NASA TECHNICAL MEMORANDUM NASA TM-75542

PRELIMINARY RESULTS OF STUDY OF INFRARED SPECTRA OF VENUS FROM THE ORBITAL SPACECRAFT "VENERA-9" AND "VENERA-10"

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Translation of "Predvaritel'nyye rezul'taty issledovaniya infra-krasnogo spektra Venera na orbital'nykh apparatakh "Venera-9" i "Venera-10", Academy of Sciences USSR, Institute of Space Research, Moscow, Report PR-273, 1976, pp 1-33

(NASA-TM-75542) PRELIMINARY RESULTS OF STUDY OF INFRARED SPECTRA OF VENUS FROM THE ORBITAL SPACECRAFT VENERA-9 AND VENERA-10 (National Aeronautics and Space Administration) 35 p HC A03/MF A01 CSCL 03B G3/91 31624
N78-32961
Unclas

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. 20546 SEPTEMBER 1978

STANDARD TITLE PAGE

1. Report No. NASA TM-75542	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PRELIMINARY RESULTS OF STUDY OF INFRARED SPECTRA OF VENUS FROM THE ORBITAL SPACECRAFT "VENERA-9" AND "VENERA-10"		5. Report Date September 1978
		6. Performing Organization Code
7. Author(s) V. Gnedykh, V. Zhegulev, L. Zasova, V. Moroz, N. Parfent'yev and G. Tomashova		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates, Redwood City, California		11. Contract or Grant No. NASW-3199
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Predvaritel'nyye rezul'taty issledovaniya infra-krasnogo spektra Venera na orbital'nykh apparatakh "Venera-9" i "Venera-10"," Academy of Sciences USSR, Institute of Space Research, Moscow, Report PR-273, 1976, pp. 1-33

16. Abstract

The IR spectrum of Venus measured by spectrometers aboard the "Venera-9" and -10 satellites indicates the formation of carbon dioxide absorption bands near 2 microns inside the scattered cloud medium. Absorption bands behave according to a scattering model. The upper boundary of the cloud layer is located at a height of 65-68 km. A height scale of approximately 3 to 5 km describes the vertical profile of the cloud layer. The horizontal profile is smooth at scales of 50-100 km. Luminance in the continuous spectrum can be explained by a model of a semi-infinite atmosphere.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

ABSTRACT

The infrared spectrum of Venus in the spectral range 1.6 to 2.8 μm was measured by means of the spectrometers aboard "Venera-9" and "Venera-10" orbital spacecrafts. Approximately 20 series of measurements were made near the pericenter of the orbit, each of which contains 150 spectra for each path intersecting the planet from the terminator to the limb. Phase angles lie within the limits from 60 to 120°. Preliminary processing and interpretation of data provided the following conclusions:

a) Carbon dioxide absorption bands near 2 μm are formed inside the scattered cloud medium. The behavior of absorption bands with a change in phase angle and the center-limb effect satisfy the model with scattering and do not agree with the model of simple reflection.

b) The upper boundary of the cloud layer (defined as a level at which concentration decreases "e" times) is located at a height of 65-68 km.

c) The vertical profile of the cloud layer is described by a height scale $H_a \approx 3 \div 5$ km.

d) The horizontal profile of the upper boundary at scales of 50-100 km and greater is very smooth: its height variations do not exceed 1-2 km.

e) Luminance in the continuous spectrum in the range 2.2 to 2.4 μm with regard to absolute value and angular relations can be explained by a model of a semi-infinite atmosphere at $a \approx 0.98$ and $g \approx 0.7$.

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Carbon dioxide is the main component of the atmosphere of Venus. A majority of CO_2 bands of diverse intensity is observed in the spectrum of solar radiation reflected by the cloud layer of the planet. The equivalent width of the CO_2 band depends not only on the content of carbon dioxide in the atmosphere, but also on the height of the upper limit of the cloud layer, the vertical profile of particle concentration in its upper section, and on the horizontal profile of the upper limit. /5*

Carbon dioxide absorption bands are one of the important sources of information on the physical characteristics of the upper portion of the cloud layer of Venus equally with photometry, polarimetry and infrared radiometry.

More than 40 years of terrestrial observations have yielded a large amount of data on CO_2 absorption bands. Spatial resolution, however, for such observations is very limited. It is usually 10^3 km or less. An integrated radiation spectrum of the entire planet is the most typical occurrence. Measurements from a spacecraft make it possible to obtain data on the behavior of absorption bands on much smaller horizontal scales, to more accurately study the dependence of absorption band intensity on angles

*Numbers in the margin indicate pagination in the foreign text.

and, in principle, to refine existing descriptions of the structure of the upper portion of the cloud layer. Therefore, an infrared spectrometer was included among the instruments aboard the "Venera-9" and "Venera-10" satellites. We were restricted to registering a comparatively small range of the spectrum from 1.6 to 2.8 μm, which on the whole, includes a system of strong CO_2 bands located near 2 μm. Spectral resolution is low--approximately /6
0.1 μm, but on the other hand, spatial resolution is quite high--up to several tens of kilometers. It is essential that such measurements are made simultaneously with radiometry, polarimetry and photometry aboard "Venera-9" and "Venera-10". All these data relate to the same moments and regions and the possibility of their combined interpretation is of great interest.

It is also important that the profile of the cloud layer at great depths, beginning almost from the upper limit, in the "Venera-9" and "Venera-10" recovery capsules is studied by several methods. The profile may be directly associated with the results of optical measurements on the satellites. An important feature of spectroscopy aboard the satellites is the absence of interferrence from CO_2 bands from the earth's atmosphere.

This report presents a brief description of the spectrometer, examples of measurements made under typical conditions (various phase angles, center, limb, terminator, etc.) and a preliminary interpretation.

1. The Infrared Spectrometer

The main characteristics of the infrared spectrometers located on the "Venera-9" and Venera-10" are almost identical. They are presented in table 1.

Figure 1 shows the optical circuit. O_1 and O_2 are the Cassegrain objectives, one of which is directed towards the planet, and the other--into space. CL is the calibration lamp; M is a shutter with reflective lobes, which modulates radiation, alternately transmitting beams focussed by both lenses to the detector. WIF is a wedge-shaped circular interference filter which assures the assigned spectral resolution. A is a diaphragm which determines angular resolution and segregates the working section of /7 WIF. L is a field lens; P--a radiation detector (uncooled lead sulfide photoresistor). E_1 and E_2 are direct current electric motors (E_2 has a reducer). WIF consists of two identical half rings. Two spectra are recorded in one revolution of the filter. Wave length is almost a linear function of the angle of rotation of WIF. As far as construction, the spectrometer is made up of two blocks (optico-mechanical and electronic) connected by cables. All elements of the optical circuit are located in the optico-mechanical unit. In the electronic block, there are two terminal amplifiers with synchronous detection, a circuit for switching the sensitivity ranges, and a voltage converter. The terminal amplifiers differ with regard to amplification coefficients by approximately 5 times. In addition, in each there are two bands

TABLE 1. MAIN SPECIFICATIONS OF THE IR-SPECTROMETERS OF "VENERA-9" AND "VENERA-10"

Spectral Range	1.6--2.8μm
Resolving Power	20
Angular Resolution	0.0166x0.0067 rad
Recording Time of One Spectrum	10 seconds
Relative Accuracy of Measurements at a Maximum Output Signal	2%
Range of Measurable Intensities (λ 2 μm)	10^{-5}--$5\cdot10^{-2}$ $W\text{-}cm^{-1}\mu m^{-1}sr^{-1}$
Modulation Frequency	200 Hz
Time Constant	0.1 seconds
Weight	4.6 kg
Power Consumption	5.6 W

(differing in amplification by 20 times), which are automatically /8 reversed when the signal reaches a defined level. All the amplification channels are linear. The optical unit also houses a pre-amplifier.

The spectrometer is fastened to the AMS housing and is oriented in the same direction as the other optical devices intended for studying the cloud layer. At some point close to the pericenter of the orbit, the optical axis intersects the terminator. The planet is then linearly scanned due to travel of the spacecraft. As many as 150 spectra are recorded in one measurement session. The phase angle remains unchanged for a session, but it is possible to take measurements at different phase angles in different series by appropriate orientation of the AMS. The height of the AMS at the pericenter is approximately 2000 km, however, in the first months of satellite travel the pericenter was found over the nocturnal side of the planet. As a result, typical values of slant range from observations of the diurnal hemisphere are from 3000 to 10,000 km and greater. A distance of 5000 km formally corresponds (without regard to blur from motion of the spacecraft) to spatial resolution 90 x 35 km. The aperture was oriented approximately in the plane of the orbit. The calibration lamp goes on for 2 minutes at the beginning and end of each measurement series (usually before passing the terminator and after intersecting the limb), which makes possible sensitivity control of the device. During laboratory calibration, a type A source (incandescent lamp) and a model of a low-temperature absolute blackbody were used. The CL lamp serves as an intermediate standard making it possible to convert readings of the device into absolute luminosity units.

2. Results of Measurements

Measurement data from the infrared spectrometer were obtained in some 20 sessions on both orbital spacecrafts. Figure 2 shows the position of three typical paths of measurements (the track of the optical axis at the visible upper boundary of the cloud layer is designated as a path). The path for "Venera-10" on 11/6/75 traverses the equatorial zone (a band from 0° to -20°). Its phase angle is equal to 62°. The path of "Venera-9" on 11/9/75 lies at high latitudes at almost the same phase angle (63°) and the path of "Venera-9" on 11/13 lies at central latitudes at a relatively large phase angle--approximately 122°.

