NASA TECHNICAL MEMORANDUM NASA TM-75299

PLANETS OF THE SOLAR SYSTEM

K. Ya. Kondrat'yev

and

N. I. Moskalenko

(NASA-TM-75299) PLANETS OF THE SOLAR SYSTEM (National Aeronautics and Space Administration) 133 p HC A07/MF A01 CSCL 03B
N78-24013
Unclas
G3/90 16688

Translation of " Itogi Nauki i Tekhniki; Issledovaniye kosmicheskogo prostranstva. Tom 7. Planety Solnechnoy Sistemy (Advances in Science and Technology. Series: Space Research. Vol.7, Planets of the Solar System), Moscow, VINITI, 1976, Edited by I.S. Shcherbina-Samoylova, pp 8-98 and 119-153

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 APRIL 1978

STANDARD TITLE PAGE

1. Report No NASA TM-75299	2 Government Accession No	3 Recipient's Catalog No
4 Title and Subtitle PLANETS OF THE SOLAR SYSTEM		5 Report Date April 1978
		6 Performing Organization Code
7 Author(s) K. Ya. Kondrat'yev and N. I. Moskalenko		8 Performing Organization Report No.
		10 Work Unit No
9 Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063		11 Contract or Grant No NASw-2790
		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 "Itogi Nauki i Tekhniki; Issledovaniye kosmicheskogo prostranstva. Tom 7. Planety Solnechnoy Sistemy," (Advances in Science and Technology. Series: Space Research. Vol. 7, Planets of the Solar System), Moscow, VINITI, 1976, Edited by I.S. Shcherbina-Samoylova, pp 8-98 and 119-153

16 Abstract Venera and Mariner spacecraft and ground based radio-astronomy and spectroscopic observations of the atmosphere and surface of Venus are discussed, the composition and structural parameters of the atmosphere are presented, as the basis for development of models and theories of the vertical structure of the atmosphere, the greenhouse effect, atmospheric circulation and cloud cover, and recommendations for further meteorological studies are discussed. Ground based and Pioneer satellite observation data on Jupiter are presented and discussed, and calculations and models of the cloud structure, atmospheric circulation and thermal emission field of Jupiter are presented and discussed.

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

Table of Contents

METEOROLOGY OF VENUS

K.Ya. Kondrat'yev

Introduction

A new chapter in the study of Venus, opened by the results /8* of the unmanned interplanetary spacecraft Venera-4, succeeding launches of interplanetary spacecraft of this series, the successes achieved by the American Mariner spacecraft launched towards Venus, and the active development of ground radioastronomical an spectroscopic methods have all produced the present ideas of the properties of the atmosphere and surface of Venus, and they have produced numerous studies, devoted to interpretation of the diverse (sometimes contradictory) measurement data, for the purpose of understanding the basic regularities of the processes occurring in the atmosphere and on the surface of the planet. It would be highly interesting and informative to follow the evolution of our ideas of Venus in the last decade. Since, however, the limited size of the present survey does not permit this to be done, we turn to discussion primarily of present ideas of the composition, structural parameters, thermal conditions and atmospheric circulation of Venus, of everything which determines understanding of the meteorology of the planet, in continuation of the examination begun with a booklet on the meteorology of Mars [31].

1. Composition and Structural Parameters (Model of the Atmosphere)

1. Introduction

Basic information on Venus as a planet (orbital data, mass, etc.) can be found in known monographs and surveys [7,16-18,27,28, 43,44,61,101-103,126]. We present here only the following data, /9 taken from the work of D.M. Hunten and R.M. Goody [124]:

Length of year	224.70 earth days
Synodic year	583.92 earth days
Sidereal day	243.09 earth days
Solar day	116.77 earth days
Radius	6053 km
Height of visible clouds	57 km

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

To understand the processes which occur in the atmosphere of Venus, first and foremost, information on the composition of the atmosphere (including clouds), the characteristics of its thermal conditions and dynamics are required. Problems of the atmospheric circulation, as well as the composition and structure of the clouds will be discussed later (Sections 2-4). Therefore, we now turn to discussion of the regularities of composition of the lower layers of the atmosphere and the vertical profiles of the structural parameters. The schematic vertical structure of the atmosphere of Venus, constructed by analogy to the atmosphere of the earth, is shown in Fig. 1 [157].

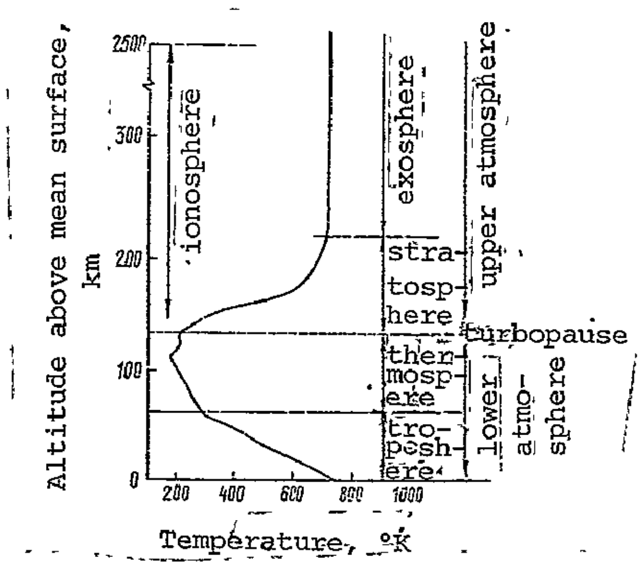

Fig. 1. Vertical structure of atmosphere of Venus.

