THE SPECTRAL CHARACTERISTICS AND PROBABLE STRUCTURE OF THE CLOUD LAYER OF SATURN

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Abstract. Spectrophotometric (photographic and photoelectric) measurements of the intensity of CH_4 absorption bands at 6190 and 7250 Å over different regions of Saturn's disk show an increase in intensity toward the poles and a decrease toward the equatorial limb. In the bright equatorial belt of Saturn the methane absorption is about 25–28% less than in the south temperate belt (latitude about $-20°$).

Absolute photoelectric spectrophotometry of Saturn's disk gives a value for the single-scattering albedo of the aerosol particles $\tilde{\omega}_c \simeq 0.99$ at λ 6200–6500 Å at the center of the disk. Calculations of the curves of growth for the absorption lines formed in the thin gas and in the cloud layer were made and the comparison with observations of Jupiter and Saturn lead to the mean value of the volume scattering coefficient of the aerosol layer $\sigma_a < 5 \times 10^{-6}$ cm^{-1}. In the equatorial region of Saturn σ_a is larger than in the temperate region by a factor 1.3 to 1.8.

The models of Saturn's atmosphere that fit well the observational data preclude the condensation of methane. An aerosol layer of ammonia is more probable in the atmosphere of Saturn. Calculations of the distribution of the ammonia aerosol volume density (Q_a) give $Q_a \simeq 10^{-9}$ to 10^{-7} gm/cm^3 for relative abundances of ammonia $A = 10^{-6}$ to 10^{-4}. Observational estimates of Q_a derived from the values of σ_a give $Q_a < 10^{-9}$ gm/cm^3. Apparently Saturn's atmosphere departs from conditions of ordinary convection.

Some very interesting variations in the spectral reflectivity of the different regions of Saturn are observed, especially in the ultraviolet. These data, as well as a systematic study of the methane absorptions in the near infrared strong bands are needed in future studies of Saturn's atmosphere.

1. Introduction

Spectral observations of Jupiter and Saturn made at the Observatory of the Astrophysical Institute reveal many peculiarities in the distribution of molecular absorption across the disks of these planets, showing the importance of the role of their aerosol layers in forming absorption lines and bands. In this work, we bring together the results of spectral (photographic and photoelectric) observations of Saturn and a few tentative results of theoretical calculations. Although the radiation regime of the atmosphere of Saturn is somewhat more severe than that of Jupiter (the solar constant at Saturn's orbit is 0.02 cal cm^{-2} min^{-1}), a few effects connected with molecular absorption turn out to be expressed more sharply than on Jupiter, giving evidence of greater inhomogeneities in the aerosol layer in the latitudinal direction than occur on the larger planet.

2. The Continuous Spectrum

Photoelectric tracings of the continuous spectrum of the central meridian and east and west ansae of Ring B were obtained with the 70 cm telescope using a spectrometer with dispersion 30.4 Å/mm (resolution ~500) in the course of three nights in September, 1968. For absolute calibration of the tracings, spectra of the stars α Aurigae and

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β Arietis were also made. After the appropriate reductions we obtained the important coefficient of brightness of the center of the disk of Saturn and the rings as presented in Figure 1. The reflection properties of the planet are almost monotonic, decreasing

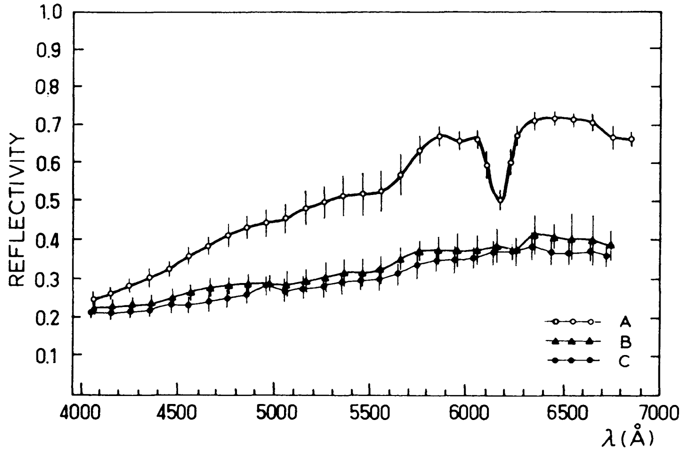

Fig. 1. Spectral reflectivity of the bright equatorial belt of Saturn near the center of the disk (A), of the west ansa (B) and of the east ansa (C) in 1968.