The results of readings can be presented in two ways: a) a sequence of spectra, b) photometric sections at selected wave lengths. Figures 3 and 4 present examples of spectra characteristic for the two selected phase angles (approximately 60° and 120°) at various parts of the dial (limb, central section, terminator). Luminance coefficients are given along the axis of the ordinate

$$\rho = \frac{\pi I}{F} \qquad (1)$$

where I--measured luminance, F--extra-atmospheric solar illumination of the horizontal area. A lab reading of the CO_2 absorption spectrum by a difraction spectrometer having several tens of times greater resolution than ours is presented in fig. 3b. This recording shows that a group of strong CO_2 bands is concentrated near 2 μm; they are identified in the figure. In low resolution, they are registered as a single absorption element. For brevity, it will be designated as the "λ 2 μm band". The group of CO_2 bands near 1.6 μm and the main band at 2.7 μm are located at the edges of the spectral range. Their equivalent widths cannot be measured with sufficient accuracy. Therefore, mainly the behavior of the /10 λ 2 μm band will be studied.

Table 2 indicates typical values of the equivalent widths of the λ 2 μm band and the luminance coefficients at wave lengths

1.75 and 1.4 μm obtained on the paths of "Venera-10" on 11/6 and of "Venera-9" on 11/9 and 11/13. Three spectra each are taken for each path--close to the limb, in the middle section and at the terminator. Photometric angles corresponding to these spectra and other accompanying data are also presented in table 2. α is the phase angle, μ_1 and μ_2 are the cosines of the angles of incidence and reflection,

$$M = \frac{I}{\mu_1} + \frac{I}{\mu_2} \qquad (2)$$

is the air mass (given everywhere without regard to sphericity, except for the terminator range on 11/13, where a value for the horizontal air mass in a spherical atmosphere is used). A is the azimuthal angle between the plane containing the incident ray and the normal to the surface, and the plane containing the reflected ray and normal.

Figure 5 shows photometric sections for 4 wave lengths (1.64, 1.75, 2.02 and 2.20 μm) obtained from readings on 11/6/75. Luminances are given in per unit values along the axis of the ordinate. In addition, a profile of the luminance coefficient at the wave length λ 2.20 μm and relations of luminance coefficients at 2.02 and 2.20 μm are given. Equally with equivalent width W, the latter can serve as a measure of absorption band intensity (the less the relation, the stronger the band). Figure 6 gives the values μ_1, μ_2, M and A for the entire path.

TABLE 2. EQUIVALENT WIDTH OF THE CO_2 BAND λ 2 μm UNDER VARIOUS OBSERVATION CONDITIONS

OS	Date	α	Spectr Number	Position on Path	Latitude φ	Local Solar Time	μ_0	μ_2	M	Azimuth A	Equiv. Width cm^{-1}	Luminance Coefficients 1.75 μm	2.4 μm
V-10	11/6/75	62°	20	Term.	-I5°	$6^h,9$	0,22	0,80	5,8	I20	340	0,35	0,28
			92	Middle Section	-I,5°	I0,2	0,86	0,80	2,4	45	4I8	0,67	0,43
			I2I	Limb	-I,7°	II,9	0,998	0,5I	3,0	45	400	0,37	0,27
V-9	11/9/75	63°	26	Term.	38°	7,2	0,20	0,92	5,9	I3I	4I0	0,25	0,22
			67	Middle Section	52°	I0,2	0,49	0,72	3,4	99	4I0	0,35	0,28
			9I	Limb	52°	I3,7	0,50	0,25	6,0	II2	400	0,30	0,23
V-9	11/13/75	I22°	5	Term.	20°	6,0	0,005	0,79	50	33	260	0,38	0,37
			II	Middle Section	24°	6,9	0,I8	0,63	7	33	330	0,75	0,65
			I8	Limb	30°	8,2	0,44	0,35	5,3	36	280	0,60	0,47

Commas in tabulated material are equivalent to decimal points.

3. Preliminary Model of the Vertical Profile of the Cloud Layer Close to the Upper Limit /12

When analyzing observations of the absorption bands in Venus' atmosphere, one of two idealized models is usually used.

a) Model of Simple Reflection. It is assumed that the cloud layer has a pronounced boundary optically equivalent to a solid surface, and the absorption bands are formed in a purely gaseous atmosphere located above this boundary. Use of ordinary growth curves gives a quantity u of absorbing gas in a vertical column of a single section above the cloud layer and complete pressure p_c at the upper limit of the clouds.

b) Model with Scattering. It is assumed that the absorption bands are formed inside the cloud layer. For some particular cases (isotropic scattering, isolated line), accurate growth curves are derived which permit determination of the parameter

$$k = n_g/\sigma \quad (3)$$

the ratio of the concentration of absorbing molecules to the volumetric scattering coefficient σ (cm^{-1}), and effective pressure inside the cloud layer p_c^*. A criterion for choosing between the models is the dependence of equivalent width (complete intensity) of the absorption band on the phase angle, and also the center-edge relation. In model (a), equivalent width should monotonically increase with an increase in air mass M; this does not occur in model (b). A simple comparison of the values W and M presented in table 2, and also the values $\frac{\rho_{2.0^{\circ}2}}{\rho_{2.0^{\circ}2}}$ (fig. 5) and M (fig. 6) favors selection of the scattered atmosphere model.

A simplified model of the group of bands near 2 μm is used for quantitative analysis of measurements W. It is assumed that /13

$$W = \Sigma A_i D_i \quad (4)$$

where A_i--Alsace band transmission (a sequence of equidistant Lorentz lines) restricted by the range D_i. In this range, the integral absorption coefficient S_i remains constant. Figure 7 shows the dependence of S_i on the wave number ν, taken for further analysis. It is based on data [3, 4] and laboratory spectra presented in [1, 2]. The distance between the lines is accepted as being equal d=1.6 cm^{-1}.

The volumetric absorption coefficient of an individual rotational line

$$\varkappa_\nu = \varkappa_0 \frac{\alpha^2}{(\nu-\nu_0)^2 + \alpha^2} = \varkappa_0 \varphi(\nu) \quad (5)$$

where

$$\varkappa_0 = \frac{10^6 S_i}{\pi k \alpha_0 T_0}, \quad (6)$$

ν_0--the center of the line, P--pressure, k--Bolzman's constant

$$\alpha = \alpha_0 \cdot P \frac{T_0}{T}, \quad (7)$$

α_0=0.065 cm^{-1}, T_0=293° K. The inversely proportional dependence α on T in the case of self-widening was found in [5]. The volumetric absorption coefficient in the center of the line $\varkappa_0$ in the approximation considered does not depend on P and T. In the model of simple reflection, the equivalent width of a particular line

$$W_l = \int_0^{\infty} (1 - e^{-\tau_\nu})\, d\nu, \tag{8}$$

where

$$\tau_\nu = \varkappa_\nu \cdot HM, \tag{9}$$

H--height scale, M--air mass.

In the model with scattering /14

$$W_l = \int_0^{\infty} \left(1 - \frac{\rho_\nu}{\rho_c}\right) d\nu, \tag{10}$$

where ρ_ν--luminance coefficient inside the line, ρ_c--luminance coefficient in the continuous spectrum. The luminance coefficient inside the line

$$\rho_\nu = f(a, \mu_1, \mu_2, \alpha, g, \tau_c, A),$$

where a--albedo of single scattering,

$$a = \frac{\sigma}{\sigma + \varkappa_\nu + \varkappa_c} \tag{12}$$

$\varkappa_c$--the volumetric absorption coefficient in the continuous spectrum, is determined by formula (5), g--the parameter describing extension of the indicatrix, τ_c--complete optical thickness, A--the albedo of the underlying surface. For a quite large value $\varkappa_c$, dependence on τ_c and A disappears (approximation of a semi-infinite atmosphere). Apparently, just this case ($\varkappa_c/\sigma \simeq 0.01$) is realized in the range near 2 μm. An analysis of terrestrial photometric and polarimetric observations leads to the value $g \simeq 0.7$ [6]. The value a is assumed not dependent on height. For saturated lines at $\varkappa_\nu \gg \varkappa_c$, this means that these conditions are also met

$$\sigma \propto \varkappa_\nu \propto P^2 \qquad (13)$$

(see formula (5) at $\nu-\nu_0 >> \alpha$). Thus, our calculations will be correct and will yield consistent results (at various μ_1 and μ_2), if the concentration of scattered particles close to the upper limit of the cloud layer changes according to the rule

$$\sigma = \sigma_0 \cdot e^{-z/H_a}, \qquad (14)$$

where the aerosol height scale H_a is equal to half the gas height scale H_g= 5 km, i.e.

$$H_a \simeq 2.5 \text{ km} \qquad (15)$$ /15

Figure 8 shows the function $\rho(a)$ for α=60° and α=120° at μ_1 and μ_2 in the range from 0.5 to 1.0. It is obtained by using various theoretical and semi-empirical data and has an approximate nature. At $a \leq 0.5$ the single scattering approximation is used for the Henye-Grinstein indicatrix at g=0.7; at a>0.5--the van de Hulst similarity principle [7], Rozenberg's approximate theory [8], and model experiments [9]. Assigning the defined value σ at some level z, a_ν can be found using formulae (5) and (12), and from the curve in fig. 8 $\rho_\nu(a)$. Then this value can be integrated within the limits from $\nu=\nu_0$ to $\nu=\nu_0 \pm d/2$. Performing this operation for each value i (see formula (4)) by numerical integration, we find

$$A_i = \frac{1}{d}\int_0^{d/2}\left[1 - \frac{\rho_\nu(a)}{\rho_c}\right] d\nu, \qquad (16)$$

and the value W. When calculating $\rho_\nu(a)$, overlap of adjacent lines should be considered. Figure 9 shows the dependence W on height z_c, at which σ reaches some assigned value in the range from $3 \cdot 10^{-6}$ cm^{-1} to $3 \cdot 10^{-5}$ cm^{-1}.

