle z measured from the local vertical, expressed as follows

(1) $$cos(z) = cos(\theta)cos(z_{\Theta}) - sin(\theta)sin(z_{\Theta})cos(\varphi)$$

where z_{Θ} is the solar zenith angle. The values of z vary in the range $z_{\Theta} \pm 6^{0}$. The extreme quantities correspond to the peripheral points in the picture for which $\varphi = 0^{\circ}$ or $\varphi = 180^{\circ}$. We reckon azimuth φ in the image plane from its intersection with Sun's vertical where $z = \max$. All further formulae hold true for monochromatic radiation, so the dependence on the wavelength is not explicitly shown. The numerical quantities in the figures refer to wavelength of 0.55 μm and to atmospheric models for summertime at middle latitude [2]. The optical characteristics of aerosols are taken from the models in [3]. These do not confine the general use of considerations.

Atmospheric transmittance and optical depth

We use the plane-parallel and horizontally homogeneous model of the atmosphere which is acceptable when the zenith angle z of the beam is not greater than 75^0. In this case, the optical depth T of a slant path is a product of the optical depth T_0 of the corresponding vertical path between the two altitudes h_1 and h_2 and the airmass factor $m(z) = \sec(z)$. Generally, we have

$$(2) \qquad T(z) = T_0\, m(z)\ , \qquad T_0 = \int_{h_1}^{h_2} \alpha_e(h)\, dh\ .$$

Here, $\alpha_e\,(h)$ is the vertical distribution of the coefficient of extinction, measured in km^{-1}. When the path encompasses the entire height of the atmosphere from sea level to the top of the atmosphere, h_1 is equal to 0 and h_2 is denoted by H_a. We can find the atmospheric transmittance along any slant path utilizing the Bouguer-Lambert's law

$$(3) \qquad \tau(z) = \exp\left(-m(z)\, T_0\right) = {\tau_0}^{m(z)}$$

if $\alpha_e\,(h)$ is known. In (3), the transmittance along the vertical path is denoted by τ_0.

The distribution of the transmittance $\tau(z(\theta,\varphi))$ for an arbitrary point (θ,φ) in the image plane shows the directional dependence of the transfer through the medium of the radiance coming from a unit uniform light source. In other words, $\tau(z(\theta,\varphi))$ is a multiplier modifying the space distribution of the coronal image. The airmass factor is an even function of the azimuth angle φ and τ is mirror-symmetric about axis $\varphi=0^0 | 180^0$.

It follows from formulae (1), (2), and (3) that for a given vertical stratification $\alpha_e(h)$, the Sun's zenith angle z_Θ, and altitude of observation h_1, the dependence of the transmittance on the direction of the beam is only geometrical. The behavior of the transmittance $\tau(\theta)$ from the center to the periphery of the image (at the sea level) for different values of φ is presented in Fig. 1.