toward shorter wavelengths, and this must be connected with the existence of true absorption of light by a particulate aerosol layer. Of great interest is the region of the spectrum where methane absorption bands occur. In the region 6200–6600 Å, the brightness coefficient of the center of the disk of Saturn reaches the maximum value $\rho_\lambda = 0.72$. This gives the albedo of single scattering $\omega_c = \sigma_a/(\sigma_a + \kappa_a) = 0.984$ for isotropic scattering and $\omega_c = 0.990$ for the indicatrix of scattering $x(\gamma) = 1 + \cos\gamma$. In the region 4000–4100 Å, $\rho_\lambda = 0.25$ and ω_c is approximately equal to 0.79 or 0.88, depending on the form of the scattering indicatricies. This means that the magnitude of the coefficient of true absorption in the aerosol, k_a, increases in the ultraviolet region of the spectrum by about 14–17 times, if the coefficient of scattering σ_a does not depend on wavelength. In the case of aerosol particles of small size ($r \sim 10^{-1}\,\mu$), the volume scattering coefficient must increase in the short wavelength region while the true absorption must increase more strongly.

For different parts of the disk of Saturn the absorption changes non-uniformly with wavelength. Spectrograms of the central meridian of Saturn obtained in August and September, 1969, in the region 3200–6800 Å clearly reveal differences in the colors of individual cloud bands on the planet. The equatorial band of Saturn, the brightest region on the planet at $\lambda < 4500$ Å, was quite dark at $\lambda < 4250$ Å. At that time the north polar region of Saturn, which seems to be the darkest region on spectrograms and photographs taken in red light, was the brightest detail on blue light photographs and on spectrograms in the region $3500 < \lambda < 4300$ (Figure 2). At $\lambda < 3500$ Å the brightness of the disk of Saturn increases, thus confirming the photoelectric measure-

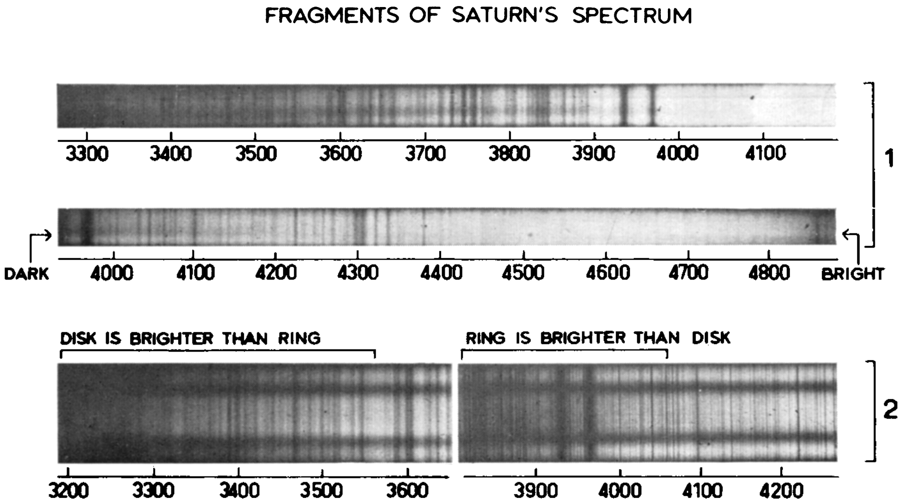

Fig. 2. Spectrograms of the central meridian (1) and of the equator of intensity (2) of Saturn in 1969.

ments of Younkin and Münch (1963) and ultraviolet rocket measurements by Bless *et al.* (1968).

3. Absorption Bands of CH_4

Photographic spectral measurements of the relative intensity in the center of the CH_4 6190 Å absorption band, made in 1966 and 1968, and also photoelectric measurements of the contours and equivalent widths of the 6190 Å and 7250 Å bands in 1968, reveal the following peculiarities of the change of intensity of methane absorption across the disk of Saturn. Along the equator of Saturn the absorption gradually decreases toward the edge of the disk. At the same time an increase in absorption was observed toward the poles of the planet, that is, in the light equatorial zone of Saturn the absorption was minimum, but sharply increased in the darker northern temperate regions (Table I and Figure 3).

