INTERPRETATION OF THE ILLUMINATION MEASUREMENTS BY THE AUTOMATIC INTERPLANETARY STATION 'VENERA 8'

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Abstract. Measurements of the downward light flux during the descent from an altitude of 50 km to the ground have been made. Atmospheric layers with different optical thicknesses have been discovered. The optical properties of Venus atmosphere for different cloud models have been studied.

The scientific program of 'Venera 8' included measurements of the downward light flux – the illumination $F_{\downarrow}(z)$ during descent from an altitude $z=50$ km to the ground, $z_z=0$. The sensor was a cadmium-sulfide photoresistor; its spectral range was 0.4–0.8 μm, and the effective wavelength $\lambda_{\text{eff}}=0.63$ μm. The duration of the measurements was 56 min, the mean zenith distance of the Sun $\zeta=84.5° \pm 2.5°$.

The main direct result of the illumination measurements is that the thick Venus atmosphere transmits light. The measurements have given:

$$100 \frac{F_{\downarrow}(0)}{\mathcal{S}_{0,\lambda_{\text{eff}}} \cos\zeta} = 1\%^{+1}_{-0.5}.$$

$\mathcal{S}_{0,\lambda}$ is the spectral solar constant.

A second direct result of the measurements is the discovery of layers with different optical thicknesses: the light extinction per km is equal to 0.15 in the layer from 0 to 35 km, 0.20 from 35 to 50 km, and 0.35 between 50 and 70 km (if the extinction at $z>70$ km is neglected). Thus the optical thickness increases with decreasing density.

The authors have attempted to study the optical properties of the Venus atmosphere by selecting an atmospheric model with a calculated flux $F_{\downarrow}(z)$ near the measured one. Such a model is obviously not unique, because of the large number of parameters influencing the flux.

The scattering properties of the pure molecular Venus atmosphere are known (Galin *et al.*, 1971). Therefore, it seemed reasonable to calculate $F_{\downarrow}(z)$ for a pure molecular scattering atmosphere with albedo of the underlying surface $A_0=0$, and then for an increasing succession of the scattering σ and absorption α coefficients, the albedo and the elongation of the scattering function $\gamma(\varphi)$. The parameters used were (instead of the ones mentioned): the optical thickness τ, the single scattering albedo,

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$\omega = \sigma/(\alpha + \sigma)$ and the mean cosine of the scattering angle

$$x_1 = \tfrac{3}{2} \int_{-1}^{1} \gamma(\mu)\, \mu \, \mathrm{d}\mu, \qquad \mu = \cos\varphi$$

or the elongation

$$\Gamma = \tfrac{1}{2} \int_{0}^{1} \left\{ \gamma(\mu, \mu')\, \mathrm{d}\mu' - \int_{-1}^{0} \gamma(\mu, \mu')\, \mathrm{d}\mu' \right\} \mathrm{d}\mu;$$

μ and μ' here are the cosines of the vertical angles. The elongation is the difference between the parts of the light scattered into the upper and lower hemispheres. The parameter x_1 (or $l = 4/(3 - x_1)$) is used in asymptotic methods of the theory of transfer for large optical depths (Sobolev, 1972); and the parameter Γ, in two-stream approximations. In the present work both methods are used.

The main part of the calculations was made in the Schwarzschild approximation, generalized for the case of anisotropic scattering:

$$\frac{1}{2} \frac{\mathrm{d}(F_\uparrow - F_\downarrow)}{\mathrm{d}\tau} = -(1 - \omega)(F_\uparrow + F_\downarrow), \tag{1}$$

$$-\frac{1}{2} \frac{\mathrm{d}(F_\uparrow + F_\downarrow)}{\mathrm{d}\tau} = q(F_\uparrow - F_\downarrow). \tag{2}$$

$F_\uparrow$ and $F_\downarrow$ are here the upward and downward fluxes;

$$q = 1 - \omega\Gamma .$$

These equations were chosen because they give exact solutions for Rayleigh scattering and an error not bigger than 15% for strongly elongated scattering functions and thick layers.