Despite the wide publicity of the Venera-4 data, they should be recalled here once again, in view of the pioneering nature of the studies performed by means of this unmanned interplanetary spacecraft [UIS] [10-13,198]. The equipment used aboard Venera-4 for direct measurements of the chemical composition (carbon di- /10
oxide, nitrogen, oxygen and water vapor) of the atmosphere of Venus included 11 gas analyzers, consisting of two sets, of which the first (5 cells) was actuated at a pressure of about 550 mm and the second (6 cells), at about 1500 mm. The ambient temperature at these levels was 25±10°C and 90±10°C, respectively. Analysis of the measurements showed for the first time that the Venusian atmosphere consists basically of carbon dioxide (90±10%). The oxygen content cannot exceed 1-1.5% and nitrogen, 7% (possibly less than 2.5%). The water vapor concentration is 1-8 mg/ℓ. The

presence of small amounts of argon and other inert gases in the atmosphere of Venus is not excluded.

As Yu.N. Vetukhnovskiy and A.D. Kuz'min have noted [9], the direct measurements of the composition and structural parameters of the Venusian atmosphere obtained aboard Venera-4 permitted a more reliable interpretation of the previously obtained ground radioastronomical and radar measurements and, on the basis of combined analysis of all this information, new information to be obtained on the atmosphere of Venus. In particular, measurements of the atmospheric composition made it possible to explain the variability of the radiobrightness temperature and the effective cross section of reflection of the radar signal (absorption of radio emissions was due mainly to carbon dioxide), while the radioastronomical and radar measurements permitted the temperature and pressure to be estimated at the level of the mean surface of the planet.

Analysis of the radioastronomical and radar measurements led to the conclusion [37,138] that the temperature onthe surface of Venus is 700±100°K, and that the atmospheric pressure is 65^{+25}_{-15} atm, although a lower temperature (650^{+100}_{-50} °K), but higher pressure (130 atm) are possible. Direct and radio occultation measurements show an increase of temperature and pressure in the 50 km altitude range (with decrease in altitude), from 240 to 600°K and from 0.03 to 27 atm, respectively. The most likely temperatures and pressures at the surface apparently are 700±100°K and 75_{-25}^{+50} atm. Radioastronomical observations have shown the absence of appreciable differences in the surface temperature of Venus on the night and day sides. Study of radio wave propagation in the dense lower layers of the atmosphere [36] led to the interesting conclusion of the possibility of superrefraction of radio waves. Radio waves should bend around the surface of the planet at zenith angles $\theta>84°$, if the surface pressure $P_s \approx 50$ atm and at $\theta>82°$, with $P_s \sim 70$ atm.

In connection with interpretation of the radioastronomical measurements of the parameters of the atmosphere and surface of Venus, D.O. Muhlemann [153] carried out calculations of the thermal radio emissions for various models of the atmosphere (see also [48]). A low optical thickness in the centimeter range turned /11 out to be characteristic of the greater part of the models. However, radar studies indicate that, at wavelengths shorter than 4 cm, the opacity of the atmosphere of Venus is quite substantial. Therefore, D.O. Muhleman also examined the results of opacity determination for the UHF range. Measurements of the apparent surface albedo disclosed a considerable increase of it, with increase in wavelength from 3.6 cm to 1 meter. These data are in agreement with the results of calculations, for models which define the actual albedo of 15.1±0.6%. This corresponds to a dielectric constant of 4.80±0.30 and to the inverse proportionality of the optical thickness of the atmosphere to the square of the wavelength.

Calculations of the microwave emission spectrum of Venus, for surface pressures of 60, 78.5 and 100 atm, a temperature of 725°K and an atmosphere consisting of carbon dioxide showed that the results of such calculations are inadequate, for determination of the pressure from the microwave spectrum. Additional information is required for this, on the temperature distribution and polarization over the disc of the planet, which can be obtained, based on the use of interferometry.

A comparison of the results of microwave radiation calculations for models of the atmosphere, consisting of carbon dioxide, nitrogen and water vapor, with measurements of the quantities led to the conclusion that, if the Venusian atmosphere consists only of carbon dioxide, the surface pressure on Venus is 78.5±1.6 atm, and the temperature is 725°K. In this case, the total carbon dioxide content of the atmosphere of Venus is $4.25 \cdot 10^{23}$ g, which is in good agreement with estimates of the amount of carbon dioxide which was outgassed from the interior sections of the earth, during formation of the crust of the earth.

The results obtained by means of Venera-4 were used to construct the first empirical model of the structure of the atmosphere (vertical pressure, temperature and density profiles), assuming the following chemical composition of the atmosphere: 90% carbon dioxide and 10% nitrogen (average molecular weight 42.4), described by V.S. Avduyevskiy et al [1-4,65-67].

2. Composition

A summary of current information on the composition and structural parameters of the atmosphere, from Venera-4,5,6 and 7 data, can be found in the surveys of M.Ya. Marov [40,41,149], where, in particular, the basic characteristics of the equipment installed in the Soviet interplanetary spacecraft are presented [63]. The Venera-7 data also are discussed separately, in the works of M.Ya. Marov et al [40] and V.V. Kerzhanovich et al [26]. Measurements of the atmospheric composition, from Venera-4,5 and /12
6 data, obtained by A.P. Vinogradov et al [11], are presented in Table 1.

As is evident, these measurements were made at 8 levels, in the pressure range from 0.6 to 10 atm. The main result of the measurements is the establishment of the fact that the atmosphere of Venus consists almost entirely of carbon dioxide. The nitrogen content (if it exists at all) can be only negligible, not in excess of 3-5%. Molecular oxygen is practically absent in the

TABLE 1. MEASUREMENTS OF CHEMICAL COMPOSITION OF ATMOSPHERE BY VENUS BY MEANS OF VENERA-4,5 AND 6

Pressure, $kg \cdot cm^{-2}$	Temperature, °C	Measured bulk concentrations in % or $mg \cdot \ell^{-1}$				Spacecraft
		CO_2, %	N_2, %	O_2, %	H_2O, $mg \cdot \ell^{-1}$	
0,6	~25	97±4	≤3.5	—	~11	Venera-5
0,7	~25	90±10	≤7	≥0,4	>0,7	Venera-4
2,0	85	—	—	≤1,5	≤8	Venera-4
2,0	85	>56	≤9,5	≤0.3	~6	Venera-6
5,0	150	>60	≤4	≥0,1	>0,7	Venera-5
5,0	150	—	≤4	≤0,1	—	Venera-5
10,0	220	>30	≤2,5	≤0,1	>0,7	Venera-6
10,0	220	—	≤2,0	≤0,2	—	Venera-6