Measurements of scattered radiation inside the cloud layer on the recovery capsules of "Venera-9" and "Venera-10" [10] indicated that at heights of 55 to 60 km

$$\sigma \simeq 1\text{--}1.5 \cdot 10^{-5} \text{ cm}^{-1} \quad (17)$$

Land-based polarimetry indicates that the mean radius of particles in the upper portion of the cloud layer is approximately equal to 1 μm and the real part of the refractive index $n \approx 1.44$ in the visible range of the spectrum [11]. The scattering cross-section of such particles is approximately identical at wave lengths 0.8 and 2 μm, and, as a result volumetric scattering coefficients are approximately equal to each other. The measured equivalent width of the 2 μm band at $\alpha \approx 60°$ gives /16

$$z_c = 63 \text{ km} \quad (18)$$

at $\sigma = 1 \cdot 10^{-5}$ cm^{-1} and

$$z_c = 66.5 \text{ km} \quad (19)$$

at $\sigma = 3 \cdot 10^{-6}$ cm^{-1}. At $\alpha = 120°$, z_c is 2 km higher. Congruence can be considered satisfactory. The remaining 2 km divergence is apparently explained by the fact that H_a is somewhat greater than $\frac{1}{2}H_g$. The difference of 3.5 km between (18) and (19) suggests this--at $H_a = \frac{1}{2}H_g$ it should be somewhat less.

The photometric section obtained by the narrow-band spectrometer on the "Venera-10" recovery capsule indicated features at heights of 63-64 km which may be interpreted as nearness to the upper limit of the clouds [10]. Thus, the results of measurements of the 2 μm band on the satellites and narrow-band photometry on the recovery capsules may be considered in good agreement for the following model of the cloud layer in the range of the upper boundary: scattering coefficient σ does not change with height in the range from 50 to 60-65 km and on an average, is equal to approximately 10^{-5} cm^{-1}, but above this it decreases according to an exponent with the height scale

$$H_a \simeq 3 - 5 \text{ km} \qquad (20)$$

Table 3 and fig. 11 show the dependence σ, τ and of particle concentration n on height in the range of the upper limit of the cloud layer for two versions of the model differing by σ_0 and H_a. Particle concentration is calculated from the formula

$$n = \sigma/2G,$$

where G--geometric cross-section. In the first version, a constant value $\sigma=10^{-5}$ cm^{-1} is used up to a height of 65 km and then it decreases with the scale $H_a=3$ km. In the second case, $\sigma=1.4\cdot10^{-5}$ cm^{-1} up to a height of 60 km and then σ decreases with a height scale of 5 km. If the upper boundary of the cloud layer is defined as a level at which concentration decreases "e" times, then it is at a height near 68 km in model Nº 1 and 65 km in model Nº 2. /18

The model of simple reflection gives much greater discrepancies. Figure 10 shows the dependence W on z_c for this model. Moreover, z_c here has a sense of a distinct upper boundary of the clouds.

TABLE 3. PRELIMINARY MODEL OF THE CLOUD LAYER PROFILE IN THE AREA OF THE UPPER BOUNDARY

Height km	Model 1: $\sigma_0 = 1{,}05 \cdot 10^{-5}$ см$^{-1}$; $H_a = 3$ км			Model 2: $\sigma_0 = 1{,}4 \cdot 10^{-5}$ см$^{-1}$; $H_a = 5$ км		
z	σ, см$^{-1}$	n, см$^{-3}$	τ	σ, см$^{-1}$	n, см$^{-3}$	τ
60,0	$1{,}05 \cdot 10^{-5}$	170	8,4	$1{,}4 \cdot 10^{-5}$	220	7,0
62,5	$1{,}05 \cdot 10^{-5}$	170	5,8	$8{,}50 \cdot 10^{-6}$	134	4,2
65,0	$1{,}05 \cdot 10^{-5}$	170	3,2	$5{,}15 \cdot 10^{-6}$	81	2,6
67,5	$4{,}35 \cdot 10^{-6}$	70	1,3	$3{,}12 \cdot 10^{-6}$	49	1,6
70,0	$2{,}10 \cdot 10^{-6}$	34	0,63	$1{,}89 \cdot 10^{-6}$	30	1,0
72,5	$8{,}60 \cdot 10^{-7}$	14	0,26	$1{,}15 \cdot 10^{-6}$	18	0,68
75,0	$3{,}80 \cdot 10^{-7}$	6	0,11	$7{,}0 \cdot 10^{-7}$	11	0,35
77,5	$1{,}65 \cdot 10^{-7}$	2,7	0,05	$4{,}2 \cdot 10^{-7}$	6,6	0,23
80,0	$0{,}72 \cdot 10^{-7}$	1,2	0,02	$2{,}5 \cdot 10^{-7}$	4,0	0,15

Commas in tabulated material are equivalent to decimal points.

At $\alpha=60°$, $z_c=66.5$ km, and at $\alpha=120°$, $z_c=73$ km, i.e. divergence is 7.5 km. Artificial models with a "wavey" upper boundary have been suggested [12] which could give similar effects. We note, however, that the model of simple reflection can be valid in any variant only at $\sigma \gg 10^{-5}$ cm^{-1}, which could hardly agree with the results of measurements on the recovery capsules. The height of the upper boundary z_c at phase angles $\alpha \simeq 60°$ is almost identical in both models but this is apparently a random coincidence.

A remarkable fact is the absence of horizontal variations in equivalent width (with the exception of a smooth decrease to the limb and terminator). This means that the scattering coefficient σ at heights of 66-68 km remains constant for the entire area of the planet studied with accuracy to a factor of the order 2. In other words, the upper boundary of the clouds defined as a level at which σ reaches the assigned value, remains at the same height with accuracy to 1 km. In particular, latitudinal variations are absent, though some ground observations have indicated such variations [13]. The absence of horizontal variations makes it possible to hope that the vertical profile of the cloud layer obtained /19 on "Venera-9" and "Venera-10" is characteristic of the entire planet.

4. Continuous Spectrum

The luminance coefficient in the continuous spectrum (see fig. 3 and 4) decreases in the transition from the range 1.7-1.8 μm to the range 2.2-2.4 μm. Neither range is free of absorption bands, especially the first. The middle range of the second has only very weak CO_2 bands and a weak CO band (it is seen only on a few readings as a very slight depression). In this range, the luminance coefficient measured should (with accuracy to several percents) describe reflective capacity in the continuous spectrum. The behavior of the luminance coefficient in the continuous spectrum is characterized by the following features:

a) maximum values of the luminance coefficient close to λ 2.3 μm are approximately 0.43 at $\alpha \simeq 60°$;

b) maximum values of luminance coefficients increase with an increase in phase angle;

c) the maximum value of the luminance coefficient for each given path occurs at $\mu_1 = \mu_2$; luminance coefficient decreases towards the limb and terminator.

All these characteristics may be explained in a first approximation by a model of a semi-infinite atmosphere at a single scattering albedo $a \simeq 0.98$ and $g \simeq 0.7$. In the range 0.8 μm (and this is apparently true up to 1.7 μm) the cloud layer can be considered as a conservatively scattered medium. But already in the two-micron range, such a model is unsuitable. Here significant true absorption occurs. A complex part of refractive index is $k \simeq 1 \cdot 10^{-3}$. This agrees with the hypothesis that the cloud consists of an aqueous solution of sulfuric acid. /20

The equivalent width of the absorption band depends on the single scattering albedo a in the continuous spectrum. The 2 μm band is just found in the transition range where 1-a changes from the value $\leq 10^{-3}$ to $2 \cdot 10^{-2}$ with a decrease in wave length. In section 3, we used $1-a=1 \cdot 10^{-2}$ for the 2 μm band. For strong absorption bands, such a simplification is apparently not too approximate.

5. Conclusions

a) Carbon dioxide absorption bands near 2 μm are formed inside the scattered cloud medium. The behavior of the absorption bands with a change in phase angle and the center-limb effect satisfy the model with scattering and do not agree with the model of simple reflection.

b) The upper boundary of the cloud layer (defined as a level at which concentrations decreases "e" times) is located at a height of 65-68 km.

c) The vertical profile of the cloud layer is characterized by a height scale $H_a \simeq 3$-5 km.

d) The horizontal profile of the upper boundary at scales of 50-100 km and greater is very smooth: its height variation does not exceed 1-2 km.

e) Luminance in the continuous spectrum in the range 2.2 to 2.4 μm according to absolute value and angular relations may be explained by a model of a semi-infinite atmosphere at $a \simeq 0.98$ and $g \simeq 0.7$.