Figure 1 represents examples of numerical solutions of the exact equations of transfer, of the asymptotic formula, and of the Schwarzschild equations for a homogeneous model: $\omega = \text{const}$ with different values of

$$l > \tfrac{4}{3}; \qquad q \leqslant 1; \qquad \omega \leqslant 1$$

and

$$0 \leqslant A_0 < 1$$

where A_0 is the albedo of the underlying surface.

It may be seen that the albedo does not influence the flux appreciably. The three sets of solutions (exact, asymptotic and Schwarzschild) give the same result in the Rayleigh case. No choice of ω and l or Γ brings the calculations close to the measurements. Therefore, the calculations were made for two-layer models. In each layer the solutions of Equations (1) and (2) were tabulated for values of the parameters ω_i, q_i and τ_i (the optical thickness of the ith layer). On the boundary between the layers, at

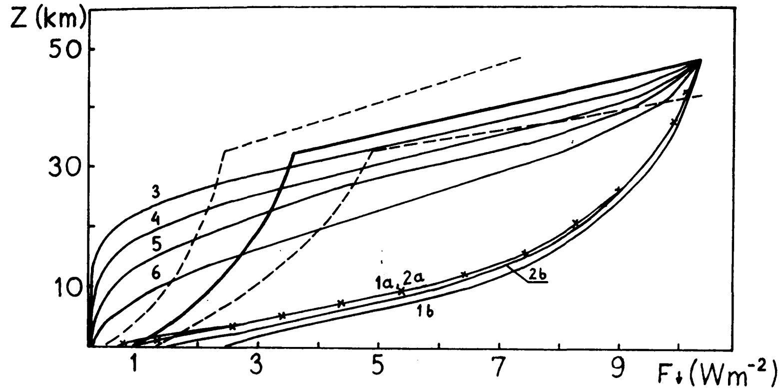

Fig. 1. Variation of the illumination with altitude. Thick line – experimental data; dashed line – error limits. Crosses – the numerical solution of the exact radiative transfer equations for $\omega = 1$, $A_0 = 0$ and $\gamma_R(\varphi)$. Curve 1a – calculations using the asymptotic formula with $\omega = 1$, $A_0 = 0$, $l = \frac{4}{3}$. Curve 1b – ditto with $l = 4$. Curve 2a – solution of Schwarzschild Equations (1) and (2) with $\omega = 1$, $A_0 = 0$, $\Gamma = 0$. Curve 2b – Schwarzschild solution with $\omega = 1$ and $A_0 = 0.85$. Curves 3–6 – ditto with $\omega = 0.90$; 0.95; 0.975; 0.999 respectively.

$z_0 = 32$ km, the conditions of continuity of the fluxes were used. At the upper boundary of the upper layer ($i = 2$), the flux $F_\downarrow(z)$ was taken equal to the measured value at the upper point, $z = 49$ km. At the lower boundary of the lower layer $A_0 = 0$ was assumed. The final condition was

$$\tau^{(i)}(z) = c^{(i)} p^{(i)}(z),$$

where $p^{(i)}$ is the pressure and $c^{(i)}$ is a contant.

Figure 2 and Figure 3 give the results of calculations for two models. For the first