At latitude $\phi \simeq -20°$ absorption was about 25–28% greater than in the equatorial zone of Saturn. This cannot be explained by a simple secant effect and must be connected with peculiarities in the structure of the aerosol layer in the atmosphere of Saturn. The nature of the variation of absorption with latitude in the relatively weak bands at 6190 and 7250 Å agrees well with the results obtained from photographs of Saturn obtained by Owen and Mason (1969) using a narrow-band interference filter centered in the strong CH_4 band at 8860 Å. This is in disagreement, however, with the results obtained from similar photographs of Jupiter. On Jupiter there is no correlation between the distribution with latitude of the intensity of weak and strong bands of methane.

It is strange that observations in 1966 show a weakening of the CH_4 absorption in all equatorial regions of Saturn. That is, in both components of the equatorial band,

TABLE I

Measurements of the intensities of absorption bands of CH_4 at 6190 and 7250 Å on the disk of Saturn, made with a photoelectric spectrometer

Date 1968	Region on the disk of Saturn	CH_4 6190 Å			CH_4 7250 Å		
		W (Å)	R	n	W (Å)	R	n
8–9.08	Center of the disk	23.5	0.258	2	93.6	0.700	12
19–20.08	Center of the disk (light zone)	26.4	0.254	17	90.5	0.678	35
6–7.09	Center of the disk (light zone)	24.3	0.234	18	—	—	—
	South temperate region	31.0	0.299	16	—	—	—
12–13.09	Equator (light zone)	27.0	0.252	16	87.4	0.670	14
	South temperate region	30.8	0.287	18	100.3	0.726	17
3–4.11	Center of the disk	24.2	0.252	4	78.6	0.630	10
	North polar region	—	—	—	99.3	—	4
5–6.11	Center of the disk	22.6	0.237	5	83.3	0.665	14
6–7.11	Center of the disk (light zone)	—	—	—	70.8	0.602	4
	Latitude −15°	—	—	—	83.4	0.648	5
	Latitude −25°	—	—	—	91.9	0.722	8
	Latitude −35°	—	—	—	106.3	0.730	3
	South polar region	—	—	—	110.3	0.757	6
	North polar region	—	—	—	104.8	0.816	5

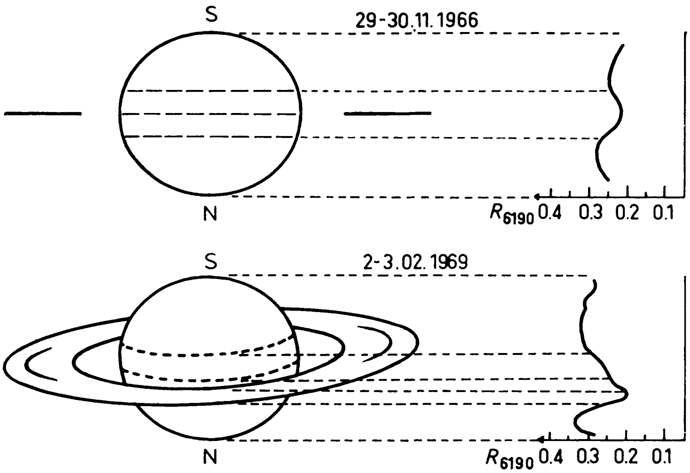

Fig. 3. Changes of the methane absorption in the band CH_4 6190 Å along the central meridian of Saturn in 1966 and 1969. R_{6190} is the central depth of CH_4 6190 absorption band.

of which, as shown in photographs at λ 3550 Å by Marin (1968), the southern component was light and the northern component was very dark.

We carried out calculations of the curves of growth for absorption lines forming in a pure gas as well as in a gas-aerosol mixture. Calculations for the center of the disk

($\mu=1.0$) and for limb regions ($\mu=0.5$) allow us to find the dependence of the relative intensity of lines

$$\beta = \frac{W(0.5)}{W(1.0)}$$

with parameters of the characteristic absorption in the outer, pure gaseous atmosphere

$$u_0 = \frac{N_0 S H_0}{\pi \alpha_0}, \tag{1}$$

and in the aerosol layer

$$u_1 = \frac{N_1 S}{\pi \alpha_1 \sigma_a}. \tag{2}$$

Here, N is the number density of absorbing molecules, S is the coefficient of absorption for a single molecule, α is the mean half-width of the line, H_0 is the scale height for the outer atmosphere, and σ_a is the mean volume coefficient of scattering of the aerosol layer.