The authors are grateful to V. G. Butkevich, I. S. Gainudinov, V. A. Martsinovskiy, L. Z. Dul'kin, M. O. Validov, F. I. Davlet-Kil'di and many others who have made significant contributions in completing this work. /21

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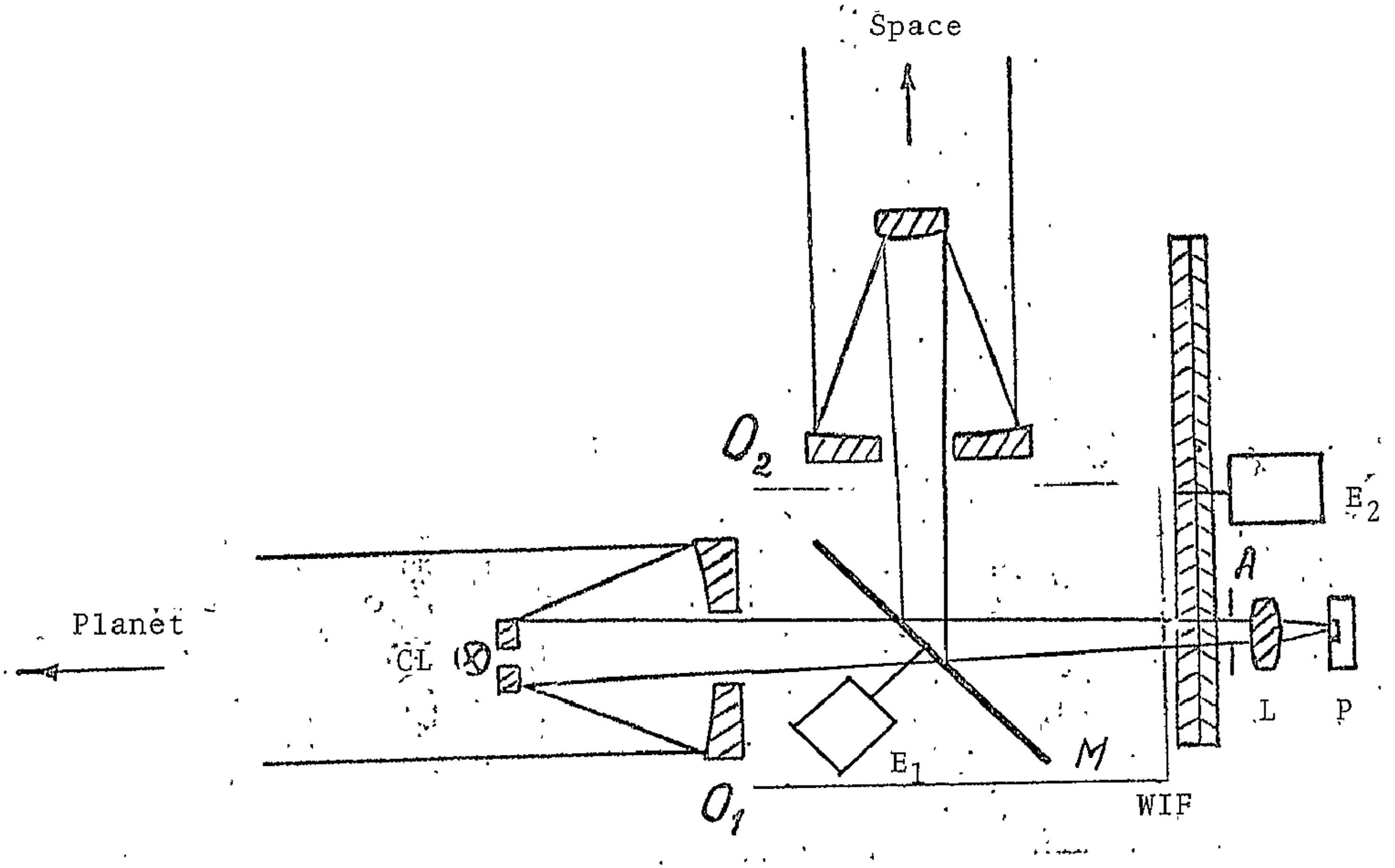

Fig. 1. Optical circuit of the spectrometer.

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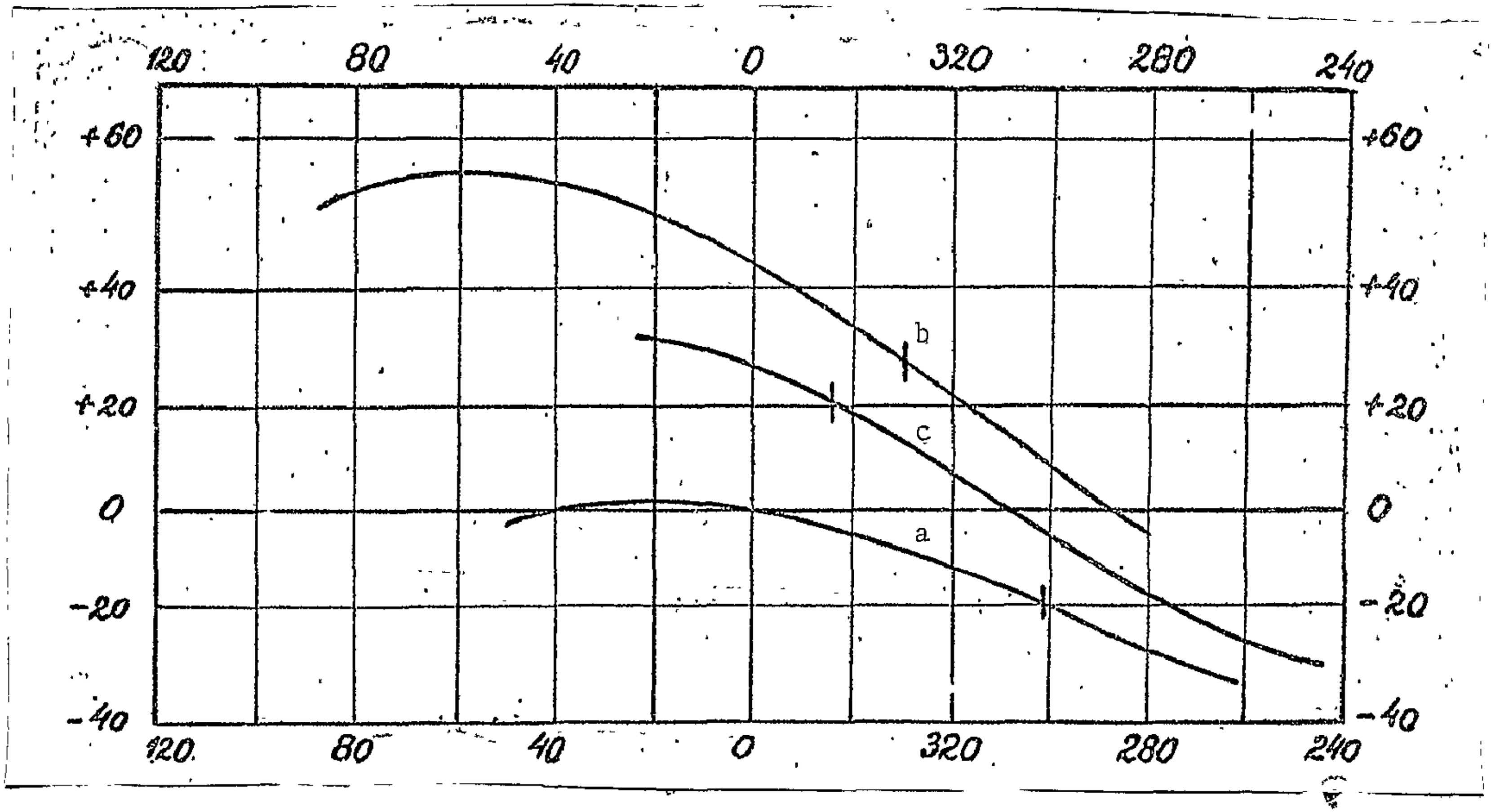

Fig. 2. Three characteristic measurement paths: a) "Venera-10" on 11/6/75, b) "Venera-9" on 11/9/75, c) "Venera-9" on 11/13/75. Paths a) and b) correspond to a phase angle of about 60°, path c)--a phase angle of approximately 120°. The terminator is designated as the vertical dash.