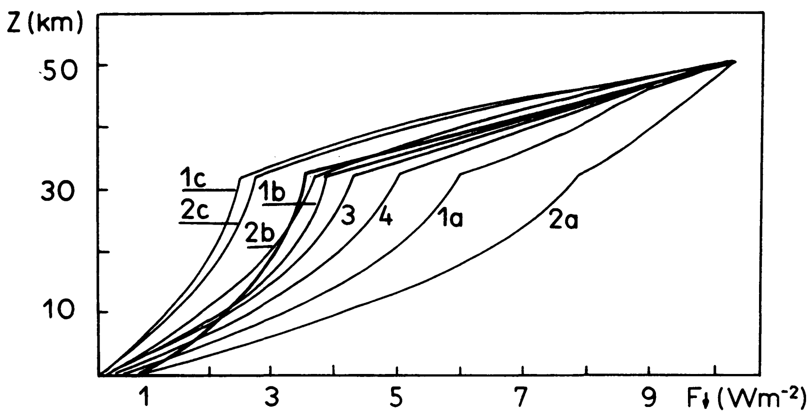

Fig. 2. Illumination profiles for two-layer model I. Thick line – experimental data. In the lower layer in each case $\omega^{(1)} = 1$; $\Gamma^{(1)} = 0$; $\tau^{(1)} = \tau^{(1)}{}_{R,\lambda\,\mathrm{eff}} = 9$. In the upper layer in all cases $\tau^{(2)} = 3$ (except curve 3, with $\tau^{(2)} = 5$). Curves 1a, 1b, 1c, and 3 – $\Gamma^{(2)} = 0.73$. Curves 2a, 2b, 2c – $\Gamma^{(2)} = 0$. Curve 4 – $\Gamma^{(2)} = 0.5$ Curves 1a, 2b, 3, 4 – $\omega^{(2)} = 0.95$. Curves 1b, 2c – $\omega^{(2)} = 90$. Curves 1c – $\omega^{(2)} = 0.80$.

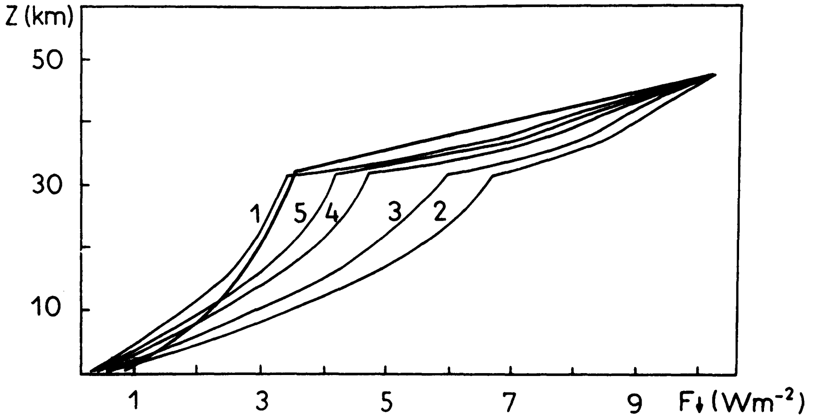

Fig. 3. Illumination profiles for model II. In all cases $\omega^{(2)} = 1$. Curves 1, 2 – $\tau^{(2)} = 20$. Curve 3 – $\tau^{(2)} = 25$. Curve 4 – $\tau^{(2)} = 40$. Curve 5 – $\tau^{(2)} = 50$. Curve 1 – $\Gamma^{(2)} = 0$. Curves 2–5 – $\Gamma^{(2)} = 0.73$.

model the upper layer (32 km $\leqslant z \leqslant$ 49 km) is absorbing ($\omega_1 \approx 0.95$) and optically rather thin, close to the Rayleigh case:

$$\tau^{(2)} = 3, \quad \text{with} \quad \tau^{(2)}_{R, \lambda_{eff}} \approx 1 .$$

The second model gives

$$\tau^{(2)} \approx 20 - 50 ; \qquad \omega \approx 1 ,$$

In both cases the lower layer is purely molecular scattering. Figures 2 and 3 allow us to conclude:

(a) The lower part of the Venus atmosphere ($z \leqslant 32$ km) is not significantly hazy, which corresponds to the small wind velocities here (Marov *et al.* 1973). There is no significant absorption. The correspondence between the calculations and the measurements for the very lowest layers may be improved by selecting $A_0 > 0$ (see Figure 1).