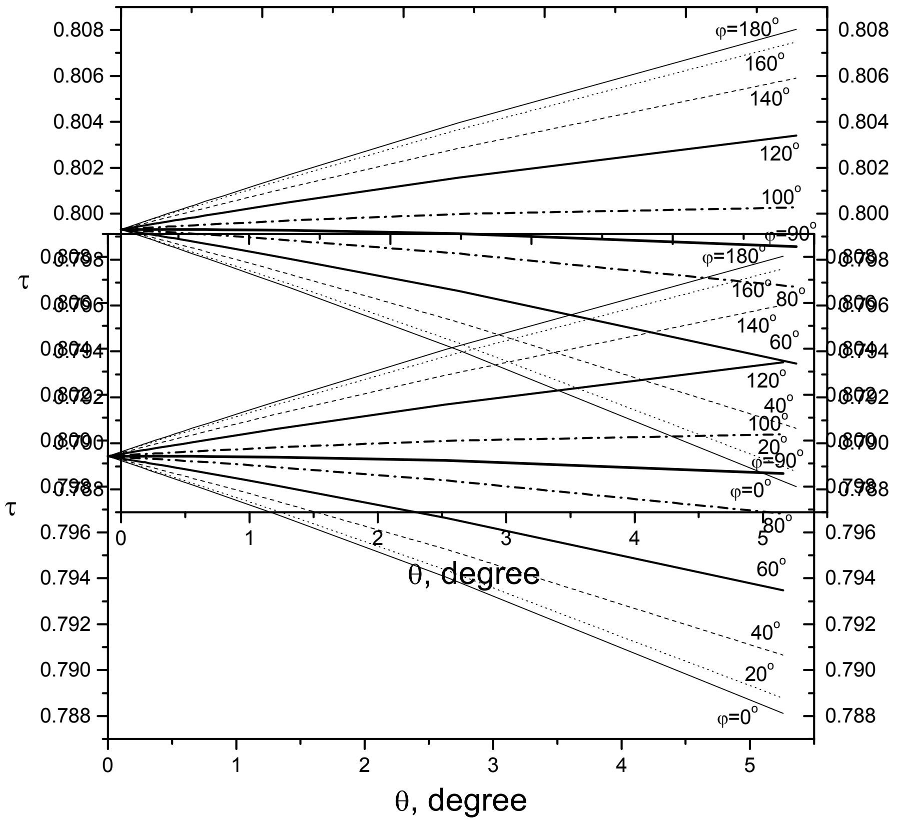


Figure 1. Distribution of the spectral transmittance τ(θ) (for λ=0.55 μm) from the center to the periphery of the image for different values of φ through the entire atmosphere.

The transmittance decreases when φ varies from 0^0 to 90^0 and it grows up for $90^0 < \varphi < 180^0$. The transmittance practically keeps its value in the limits of the considered optical angle of view in the direction $\varphi = 90^0$ which is normal to the Sun's vertical. For an arbitrary value of θ, the transmittance has a minimum at $\varphi = 0^0$ and is maximal for $\varphi=180^0$. This asymmetry of the transmittance distribution in the image plane is illustrated in Fig. 2 where τ(φ) is shown for three values of the polar angle θ. We have to mention that the asymmetry is stronger manifested at higher values of θ.

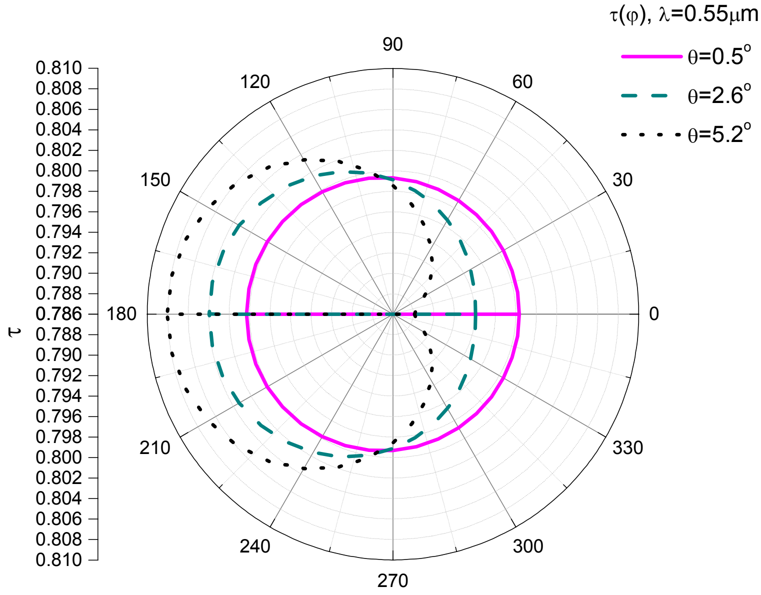


Figure 2. Asymmetry in the distribution of the transmittance $\tau(\varphi)$ for three values of the angle θ.

Computations of the dependence $\tau(z(\theta,\varphi))$ for all possible directions inside the view field are necessary to account for the influence of the atmosphere on the transfer of the direct radiance from different parts of the corona. The measured radiance should be divided by $\tau(z(\theta,\varphi))$ in order to obtain the real value. Strictly speaking, this is true only when the direct radiance exceeds significantly the background of the scattered light. Such a light source is the corona only near the solar limb because its radiance decreases rapidly along the radial direction (more than 10^6 times at distance of $20R_\Theta$ [1]).