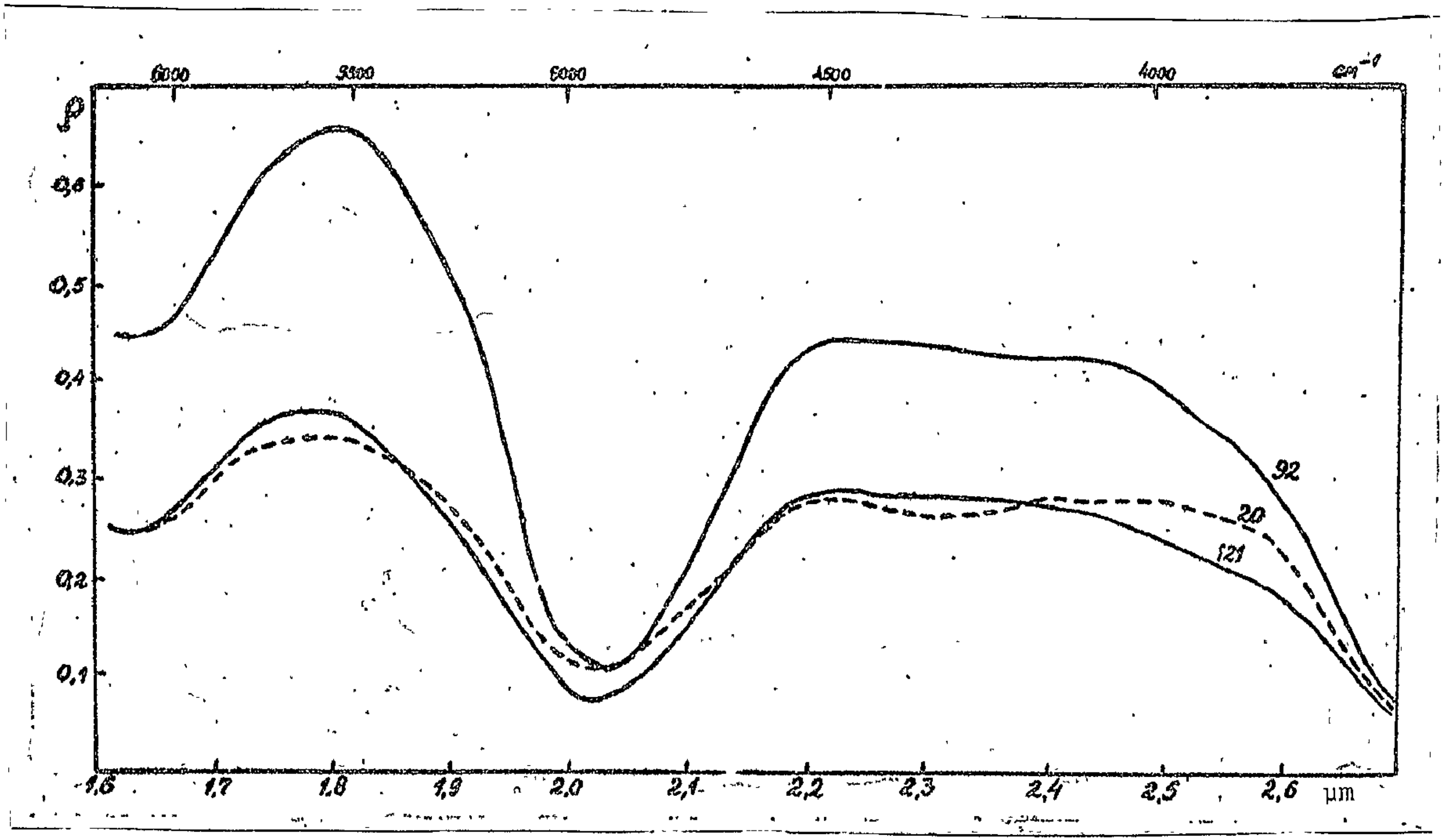

Fig. 3a. Spectra Nº 20 (terminator), Nº 29 (middle section of the path) and Nº 121 (limb) obtained by "Venera-10" on 11/6/75 (phase angle of 62°. Luminance coefficient lies along the axis of the ordinate.

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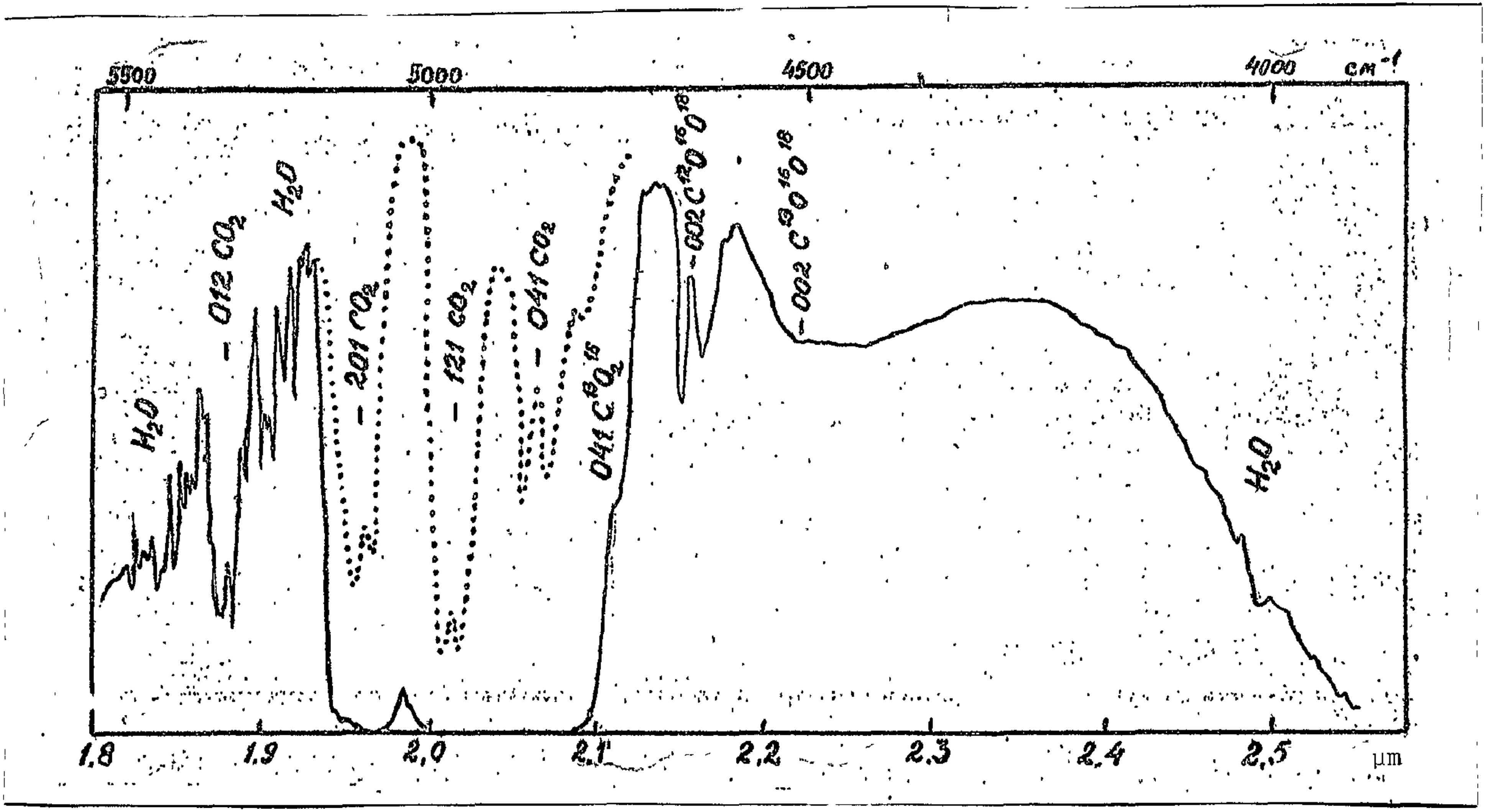

Fig. 3b. Laboratory readings of CO_2 transmission spectrum obtained at resolution $\lambda/\Delta\lambda \simeq 1000$ [1, 2]. The length of the path is 80 m; continuous line corresponds to pressure of 4 atm.; dotted line--0.11 atm.

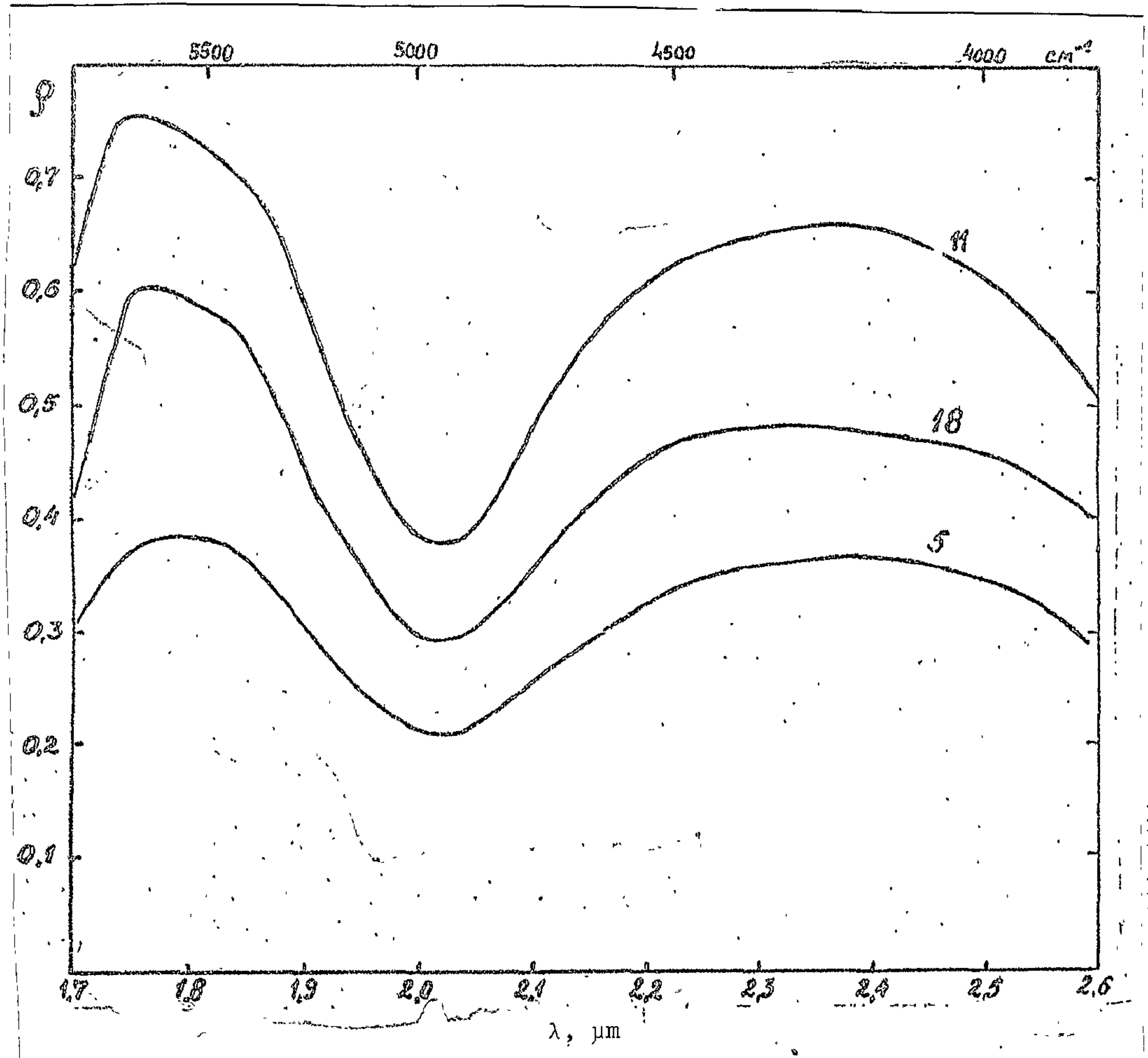

Fig. 4. Spectra Nº 5 (terminator), Nº 11 (middle section of path) and Nº 18 (limb), obtained by "Venera-9" on 11/13/75 (phase angle 122°).