(b) Two alternative models are equally probable for the upper layer ($i = 2$; $32 \leqslant z \leqslant$ $\leqslant 49$ km). The first (model I) is an absorbing and optically thin medium: the second (model II) represents an optically thick and almost purely scattering layer. As $\tau_1^{(2)} \approx 3\tau^{(2)}_{R, \lambda eff}$, the scattering function must differ somewhat from the Rayleigh case; i.e. Γ must be taken > 0. Figure 2 shows that this supposition is consistent with $\omega < 0.95$. So the radiative transfer conditions for the first model appear to be:

$$\tau \approx 3 - 5 ; \qquad 0.9 \leqslant \omega \leqslant 0.95 .$$

The second model is naturally associated with strongly elongated scattering functions. The calculations for the case ($\omega = 1$; $\Gamma = 0.73$; $\tau = 50$) corresponds satisfactorily to the mesurements (see Figure 3).

The first model suggests the penetration of a small number of cloud particles below a cloud layer with a lower boundary higher than 50 km. The significant absorption in this case may be connected with an assumed absorption (see for instance Galin *et al.*, 1971) in the cloud layer for $\lambda \leqslant 0.6\ \mu$m. Galin obtained $\omega = 0.998$ for $\lambda = 0.55$. As $\sigma_{cl} \gg \sigma^{(2)}$, we get $\omega_{cl} > \omega^{(2)}$ (the index 'cl' refers to the cloud layer). The idea of a cloud extending downward to the level ≈ 32 km is natural for model II. We note that the boiling point of water occurs at 35 km.

An independent check of the above evaluations is given by the equation for the illumination at depth in the scattering medium, where

$$F_{\downarrow}(z) \sim \exp[-k\tau(z)]$$

and

$$k = 2\left(\frac{1-\omega}{l\omega}\right)^{1/2}.$$

For

$$k = \frac{1}{\tau^{(2)}} \ln \frac{F_{\downarrow}(49)}{F_{\downarrow}(32)}, \qquad l \geqslant \tfrac{4}{3},$$

and $\tau^{(2)}$ corresponding to models I and II, we get:

$$\omega_1 \leqslant 0.96 \quad \text{and} \quad \omega_2 \approx 0.999.$$

in agreement with the evaluations by the selection method.

The mean scattering coefficient $\sigma^{(2)} = \tau^{(2)}/H$, with $H = 17$ km, is approximately 0.2 km^{-1} for model I and 2.5 km^{-1} for model II. The corresponding absorption coefficients $\alpha^{(2)} = (\sigma/\omega)(1-\omega)$ are 0.01 km^{-1} for model I with $\omega = 0.95$, and 0.005 km^{-1} for model II with $\omega = 0.999$. We may regard both values of $\alpha^{(2)}$ as the same because of the low accuracy of the evaluations.

Let us consider one more evaluation of the absorption coefficient. The visual albedo of the planet is 80%. The transmission is only a few per cent. Therefore, the absorption is 15–20%. The optical thickness of the combined cloud (1) and under cloud layers (2) is of the order of 10–50 for model I, and 30–100 for model II. The mean path length of photons $l = nH$, where $n \approx 3$–6 for $\tau = 10$–100, and $H = 20$–30 km is the thickness of the system. The absorption $A \approx 0.2 = \exp(-\alpha l)$, so $\alpha = 0.01$–0.005 km^{-1}, in agreement with the previous results. The number of particles per unit volume of layer (2) may be obtained from the equation

$$N = \frac{\sigma}{\pi r^2 K}.$$

Supposing that the layer consists of large particles $r \geqslant 10\ \mu$m with scattering cross section $K = 2$, we find:

$$N_1 \lesssim 0.3 \text{ part cm}^{-3}, \quad \text{or} \quad N_2 \lesssim 5 \text{ part cm}^{-3}.$$

In conclusion we remark that both models may agree with the known reflection spectrum of the planet. A cloud layer with an optical thickness of tens and $0.99 \leqslant \omega \leqslant 1$ agrees with the measured value of $F_{\downarrow}(z)$ at $z = 49$ km.

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