Venusian atmosphere, and there is very little (near the cloud top level) water vapor, amounting to ≤1%. Ground spectroscopic measurements gave still smaller possible upper limits of the relative oxygen and water vapor content. This can be seen in Table 2, compiled by M.Ya. Marov and O.L. Ryabov [151], from all available measurement data. Information also is presented here, relative to many other small gaseous components of the atmosphere of Venus. The Table 2 data were obtained on the basis of the use of the measurement methods indicated in the third column (OAO-orbiting astronomical observatory). These data correspond to an average molecular weight of 43.4, at altitudes up to 120 km, where the CO_2 concentration is considered constant. In those cases where different values of the relative content of the same component in the atmosphere are indicated, it means that the data of different measurements diverge. A comparison of direct and spectroscopic measurements impels the conclusion to be drawn that the oxygen content obtained from Venera-4 data should be considered overstated.

Concerning the disagreement of the direct and spectroscopic measurements of water vapor content, the cause of the disagreement /14
in this case may be differences in levels with which the data under consideration are associated (spectroscopic data characterize the moisture of the part of the atmosphere above the clouds). It is significant that, according to the Venera data, the water vapor concentration decreases considerably with increase in altitude above the surface of the planet. Processing of the ground measurements of R.A. Schorn et al [185], carried out in November and December 1967, gave a water vapor content of the part of the atmosphere above the clouds of about 30-40 μm, and it was found

that the intensity of the water vapor absorption lines in the 0.83 μm band is greater above the equator than above the pole.

TABLE 2. CHEMICAL COMPOSITION OF ATMOSPHERE OF VENUS FROM SPECTROSCOPIC AND DIRECT MEASUREMENT DATA

Gas	Mixing ratio	Method	Note
CO_2	$0.9^{+0.03}_{-0.04}$	Venera-4,5,6	
N_2 including inert gases	2.10^{-2}	" "	
H_2O	$(0.6-1.1)\cdot 10^{-2}$	" "	At P=2–0.6 $kg\cdot cm^{-2}$
H_2O	$(1\pm1)\cdot 10^{-3}$	Radioastronomy	
H_2O	$\sim 7\cdot 10^{-5}$	Spectroscopy	
H_2O	$(0.6-1)\cdot 10^{-6}$	" " "	
O_2	$<10^{-3}$	Venera-5,6	
O_2	$<10^{-5}$	Spectroscopy	
CO	$(1-3)\cdot 10^{-5}$	" " "	
HCℓ	2.10^{-7}	" " "	
HCℓ	$<10^{-6}$	OAO	At 1 atm•km CO_2
HF	$(1-3)\cdot 10^{-9}$	Spectroscopy	
CH_4	$<10^{-6}$	" " "	
$CH_3C\ell$	$<10^{-6}$	" " "	
CH_3F	$<10^{-6}$	" " "	
C_2H_2	10^{-6}	" " "	
HCN	$<10^{-6}$	" " "	
O_3	$<10^{-8}$	" " "	
O_3	$<3\cdot 10^{-9}$	OAO	At 1 atm•km CO_2
SO_2	$<3\cdot 10^{-8}$	Spectroscopy	
SO_2	$<10^{-8}$	OAO	At 1 atm•km CO_2
COS	$<10^{-6}$	Spectroscopy	
COS	$<10^{-8}$	" " "	
COS	$<10^{-7}$	OAO	At 1 atm•km CO_2
C_3O_2	$<5\cdot 10^{-7}$	Spectroscopy	
C_3O_2	$<10^{-7}$	OAO	At 1 atm•km CO_2

TABLE 2 (continued)

Gas	Mixing ratio	Method	Note
H_2S	$<2\cdot10^{-4}$	Spectroscopy	
H_2S	$<10^{-7}$	OAO	At 1 atm·km CO_2
NH_3	$<3\cdot10^{-8}$	Spectroscopy	
NH_3	$10^{-4}-10^{-3}$	Venera-8	At P=2-10 $kg\cdot cm^{-2}$
NH_3	$<10^{-7}$	OAO	At 1 atm·km CO_2
NH_3	$<10^{-5}$	Radioastron.	
NO	$<10^{-6}$	OAO	At 1 atm·km CO_2
NO_2	$<10^{-8}$	"	" " "
N_2O_4	$<4\cdot10^{-8}$	"	" " "
HCHO	$<10^{-6}$	"	" " "
CH_3CHO and higher aldehydes	$<10^{-6}$	"	" " "
CH_3COCH_3 and higher ketones	$<10^{-6}$	"	" " "

Direct measurements of the ammonia content were first carried out aboard Venera-8 [57,59]. Measurements at altitudes of about 46 km and 33 km showed that the relative bulk concentration of ammonia is not over 0.1-0.1%. The detection of ammonia in the atmosphere of Venus permitted the proposal of an ammonia model of the cloud layer of Venus, according to which, the clouds are in three layers, and there is a mixture of ammonium salts with water ice in the upper part of it [57]. However, this makes it necessary to find out the reasons for the strong disagreement in the maximum possible ammonia content, from direct and spectroscopic measurements (see Table 2), although these data are associated with different altitudes [98].