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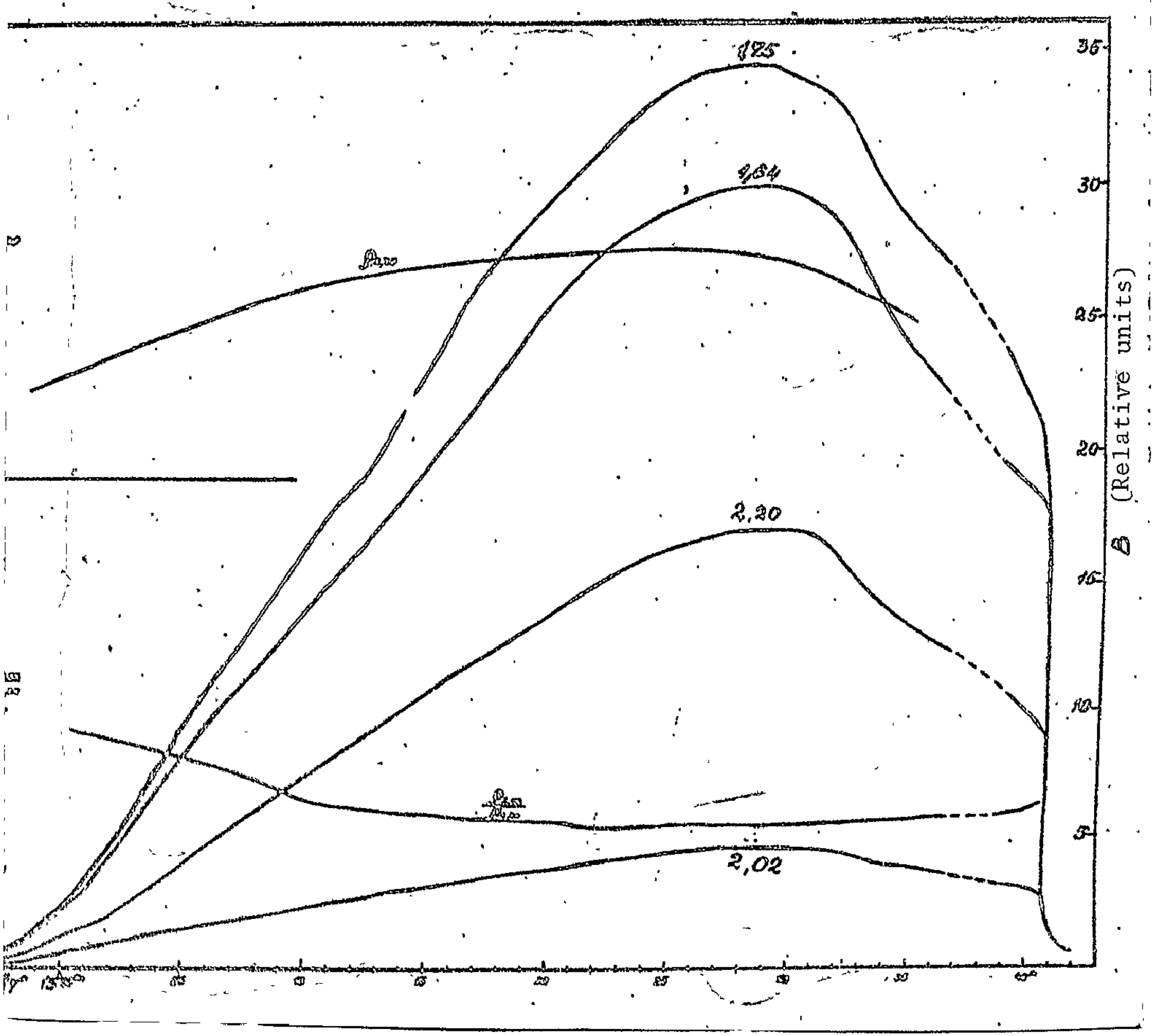

Fig. 5. Photometric sections along the path of "Venera-10" on 11/6/75. Luminance profiles are given in per unit values for 4 wave lengths (1.64, 1.75, 2.02 and 2.20); luminance coefficients for λ 2.20 μm; relations of luminance coefficients at 2.02 and 2.20 μm. Moscow time indicated along x-axis.

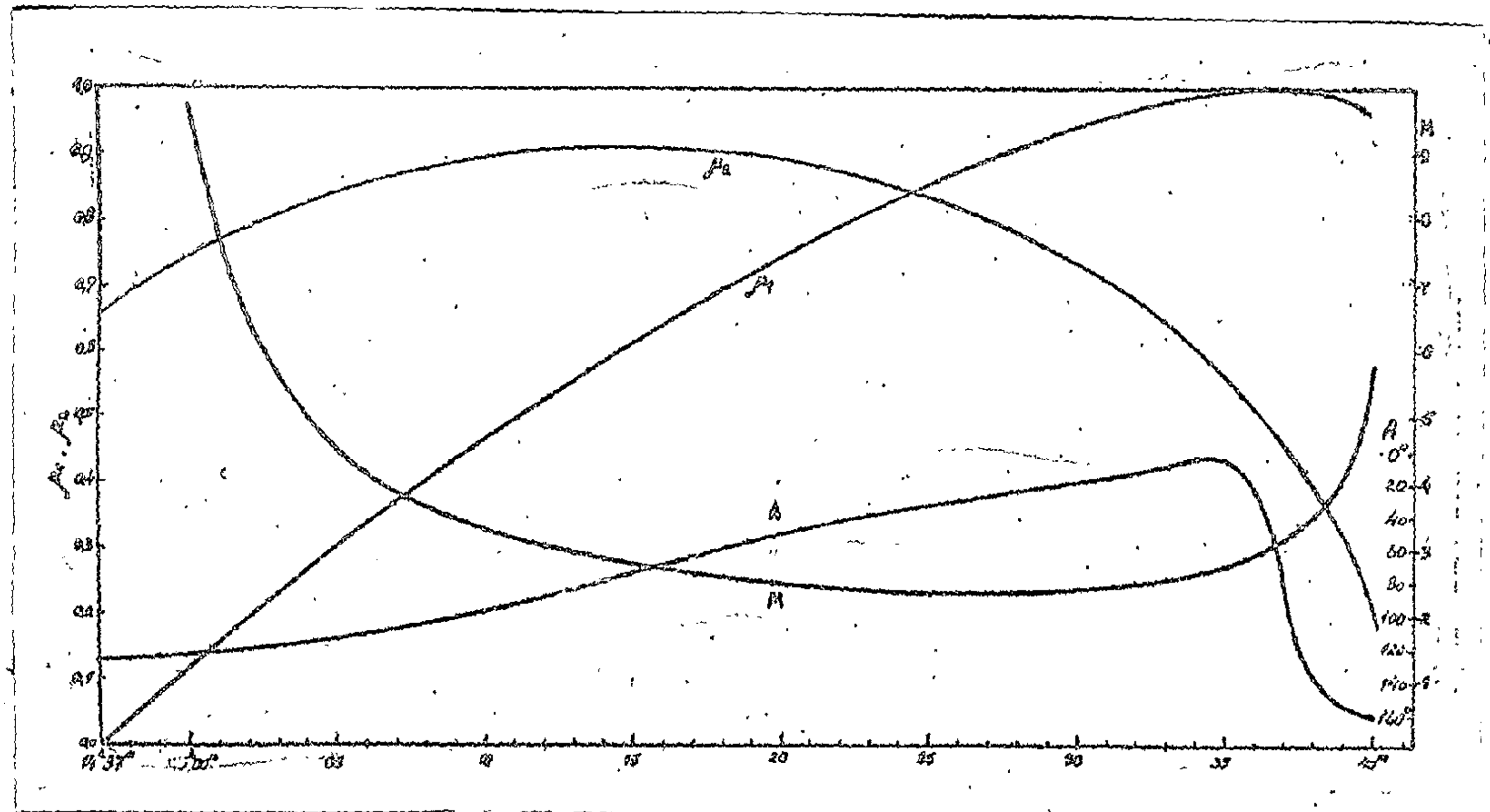

Fig. 6. Cosine of the angle of incidence μ_1, cosine of the angle of reflection μ_2, air mass M and azimuth A for the path on 11/6/75.