This dependence is shown in Figure 4 for two cases: $\omega_c=1.0$ and $\omega_c=0.975$, for

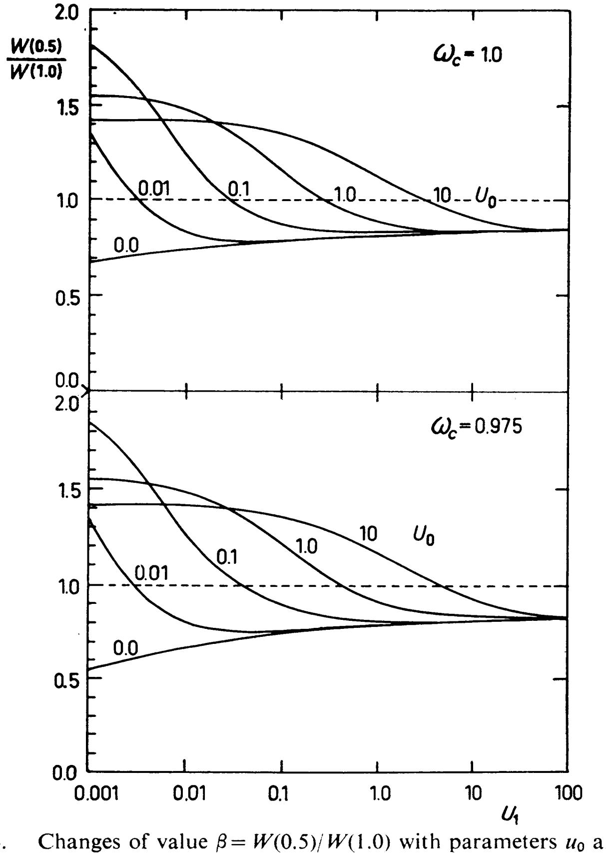

Fig. 4. Changes of value $\beta=W(0.5)/W(1.0)$ with parameters u_0 and u_1.

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the scattering indicatrix $1+\cos\gamma$, and for several fixed values of the parameter u_0. The figures show that in the case of line and band formation originating only in the aerosol layer ($u_1 \geqslant u_0$), the line intensity at the limb is smaller than in the center, such that $0.5<\beta<1$. If we know from laboratory measurements and observations the values of N, S, H_0, and α and also β, we can, as is shown in Figure 4, find u_1, from which we can determine σ_a. Analysis of a sufficiently large number of observations of Jupiter leads to the following probable limit of the mean value of σ_a for the aerosol layer:

$$5 \times 10^{-8} < \sigma_a < 5 \times 10^{-6}\ \mathrm{cm}^{-1}. \tag{3}$$

The lower limit is obviously too small. But the determination gives a value of σ_a that is somewhat smaller than, for example, terrestrial stratus clouds where $\sigma_a \sim 10^{-4}\ \mathrm{cm}^{-1}$. This confirms the conjectural statements in the literature that the cloud layer of Jupiter has its own aerosol haze.

The decrease in intensity of CH_4 bands from the center of the disk toward the equatorial limb of Saturn has been insufficiently studied. It is obvious only that for Saturn $\beta<1$, but the exact quantity is uncertain, and we may say only that in the aerosol layer of Saturn the magnitude of σ_a cannot be of the nature of that for Jupiter, although the thicker gas layer above the clouds, seen from the data of rocket UV measurements, is approximately two times greater than for Jupiter. Therefore $u_{0\ \mathrm{Saturn}} > u_{0\ \mathrm{Jupiter}}$.

4. Theoretical Density and Physical Nature of the Aerosol Layer of Saturn

Using the existing observational data as a basis, we have computed an approximate 'gray' model of the atmosphere of Saturn, assuming $T_e=90$ K and $H_2:He=5:1$, and also a model using one of the models of Trafton (1967), where $T_e=90$ K and $H_2:He=1:0$. In Figure 5 are shown the curves $P(T)$ and $A_n \cdot P(T)$, where A_n is the relative concentration of any component of the atmosphere for full mixing. In the same figure are given curves of the variation in pressure of a saturated vapor with temperature for methane, $E_M(T)$, and for ammonia, $E_A(T)$.