<u>Single scattering in the atmosphere</u>

Scattered radiation is a parasitic additive component in the measurements. It restricts coronal observations. Determination of the Earth's atmosphere scattering properties is very important because it could be used to introduce some corrections in coronal measurements at greater distances from the solar limb.

The radiance of single scattered light is proportional to the irradiance (the surface density of the flux) from the source of initial radiation. The coefficient of proportionality describes the scattering capacity of the medium. In case of single scattering arising in the atmospheric stratum between altitude h_1 and altitude h_2, it takes the form [4]

(4) $$S_1(\theta,\varphi) = m(z)\int_{h_1}^{h_2} \tau(h_1,h)^{m(z(\theta,\varphi))}\ \tau(h,h_2)^{m(z_\Theta)}\beta(h,\theta)\ dh\ .$$

Here, β is the angular scattering coefficient of dimension km^{-1} steradian^{-1}. When the optical axis is pointing to the light source , the scattering angle is equal to the polar angle θ.

The distribution of the function S_1 in the image plane indicates the directional dependence of the single scattered radiance coming from a light source which gives unit uniform irradiance. The integral in (4) is practically independent of azimuth φ. There are some differences in the fourth significant digit when θ exceeds 5^0. That is why the asymmetry in the distribution of the single scattered radiance is due only to the airmass factor $m(z)$. As distinct from the transmittance (see (3)), the scattered light is in direct

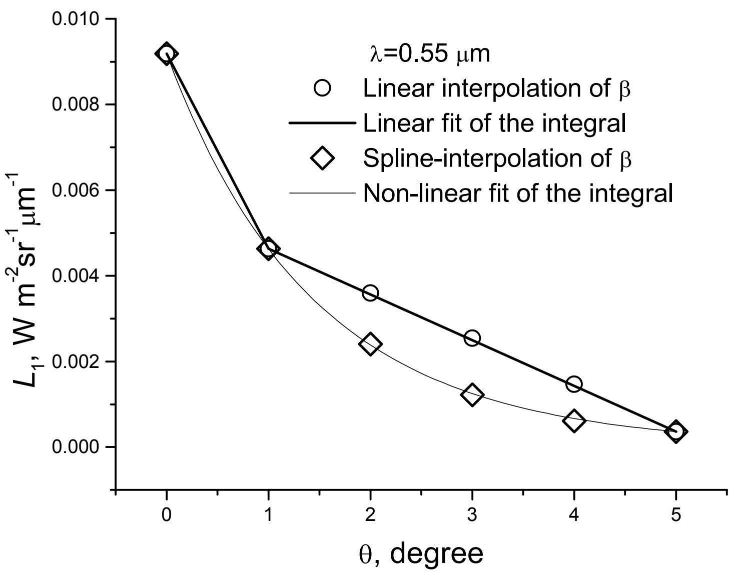


Figure 3. Radial distribution of single scattered coronal radiance

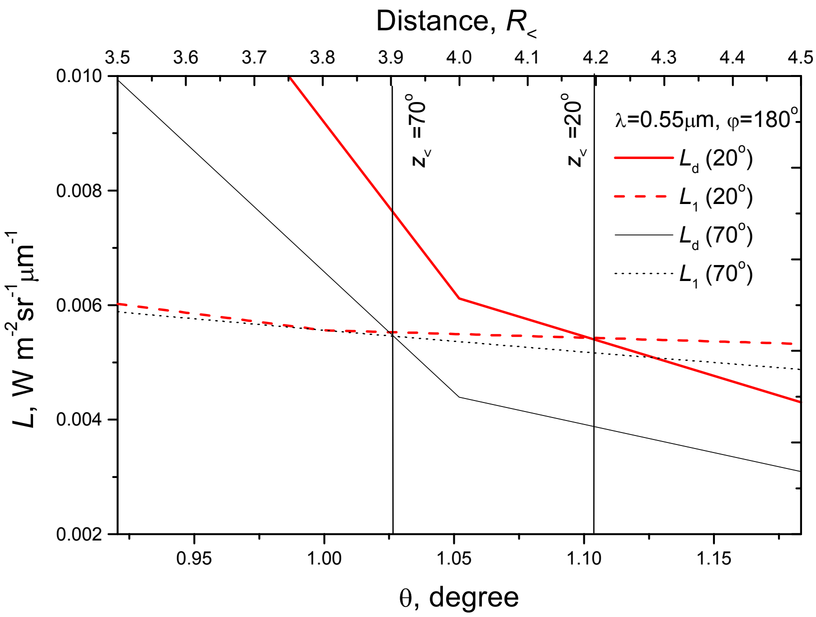
proportion to the airmass factor and is minimal for $\varphi = 180^0$. This direction is optimal for outlining the signal against the background from theoretical point of view.