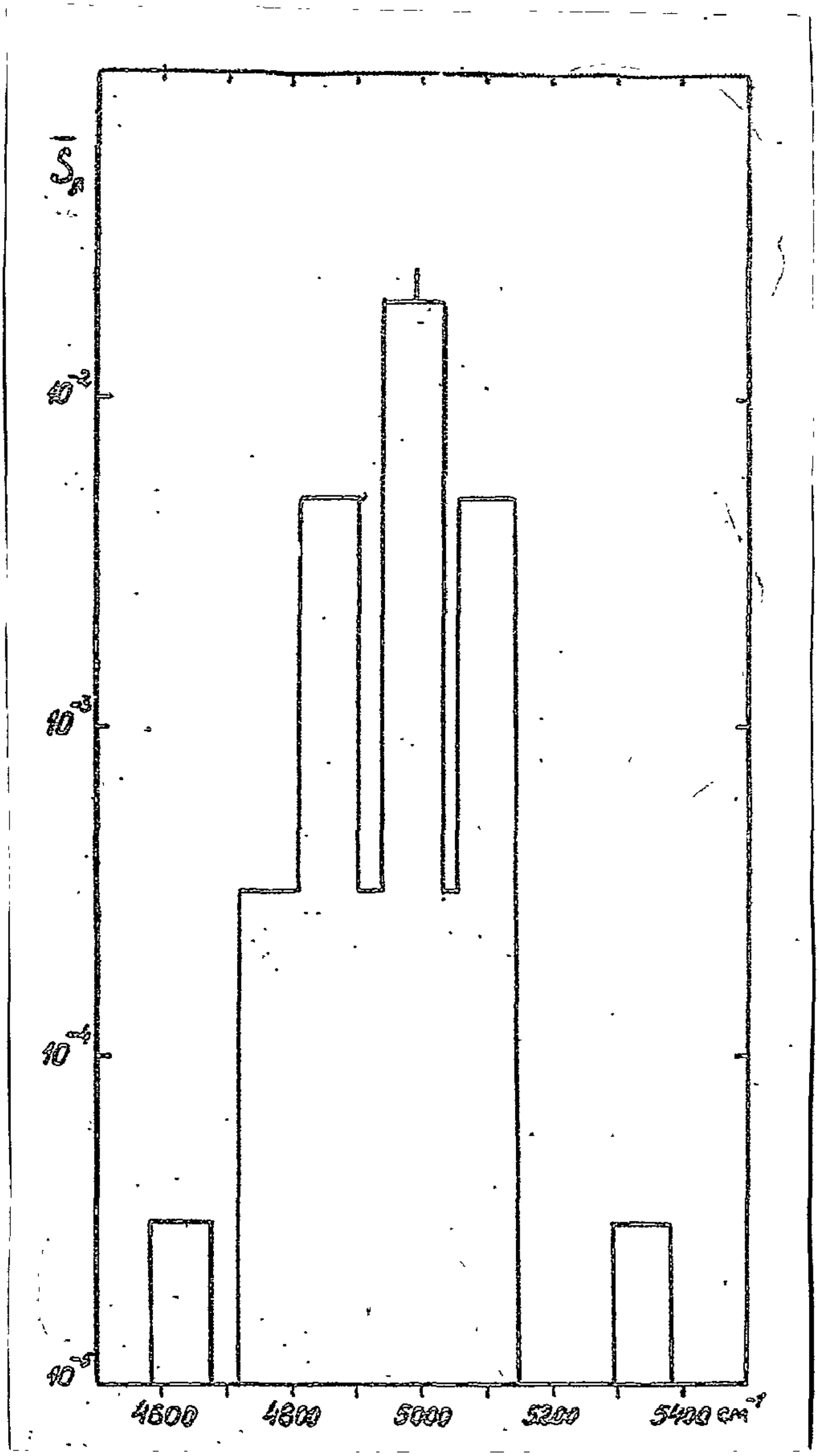

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Fig. 7. Model of the band system near 2 μm. Wave number along x-axis; mean integral absorption coefficient of rotational lines in modified Alsace model along y-axis.

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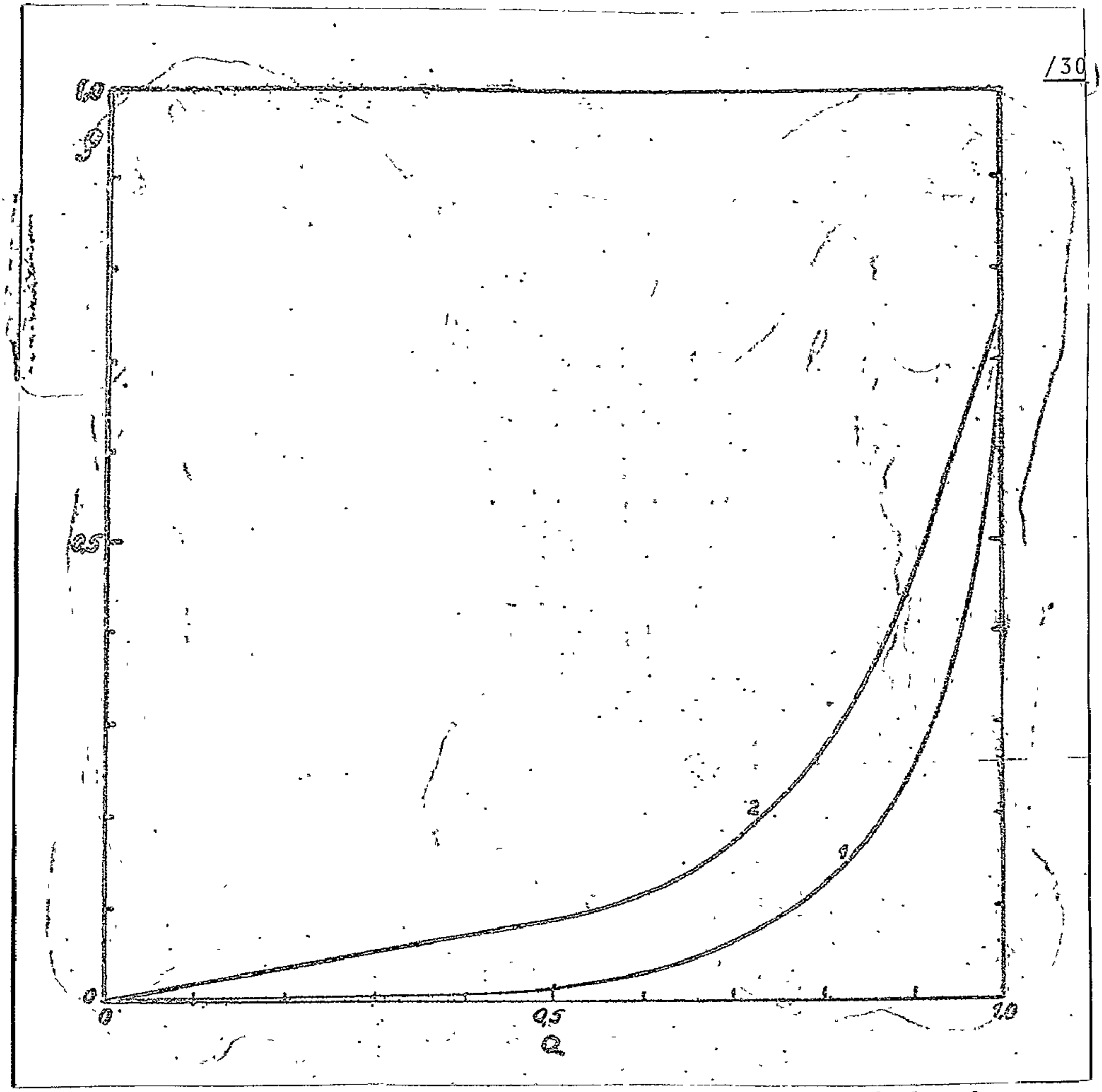

Fig. 8. Dependence of luminance coefficient ρ on albedo of single scattering $a=\frac{\sigma}{\sigma+\varkappa}$, for observation conditions (1)--spectra Nº 92 (11/6/75, V-10) and (2)--Nº 24 (11/13/75, V-9).