The water vapor problem has a special place in study of the atmospheric composition of the planets. The urgency of study of the water vapor content in planetary atmospheres is determined, in particular, by its significant role as an indicator of the evolution of the planetary atmospheres. In connection with this, U. Fink et al [92] discussed the interpretations of the infrared spectra of Venus, recorded by means of a Fourier spectrometer, installed aboard a Convair 990 flying laboratory. The data of 5 flights in January and February 1969, at an altitude of about 12.2 km (above the tropopause), were considered. In some cases, spectra of the Moon were successfully recorded before and after recording the Venusian spectra. This permitted the effect of water vapor in the stratosphere of the earth to be reliably checked. For a confident determination of the water vapor content in the layer of the atmosphere of Venus above the clouds, the measured spectra were compared with spectra, calculated with account taken of the fine structure of the absorption spectra, for various models of the Venusian atmosphere (a special analysis showed that the line profile can be considered Lorentzian).

According to the aircraft radiometric measurements and lunar infrared spectra recording data, an estimate of the total water vapor content of the stratosphere of the earth gave a value of about 8.5 "μm" of precipitated water. Additional absorption in the 1.4, 1.9 and 2.7 μm bands of the spectrum of Venus can be attributed to the effect of Venusian water vapor. Comparison with calculated data for a model of a uniform, reflecting cloud layer gave an average (from measurement data for the 1.4, 1.9 and 2.7 μm bands) content of 1.6±0.36 "μm" for the double passage of rays through the layer above the clouds. In the case of the isotropic scattering model of a semiinfinite cloud, the water vapor content for the mean free path of scattered photons was 0.25±0.10 "μm." The corresponding values of the mixing ratio (with allowance for the carbon dioxide content) are $0.6 \cdot 10^{-6}$ and $1.0 \cdot 10^{-6}$, i.e., they agree fairly well. A comparison with previously obtained spectroscopic data (see Table 2) shows that the new estimates are one or two orders of magnitude lower, as a rule. This cannot be explained by the possible effect of time variations of the water vapor content. U. Fink et al [92] consider that the mixing ratio values obtained, on the order of 10^{-6}, are characteristic of the entire Venusian atmosphere. /15

In discussing the problem of the evolution of water vapor in the atmosphere of Venus, L.L. Smith and S.H. Gross [190] noted that, if Venus outgassed during its evolution, in a manner similar to the earth, in the early stages of evolution, the Venusian atmosphere should have consisted mostly of water vapor. In such an atmosphere, dissociation in the mesosphere layer (where the temperature was 200-300°K) should have occured, producing atomic and molecular hydrogen, atomic and molecular oxygen, a certain amount of hydroxyl and ozone and, also, some small components (for example, HO_2). Under these conditions, atomic and molecular hydrogen will dominate in the thermosphere and, at higher altitudes (in the exosphere), atomic hydrogen. As a result of the absorption of ultraviolet solar radiation by hydrogen, the temperature of the exosphere can reach 100,000°K and cause considerable loss, due to the dissociation of both hydrogen and oxygen. At the same time, carbon dioxide, which is mainly below the mesopause, could have accumulated to the presnet significant level (while the water vapor underwent dissociation, and its components dissociated, due to the high temperature of the atmosphere).

If it is considered that Venus was formed of the same mixture of materials as the earth, and the existence of intense tectonic activity and fairly rapid outgassing in early stages of its development are taken into account, it can be concluded that Venus could have lost up to 300 atm of water vapor and acquired a composition, in which carbon dioxide is extremely dominant, during the first 1-2 billion years of its evolution.

Since the suggestion has been expressed that the ClOO radical is an important component of the chemical reaction cycle in the /16 atmosphere of Venus, which ensures the production of carbon dioxide, which is converted in carbon monoxide and molecular oxygen, due to photodissociation in the upper layers of the atmosphere, R.G. Prinn [165,166] discussed conditions which determine the existence and stability of this radical. It turned out that the dissociation of ClOO in the upper atmosphere is rather slow, which makes possible the reaction $ClOO + CO \rightarrow ClO + CO_2$, producing carbon dioxide, and it explains the low carbon monoxide and molecular oxygen concentration of the atmosphere of Venus.

In concluding discussion of the problem of the composition of the Venusian atmosphere, it should be emphasized that the question of the content of small, optically active components requires further, thorough investigation, since studies of the factors which determine the thermal conditions and atmospheric dynamics depends, to a significant extent, on the availability of reliable information on these components [105,185,193].

3. Structural Parameters

Direct measurements aboard the Venera unmanned interplanetary spacecraft, radio refraction measurements aboard the Mariner spacecraft and indirect ground radioastronomical and spectroscopic measurement data have permitted rather extensive information to be obtained, on the vertical profiles of the structural parameters of the atmosphere of Venus. Certain difficulties arose in interpretation of the first Venera data, in the altitude tie-in of the data obtained. However, analysis of all available results permitted these difficulties to be overcome [149].

In this connection, we note that the topography of the surface of Venus turned out to be very much smoother than was thought initially [76,135,183]. Radar measurements only detected not over a few kilometers uneveness in the relief. Although the radar map of Venus indicates the existence of a large number of craters, the radius of which sometimes reaches 160 km, the depth of these

ORIGINAL PAGE IS
OF POOR QUALITY

craters (even of the largest) is not over 400 m. Measurements of the physical and chemical properties of the surface, carried out aboard Venera-8, showed that the surface layer of the planet is rather unconsolidated in the descent region of the spacecraft and that the soil density is a little more than 1.5 g·cm^{-3}. Measurements of the gamma radiation of the surface material enabled it to be established that this material contains about 4% potassium, 0.0002% uranium and 0.00065% thorium, which is similar in radioactive element content of terrestrial granites [58].

In the case of the radio refraction measurements a serious problem is the extraction of information in itself, on the structural parameters, from the data of this kind of measurement [19,20,169]. There also are serious difficulties in the interpretation of the spectroscopic and radiometric data [161,46]. All this causes definite conflicts in the available results, but it does not prevent successful correlation of them, for the purpose of constructing models of the vertical profiles of the structural parameters. /17

In attempting to avoid repetition of this kind of material, which is contained in numerous surveys [6,122,123,140,142-145,178], we only examine current models. However, we once more recall some studies devoted to analysis of the first data of the Soviet Venera unmanned interplanetary spacecraft [1-3,42,47].