It is not difficult to see that there must be a very great relative concentration of methane

$$A(CH_4) > 5 \times 10^{-2} \tag{4}$$

for the formation of clouds or aerosol haze from the condensation of CH_4, in order to fulfil the condition $A \cdot P(T) > E_M(T)$. This amount of methane does not agree with the observed quantity. The concentration of ammonia in the atmosphere of Saturn at the level where $T>100$ K, that is, below the tropopause, can even be possibly $A(NH_3)=10^{-5}$ to 10^{-6}. Apparently the aerosol layer on Saturn, as it is on Jupiter, is composed of crystals of NH_3. Approximate calculations of the volume density of the aerosol Q_a may be made, supposing that all residual quantities of ammonia corresponding to the excess of partial pressure of NH_3 over the pressure of the saturated vapor, are transferred to the solid or liquid phase. In this case it can be computed that

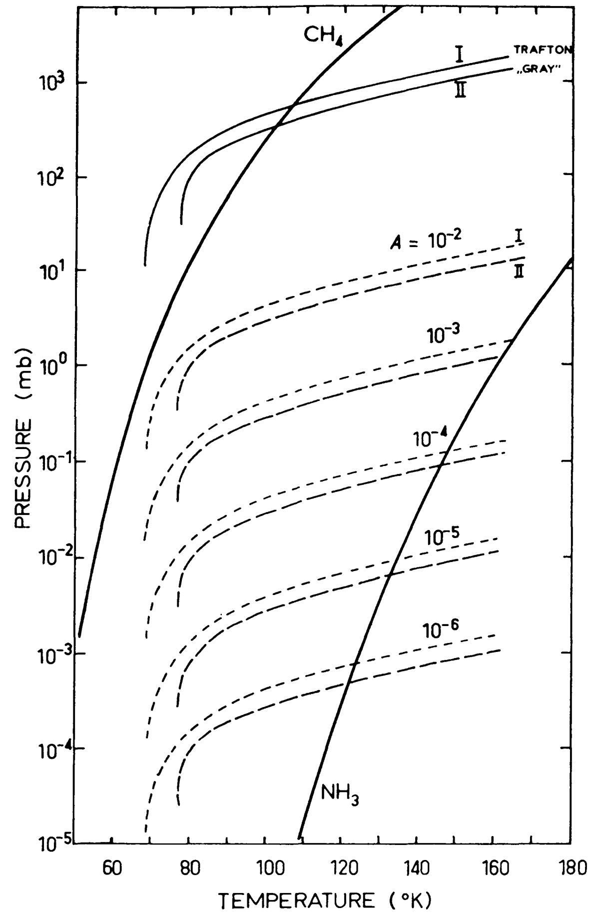

Fig. 5. Atmospheric pressure versus temperature in the atmosphere of Saturn and the pressure of saturation for CH_4 and NH_3.

the gaseous component is subjected to continuous convective mixing. Then, according to Obuchov and Golitsyn (1968)

$$Q_a = \frac{\mu_n}{RT_z}\,[A_n P_z - E_n(T_z)], \tag{5}$$

where μ_n is the molecular weight of the condensing component. Results of the calculations of Q_a for NH_3 in the atmosphere of Saturn for different values of $A(NH_3)$ are given in Figure 6. Since the function $P(T)$ for the model of Trafton (1967) and the 'gray' model differ in the region of condensation by a constant factor of two, computations were made only for the 'gray' model. Figure 6 shows that after a sharp increase near the well defined lower boundary of the aerosol layer, the density of the aerosol in the absence of intensive rising and lowering of flow very slowly diminishes with height. The upper boundary of the aerosol layer, apparently, should be connected