The integrand in (4) consists of three multipliers. Two of them describe the transmittance of the atmosphere along the paths before and after the act of scattering that occurs at altitude *h*. The dependence of their product on the direction is negligible. Most important is the angular scattering coefficient β because the aerosols phase function is extremely extended in the forward direction. It varies by more than two orders in the considered range of angles between 0^0 and 6^0. The basic problem in the evaluation of S_1 comes from the limited data available in this range, namely at 0, 1, and 5 angular degrees [3]. To make computations more precise we performed both linear and spline interpolation of the phase function in the range 0^0-180^0 with step 1^0 for all 28 known altitudes [5]. As far as the procedure of preliminary spline interpolation is too labor-consuming and only a little part of the angular range is used, another approach is also tested. The computations of (4) are carried out for only 3 values of θ (0^0, 1^0, and 5^0) for which the quantities of the phase function are tabulated. Later, $S_1(\theta, \varphi = const)$ is determined by choosing an appropriate fitting function. The results from all mentioned methods of procedure are presented in Fig. 3. As an example, the amounts of the single scattered radiance $L_1 = S_1 E_c$ from the corona during a total solar eclipse are taken. The quantity E_c is the irradiance caused by the corona. It turns out that only data elaborated for aerosol phase function could increase evaluation accuracy. The results obtained from the fit of the integral are identical to those from preliminary interpolation of the integrand β and thus time-consuming procedures can be avoided.

Comparison between direct and single scattered radiance

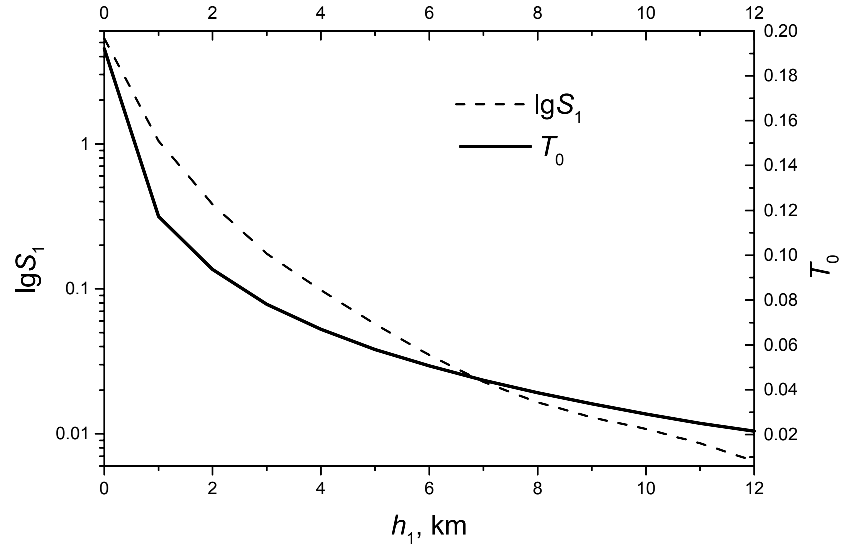
We have already discussed the directional dependence of atmospheric optical characteristics during coronal observations. As a result of our theoretical models and computations we can evaluate and compare the amounts of direct and single scattered radiance in the radial direction under various circumstances. For example, it is important to evaluate the influence of the Sun's zenith angle during eclipses that occur at particular places (latitudes) and daytime. The distances where the direct and single scattered coronal radiance at sea level equalize for $z_\Theta = 20^0$ and $z_\Theta = 70^0$ are shown in Fig. 4. It could be inferred that the lesser the zenith angle z_Θ, the better conditions for observation of the corona. On the whole, coronal observations at sea level are strongly influenced by the Earth's atmosphere and at distances of about $4R_\Theta$ scattered skylight exceeds direct radiance.