A correlation of all the Venera-4-8 and Mariner-5 data is given in works [39,93,149,151], for the purpose of constructing a model of the vertical structure of the Venusian atmosphere. Typical vertical temperature, pressure and density profiles are presented in Fig. 2, and the location of the cloud tops are indicated. According to Venera-7 data, the surface temperature of the planet is 747±20°K.[1] Here, the vertical coordinate is both the planetocentric distance r and altitude h above the mean surface level of Venus. Analysis of the measurements showed that Venera-7 landed at approximately the mean surface level, which corresponds to a planetocentric distance of 6050-6052 km. This conclusion is in good agreement with the results of ground radar measurements of the radius of Venus, which gave an average value r=6050±5 km.

All the temperature measurements in the free atmosphere are in completely satisfactory agreement. In the lower 60 km layer, the vertical temperature profile corresponds to a typical temperature distribution for an atmosphere in convective equilibrium. The constant vertical temperature gradient in this layer is about 8.6 degree·km^{-1}. However, a detailed analysis of the data discloses some deviations from an adiabatic temperature profile in the 30-40 km altitude range, especially at altitudes below 23 km. Inversions /18

[1]In a recent model [151], T_S=757°K was adopted.

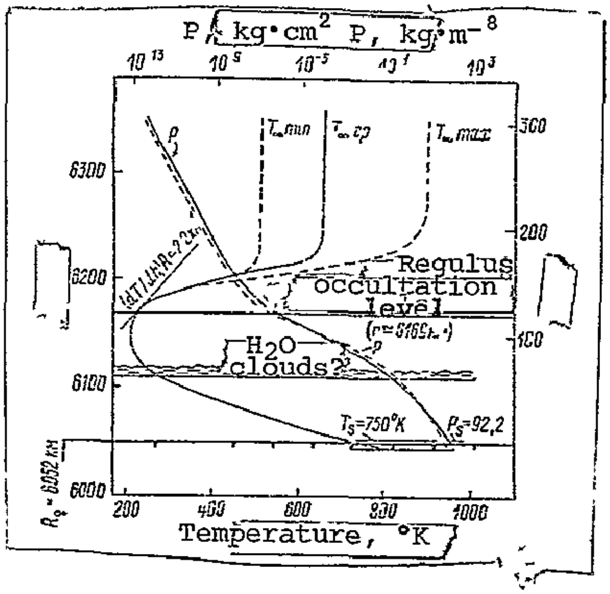

Fig. 2. Characteristic vertical profiles of structural parameters of the atmosphere of Venus.

are observed near the 50 km level and in the 80-90 km layer. The minimum temperature (approximately 195°K) occurs at an altitude of about 105 km. The temperature increase which occurs above this level is due (as in the case of the atmosphere of the earth) to increasing (up to a certain altitude) absorption of solar UV radiation. The vertical temperature gradient obtained from observation data of the occultation of Regulus is, at a planetocentric distance $r \approx$ 6169 km, about 2.2 degree·km^{-1}, and the absolute temperature at this level is 220°K.

The set of measurement data under consideration gives an average atmospheric pressure at the surface P_S=92.2 kg·cm^{-2}. It should be noted that various ground spectroscopic measurements resulted in the atmospheric pressure at the cloud top level of 0.1-0.2 atm, which is in complete agreement with direct measurements.

V.I. Moroz [45] reworked all the Venera-4-8 (altitudes from 0 to 55-58 km) and Mariner-5 (altitude interval 40-80 km) data, as well as other information available up to November 1973, for the purpose of constructing a new working model of the atmosphere of Venus, with special attention to analysis of the data associated with the 0.1-1 atm pressure range. This model was calculated on the assumption of a purely carbon dioxide atmosphere, which corresponds to a molecular weight of 44.0. The V.I. Moroz model covers the 0-150 km altitude range. The Venera results were used as the most reliable measurements for the 0-40 km range and, for the 40-75 km layer, Mariner-5 data. Theoretical calculation results were used above 75 km. Analysis of the P-T diagram, on which all the data were plotted, and a comparison of it with the adiabatic curve for 100% carbon dioxide content showed that the direct and radio refraction measurements agree well and, below the P=2 atm, T=370°K level, the measurement data completely satisfactorily approximate the adiabatic curve. Altitude tie-in of the data was done, with the use of a barometric formula, in which the level to which T_S=750°K corresponds was taken as the start. Adiabatic extrapolation to this level results in P_S=100±7 atm. The level under consideration corresponds to a planetocentric distance of 6051 km. All these data are in agreement with the conditions of the Venera-7 landing point and 1 km below the level of the Venera-8 landing point. /19

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 3. WORKING MODEL OF ATMOSPHERE OF VENUS (BASIC VARIANT)