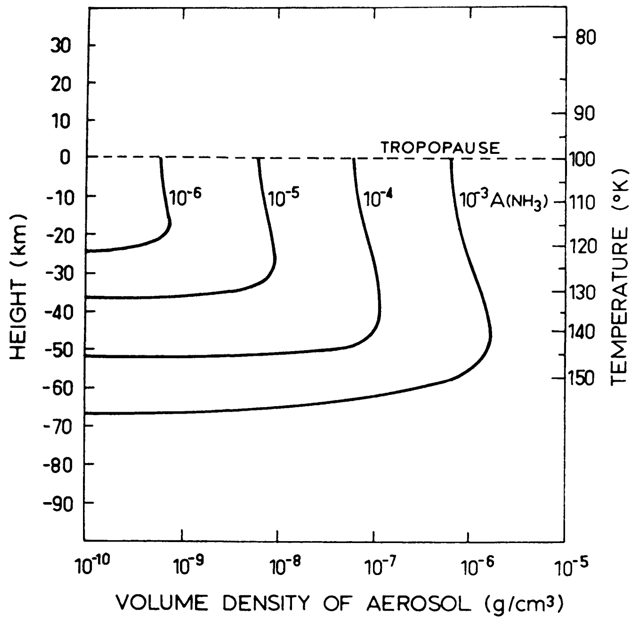

Fig. 6. Vertical distribution of the volume density of ammonia aerosol layer (Q_a) in the atmosphere of Saturn for different relative abundances of ammonia. The adiabatic lapse rate is $dT/dz = -0.88$ K/km.

with the level where convective or turbulent mixing becomes insignificant by comparison with the velocity of fall of condensing material.

Continuing, we note that as in the case of Jupiter these calculations for Saturn give a larger value of Q_a than is obtained from the value of the scattering coefficient σ_a. For $\sigma_a = 5 \times 10^{-6}$ cm^{-1} and refractive index $m = 1.33$, the volume density obtained is $Q_a \simeq 2.5 \times 10^{-10}$ to 4.04×10^{-9} gm/cm^3 for particle radii corresponding to $r = 0.05$ to 1.0 μ. The reason for the divergences should probably be sought in the differences in the characteristics of the circulation regimes of Jupiter and Saturn, from those which were used as the basis of the calculations introduced above.

On the other hand, the observed difference between the absorption of CH_4 in the light equatorial zone of Saturn and that in the north temperate belt can be explained by a change in the mean coefficient of scattering at the effective level of formation of the absorption bands. Using the curve of growth it is not difficult to find that σ_a is 1.3 to 1.8 times larger in the light equatorial region than in the temperate belt. Such a difference in σ_a is completely possible since a small increase in the upward currents in the equatorial regions can lead to a redistribution of the volume density of the aerosol and to its increase at greater altitude by a factor of approximately 1.5.

5. Conclusions

Spectral variations in absorption bands of methane on the disk of Saturn show that the volume density in the aerosol layer in the atmosphere of the planet must be significantly lower than can exist in a cloud layer analogous to terrestrial stratus clouds. The density of Saturn's aerosol haze can change with latitude, and the denser layer of haze lies near the equator. A series of questions remains yet unanswered. In particular, it is not clear what the increased ultraviolet absorption in the belt near the equator is connected with. The reason for the difference between the values of the volume density determined by spectral observations and those theoretically obtained has not been established. Photographs and spectrograms of Saturn obtained in different years show very clearly the nonstationary character of processes in the atmosphere of this planet. From this fact follows the need for regular observations. Especially important are pictures and spectrograms taken in the extreme regions of the photographically accessible spectrum. It is also necessary to study in detail the distribution of molecular absorptions across the disk of Saturn in the strong infrared bands. These bands, more than others, must be formed in the upper layers of the aerosol layer and in the atmosphere above the clouds. Using calculations analogous to those presented in Figure 5, a sufficiently accurate value of σ_a can be obtained from observations of absorption bands, or even better, individual lines. On the other hand, in investigating effects in the continuum, especially in the ultraviolet, it is probably necessary to take into account the role of scattering and absorption by particles of various sizes. It may be, if only in part, that these effects are caused by the dependence of the scattering factor K_P on the size of particles and on wavelength. At large optical thickness of the aerosol layer this cannot play a determining role. In any case it is necessary to note the absence of a reliable optical model of the cloud layer of Saturn that is able to explain all phenomena observed on the disk of this planet.

Note Added in Proof. Our new measurements of Saturn's spectra give $0.95 < \beta < 1.0$. Using Rozenberg asymptotic formulae (Rozenberg, G. V.: 1962, *Dokl. Akad. Sci. S.S.S.R.* **145**, 775) for the strongly forward scattering function we obtained $u_0 \simeq 0.098$, $\sigma_a \simeq 2.2 \times 10^{-5}$ cm^{-1} for the light equatorial zone, and $u_0 \simeq 0.094$, $\sigma_a \simeq 1.4 \times 10^{-5}$ cm^{-1} for the temperate belt of Saturn.

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