Further, we are interested in the possibility for coronal observations at higher altitudes. As it could be expected, optical thickness and atmospheric scattering capacity decrease with growth of h_1 because the medium gets thinner. This means better conditions for transfer of direct and lesser-scattered radiance. From computations using formulae (2) and (4) when $h_2 = H_a$, it follows that optical thickness decreases ten times Figure 4. Comparison between the direct L_d and the



single scattered L_1 coronal radiance at sea level for two values of the Sun's zenith angle z_Θ.

Figure 4. Comparison between the direct L_d and the single scattered L_1 coronal radiance at sea level for two values of the Sun's zenith angle z_Θ.



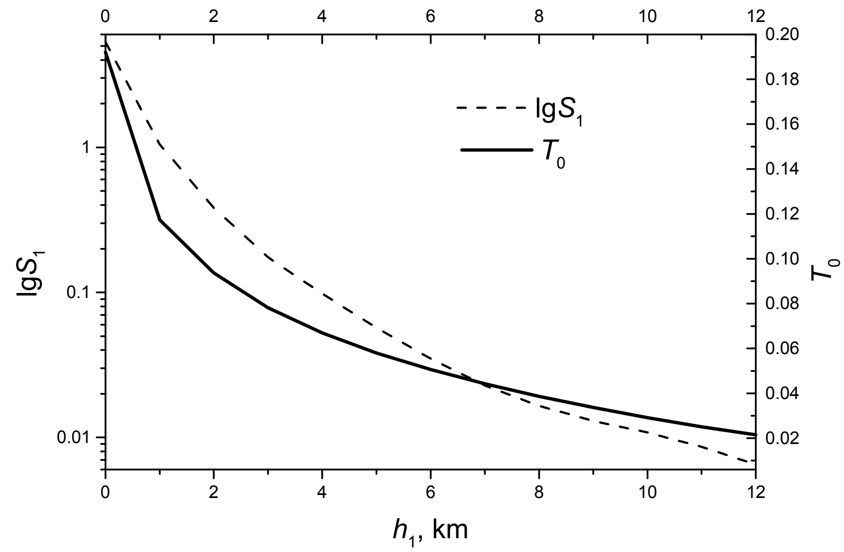


Figure 5. Vertical optical depth $T_0(h_1, H_a)$ and scattering capacity $S_1(h_1; \theta = 0, \varphi = 0)$ from altitude h_1 to the top of the atmosphere H_a.

and scattering capacity by two orders at altitude $h_1 = 12\ km$. The behavior of the atmospheric characteristics ($\lg S_1(h_1; \theta = 0, \varphi = 0)$ and $T_0(h_1, H_a)$) is shown in Fig. 5. The distances at which direct and single scattered coronal radiance equalize more and more increase at higher altitudes. For example, with sea level observation, when $z_\Theta = 31^0$ the cross point is at $4R_\Theta$, whereas, with $h_1 = 1\ km$, the cross point shifts to above $5.5R_\Theta$ and with $h_1 = 2\ km$ it shifts to above $11R_\Theta$. It is a good chance if the total solar eclipse can be observed at such a base altitude. The location of some cross points is denoted in Fig. 6. At aircraft's altitude of 12 km, the direct coronal radiance approaches the scattered one down to $20R_\Theta$. Practically, the entire corona could be observed in open-air conditions.

Figure 6. Comparison between the direct L_d and the single scattered L_1 coronal radiance for

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