Distance to center of planet r, km	Provisional altitude h, km	Temperature T, °K	Pressure p, atm	Numerical concentration n, cm^{-3}	Density ρ, g cm^{-3}	Note[2]
6051	0	750	100	9,65 10^{20}	7,10 10^{-2}	Surface level, V7
6052	1	741	93,0	9,08·10^{20}	6,67 10^{-2}	Surface level, V8
6056	5	712	73,0	7,43·10^{20}	5,46 10^{-2}	
6061	10	674	54,6	5.87 10^{20}	4,32 10^{-2}	
6066	15	635	38,2	4,26 10^{20}	3,13 10^{-2}	
6071	20	595	26,1	3,18 10^{20}	2,34 10^{-2}	End of operation V5, V6
6076	25	555	17,6	2,30 10^{20}	1,69 10^{-2}	
6081	30	514	11,4	1,61 10^{20}	1,18 10^{-2}	
6086	35	472	7,2	1,11 10^{20}	8,16·10^{-3}	
6091	40	428	4 0	6,78 10^{19}	4,98 10^{-3}	Lower boundary of "M5 section"
6096	45	384	2,2	4,16 10^{19}	3,06 10^{-3}	
6101	50	350	1,2	2,49 10^{19}	1,83 10^{-3}	
6106	95	300	5,5 10^{-1}	1,33 10^{19}	9,78 10^{-4}	Start of operation V4-8
6111	60	260	2,3 »	6,41 10^{18}	4,69 10^{-4}	
6116	65	240	1,0 »	8,02 10^{18}	2,29 10^{-4}	
6121	70	222	4,0 10^{-2}	1,31 10^{18}	9,59 10^{-5}	Upper boundary of "M5 section"
6126	75	213	1,41 »	4,79·10^{17}	3,52·10^{-5}	
6131	80	205	4,65·10^{-3}	1,65 10^{17}	1,21 10^{-5}	
6141	90	187	4,54 10^{-4}	1,76 10^{16}	1 29 10^{-6}	
6151	100	170	3,61 10^{-5}	1,54 10^{15}	1,13·10^{-7}	Mesopause
6161	110	177	2,63 10^{-6}	1,08 10^{14}	7,93·10^{-9}	
6171	120	183	2,20 10^{-7}	8,70·10^{12}	6,39·10^{-10}	Regulus occultation level
6181	130	190	1,98 10^{-8}	7,85 10^{11}	5,55 10^{-11}	
6191	140	255	2,65 10^{-9}	7,53 10^{10}	5,53·10^{-12}	
6201	150	320	5,64 10^{-10}	1,28 10^{10}	9,39·10^{-13}	

[2]V- Venera, M-Mariner.

The basic variant of the working model of the atmosphere of Venus proposed by V.I. Moroz [45] is reproduced in Table 3. The extreme (maximum and minimum) variants differ noticeably from the basic, only at altitudes over 70 km (see Fig. 3). The main differences from the model of M.Ya. Marov [39] are as follows: 1. higher temperature in 40-60 km layer (by 20-30°) and above 70 km; 2. greater deviation of extreme temperature profile amplitudes from the mean. /20

A detailed development of models of the structural parameters and composition of the atmosphere of Venus, intended for use in

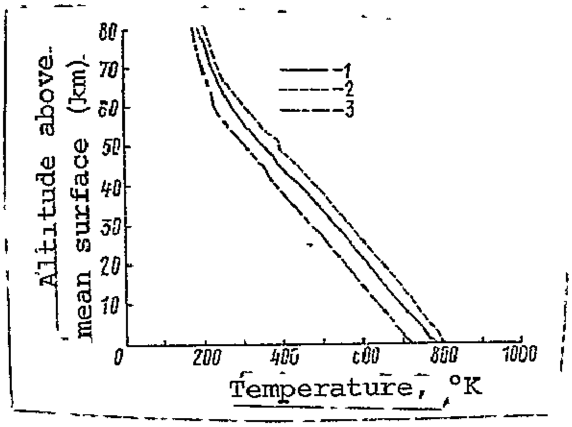

Fig. 3. Optimum and extreme vertical temperature profiles in lower layers of atmosphere of Venus: 1. most probable profile (planetocentric distance of surface r=6050 km); 2. maximum temperature (models II,III,VI; maximum molecular weight of 44 and r=6046); 3. minimum temperature (models IV and V; minimum molecular weight of 41.2 and r=6054 km).

calculations of the unmanned interplanetary spacecraft parameters and in planning appropriate missions to study the planet, was undertaken by R.B. Noll and M.B. McElroy [157]. Like those considered above, these models were based on the use of measurement data from the Veneras and Mariner-5, ground measurements and, also, those results of theoretical calculations which best agree with experiment. The set of models includes average and extreme cases, which correspond to the limiting values of the molecular weight and solar activity. Since determination of the radius of the planet is of critical importance in construction of the models, the authors [157] discussed this problem first of all, and they showed that, according to recent data, the average equatorial radius is 6050±0.5 km. The highest point in the relief corresponds to a level of 3 km.

Analysis of the data which characterize the composition of the lower layers of the atmosphere led to the conclusion that, up to now, information on the water vapor content remains contradictory. An approximately adiabatic gradient up to an altitude of 50 km is characteirstic of the vertical temperature profile. The surface temperature varies (according to different data) from 740-750°K to 774°K (it should be emphasized that there is practically no actual variability of the temperature over the surface of Venus and that only a very slight daily temperature trend is observed). /21

By varying different input parameters, the authors [157] proposed 6 variants of engineering models of the atmosphere of Venus. Data are presented in Table 4, which correspond to the optimum model (the figures in the table, which are the second "term," characterize the exponent to the base 10: for example, +05 is equivalent to 10^5).

According to the data of [157], above the primary cloud cover (altitude of its top 60 km and temperature about 240°K, which correspond to the results of radiometric measurements by S.C. Chase et al [80]), a layer of clouds (haze) is located at an altitude of

TABLE 4. MODEL NO. 1 OF ATMOSPHERE OF VENUS (1972)