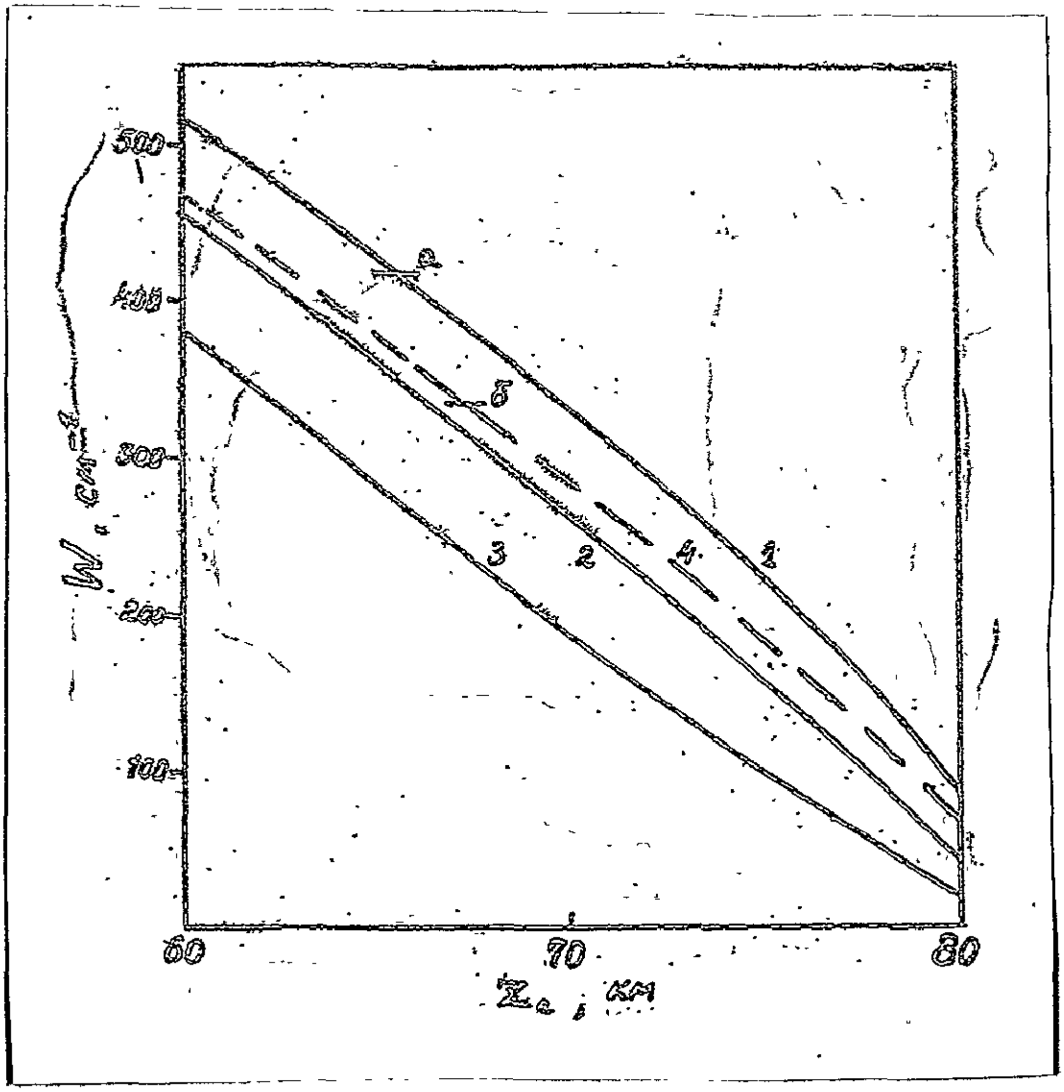

Fig. 9. Dependence of equivalent width W of the 2 μm band on the height of the upper limit of the cloud layer z_c for a model with scattering; 1--$\sigma=3\cdot10^{-6}$ cm^{-1}; 2--$\sigma=10^{-5}$ cm^{-1}; 3--$\sigma=3\cdot10^{-5}$ cm^{-1} for the level z_c at $\alpha=60°$; 4--$\sigma=3\cdot10^{-6}$ cm^{-1} for the level z_c at $\alpha=120°$.

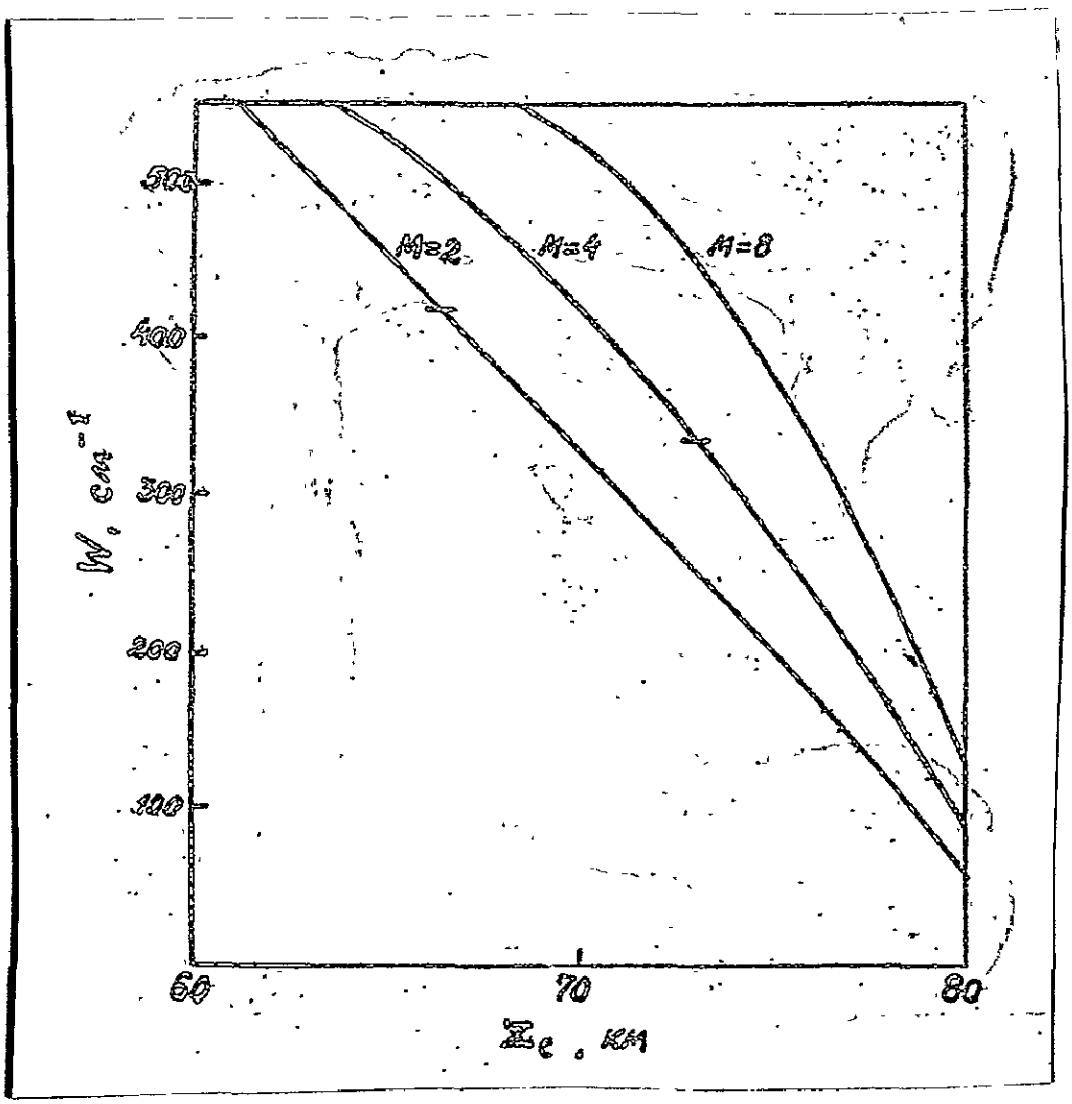

Fig. 10. Dependence of equivalent width W of the 2μm band on height of the upper boundary of the cloud layer z_c in a model of simple reflection for three air mass values.

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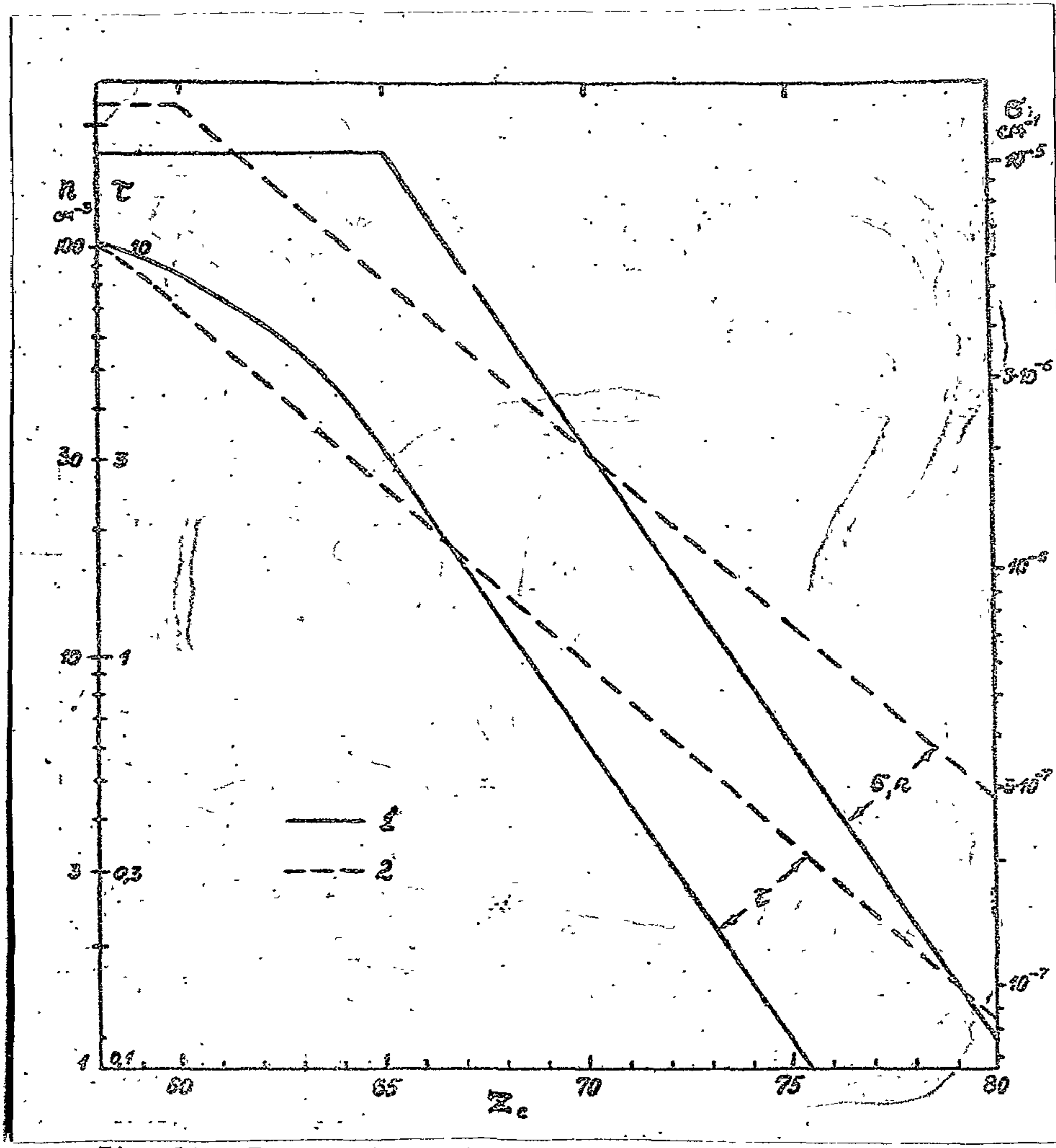

Fig. 11. Two versions of the cloud layer model (1 and 2) in the area of the upper boundary: scattering coefficient σ, particle concentration n, optical thickness τ as a function of height.