Altitude (km)	Temperature (°K)	Pressure (mb)	Density ($kg \cdot cm^{-3}$)	Velocity of sound ($m \cdot sec^{-1}$)	Molecular weight	Altitude scale for density (km)	Numerical concentration (cm^{-3})	Mean free path length (m)	Viscosity ($kg \cdot m^{-1} sec^{-1}$)
—4	798,1	1,20+05	7,89—02	426	43,531	20,52	1,09+21	1,33—09	3,33—05
0*	767,5	9,49+04	6,47—02	418	43,531	19,79	8,95+20	1,62—09	3,24—05
4	736,5	7,41+04	5,27—02	410	43,531	19,06	7,29+20	1,99—09	3,15—05
8	705,2	5,73+04	4,25—02	402	43,531	18,32	5,88+20	2,46—09	3,06—05
12	673,4	4,38+04	3,40—02	393	43,531	17,57	4,71+20	3,07—09	2,96—05
16	641,2	3,30+04	2,70—02	381	43,531	16,81	3,73+20	3,88—09	2,85—05
20	608,5	2,46+04	2,11—02	375	43,531	16,03	2,93+20	4,95—09	2,74—05
24	575,3	1,80+04	1,64—02	365	43,531	15,24	2,27+20	6,39—09	2,62—05
28	541,4	1,29+04	1,25—02	355	43,531	14,43	1,73+20	8,36—09	2,51—05
32	506,8	9,10+03	9,40—03	345	43,531	13,59	1,30+20	1,11—08	2,39—05
36	471,4	6,25+03	6,91—03	334	43,531	12,71	9,61+19	1,51—08	2,25—05
40	433,0	4,16+03	5,03—03	321	43,531	11,82	6,97+19	2,08—08	2,09—05
44	397,8	2,67+03	3,52—03	308	43,531	10,51	4,87+19	2,97—08	1,95—05
48	371,6	1,66+03	2,34—03	299	43,531	9,19	3,23+19	4,47—08	1,82—05
52	366,8	9,91+02	1,54—03	286	43,531	9,36	2,13+19	6,79—08	1,65—05
56	299,6	5,57+02	9,74—04	271	43,531	7,99	1,35+19	1,07—07	1,49—05
60	267,6	2,93+02	5,72—04	258	43,531	7,12	7,92+18	1,83—07	1,33—05
64	246,2	1,44+02	3,06—04	249	43,531	6,13	4,24+18	3,42—07	1,23—05
68	231,9	6,71+01	1,51—04	242	43,531	5,47	2,10+18	6,91—07	1,16—05
72	217,0	2,99+01	7,22—05	235	43,531	5,30	9,99+17	1,45—06	1,10—05
76	200,4	1,25+01	3,27—05	227	43,531	4,76	4,53+17	3,20—06	1,03—05
80	187,9	4,92+00	1,37—05	211	43,531	4,46	1,90+17	7,63—06	0,91—05
84	180,1	1,84+00	5,35—06	203	43,531	4,16	7,40+16	1,95—05	0,89—05
88	175,2	6,65—01	1,99—06	199	43,531	3,97	2,75+16	5,27—05	0,86—05
92	171,1	2,35—01	7,16—07	195	43,531	3,88	9,91+15	1,46—04	0,83—05
96	168,3	8,11—02	2,52—07	193	43,531	3,77	3,49+15	4,15—04	0,81—05
100	166,5	2,77—02	8,70—08	191	43,531	3,74	1,20+15	1,20—03	0,80—05
110	171,0	1,86—03	5,70—09	195	43,531	3,70	7,88+13	1,84—02	0,83—05
120	203,9	1,59—04	4,10—10	229	43,531	4,09	5,67+12	2,55—01	1,01—05
130**	214,0	1,91—05	4,67—11	234	43,531	4,75	6,46+11	2,24+00	1,09—05
140	268,0	3,01—06	5,81—12	261	42,963	5,39	8,15+10	1,79+01	1,33—05
150	378,4	7,79—07	1,04—12	308	42,015	6,92	1,49+10	9,76+01	1,85—05
160	502,4	2,98—07	2,91—13	355	40,818	9,09	4,29+09	3,39+02	2,37—05
170	591,0	1,41—07	1,13—13	390	39,404	11,62	1,73+09	8,40+02	2,67—05
180	641,4	7,51—08	5,32—14	414	37,732	13,93	8,49+08	1,71+03	2,84—05
190	674,9	4,28—08	2,73—14	435	35,781	15,66	4,60+08	3,16+03	2,96—05
200	691,5	2,58—08	1,50—14	455	33,576	17,31	2,70+08	5,39+03	3,01—05
210	700,8	1,62—08	8,66—15	475	31,179	18,70	1,67+08	8,70+03	3,01—05
220	705,5	1,06—08	5,18—15	496	28,700	20,14	1,09+08	1,34+04	3,06—05
230	707,8	7,20—09	3,21—15	520	26,266	21,71	7,37+07	1,97+04	3,06—05
240	709,0	5,07—09	2,06—15	544	23,994	23,49	5,18+07	2,81+04	3,07—05
250	709,4	3,69—09	1,37—15	569	21,963	25,54	3,76+07	3,87+04	3,07—05
260	709,4	2,75—09	9,13—16	593	20,207	27,80	2,81+07	5,18+04	3,07—05
270	709,4	2,10—09	6,68—16	616	18,719	30,21	2,15+07	6,77+04	3,07—05
280	709,4	1,64—09	4,86—16	638	17,467	32,69	1,68+07	8,68+04	3,07—05
290	709,4	1,30—09	3,62—16	658	16,409	35,15	1,33+07	1,10+05	3,07—05
300	709,4	1,05—09	2,75—16	677	15,499	37,52	1,07+07	1,36+05	3,07—05
310	709,5	8,51—10	2,12—16	696	14,699	39,74	8,69+06	1,67+05	3,07—05
320	709,5	7,01—10	1,66—16	713	13,976	41,80	7,15+06	2,03+05	3,07—05
330	709,5	5,82—10	1,31—16	731	13,306	43,71	5,95+06	2,45+05	3,07—05
340	709,5	4,89—10	1,05—16	749	12,672	45,51	4,99+06	2,92+05	3,07—05
350	709,5	4,14—10	8,46—17	768	12,063	47,24	4,22+06	3,44+05	3,07—05

*Corresponds to planetocentric radius 6050 km.

**Density at turbopause level is $1.44 \cdot 10^{-11}$ $g \cdot cm^{-3}$. Fig 3 characterizes variations of the vertical temperature profile, with respect to the optimum model.

about 81 km (the temperature at the level of this layer is approximately 180°K). Determination of the atmospheric pressure at the surface resulted in values of from 90 atm (direct measurements aboard Venera-3) to 100-102 atm (result of extrapolation). Observations of "ultraviolet" discontinuities above the cloud cover of Venus indicate the existence of retrograde rotation of the atmosphere, with a period of 4.3±0.4 earth days. This corresponds to a zonal wind velocity of about 100 $m \cdot sec^{-1}$. Venera data revealed vertical velocities from 0.3-0.5 to 1-1.5 $m \cdot sec^{-1}$ and a horizontal wind component from 2 $m \cdot sec^{-1}$ (altitude of 10 km) to 50 $m \cdot sec^{-1}$ (altitude of 45 km). The question of the wind field in the atmosphere of Venus will be considered in greater detail further on.

Models of the upper atmosphere of Venus, based mainly on the use of theoretical calculation data, also are described in detail in work [157]. According to the Mariner-5 measurement data, Venus has an extended ionosphere, with a maximum electron concentration on the day side of $5 \cdot 10^5$ cm^{-3}, at a planetocentric distance of 6190 km. The electron density remains high ($>10^4$ cm^{-3}) up to a distance of 6500 km, after which it decreases rapidly. The maximum electron concentration on the night side is $2 \cdot 10^4$ cm^{-3}; and the night ionosphere is still more extended. Measurements of the ultraviolet brightness indicated the existence of an extensive hydrogen corona. The dominant positive ion in the ionosphere is CO_2^+. O_2^+ also is probably among the major components. The greatest uncertainty as to the neutral components concerns the location of the turbopause and the O, N_2, CO and He concentrations near the turbopause. The model under consideration is based on the fact that atomic oxygen is a secondary component of the upper atmosphere (10%). The average temperature of the daytime exosphere is approximately 700°K, and it varies, depending on solar activity, as well as depending on the time of day. It is 250°K overall on the night side. /24

Of course, all the models of the atmosphere of Venus considered above are, in a certain sense, contradictory. Available measurement data are inadequate for building an adequate model (we recall that even the standard model of the earth's atmosphere is undergoing systematic refinement). It is clear that the main way to improve the models is the further accumulation and use of observation data. In this connection, there is particular interest in the unique Venera-8 data, which makes it necessary to discuss them separately. We turn to a brief consideration of the Venera-8 data, following the work of M.Ya. Marov et al [150].

The unmanned interplanetary spacecraft Venera-8 landed on the surface of Venus on 22 July 1972, at 12 hours 32 min 16 sec Moscow time, after a 55 min parachute descent. Information was received from the spacecraft in the descent stage, beginning at 11 hours 37 min 27 sec, as well as for 50 min after landing. Venera-8 landed near the equator, on the illuminated side of the planet (at a distance of about 600 km from the morning terminator). The design of the interplanetary spacecraft permitted it to function at temperatures and pressures, which reached 770°K and 120 atm, respectively. Four resistance thermometers were used for temperature measurement, in the 320-860°K, 480-710°K and 670-810°K ranges. The pressure was measured with 3 aneroid barometers and one capacitive sensor, designed for the 0-220 $kg \cdot cm^{-2}$, 0-150 $kg \cdot cm^{-2}$, 0-100 $kg \cdot cm^{-2}$ and 0-80 $kg \cdot cm^{-2}$ ranges (average measurement error is ±1.5%). The wind speed was determined from the radial component of the spacecraft velocity (the earth-Venus direction was an angle of about 38° to the local vertical), measured from the Doppler shift of the frequency of the radio signal recorded. The error in determination of the radial velocity, which varied from 130-140 $m \cdot sec^{-1}$ to 6.5 $m \cdot sec^{-1}$ is not over 0.2 $m \cdot sec^{-1}$.

The availability of a radar altimeter aboard the spacecraft permitted the altitude above the surface to be determined during the parachute descent of the spacecraft. The altitude could also be found independently, from the vertical pressure and temperature profile data. A comparison of the results obtained with the use of these methods disclosed considerable disagreement, especially above 30 km. While the first altitude measurement at 11 hours 37 min 53 sec gave a value of 45.4 km, the calculation data resulted in a value of 51.3±3 km. It is suggested that this disagreement is actual and that it is due to the fact that the spacecraft was blown horizontally to the side by the wind. The windspeed data indicate a horizontal displacement of the spacecraft of approximately 45 km, during descent from the parachute opening altitude to the 25 km level (the descent rate decreased from 70 to 15 and 8 $m \cdot sec^{-1}$ at 54 km, 25 km and at the surface, respectively). With this horizontal movement a 7° slope is sufficient to explain the altitude divergences reaching 5 km. /25

The vertical pressure and temperature profiles obtained result in values of these parameters at the surface of 93±1.5 $kg \cdot cm^{-2}$ and 741±7°K. The vertical profiles found are in good agreement with data for the night side of Venus, obtained by means of Venera-4 and -7. The only previously obtained results (Venera-7) on the surface temperature and pressure gave 90±15 $kg \cdot cm^{-2}$ and 747±20°K. Thus, it can be considered that there is no appreciable daily trend of pressure or temperature near the morning terminator on Venus. The vertical temperature profile is close to adiabatic, right down to the surface. Determination of the horizontal component of the wind speed, in the direction from the subsurface point to the landing point (this direction is about 25° with respect to the zonal), indicates an increase in speed, down to about a 10 km altitude, to 100-140 $m \cdot sec^{-1}$ at altitudes of over 48 km (the wind stays in this direction). In the 20-40 km layer, the wind speed is almost constant, at 30-36 $m \cdot sec^{-1}$. Strong vertical wind speed gradient zones occur in the 12-18 km layer and above 48 km. Venera-8 confirms the Venera-7 data on low winds near the surface, but very much stronger winds than before were obtained for the free atmosphere, although the Venera-4-7 data also indicated an increase in wind speed with altitude.

In concluding the discussion of the observations of composition and structural parameters, we note again that, although the launches of unmanned interplanetary spacecraft not only considerably enriched previously available information, but it brought in many unexpected results, Further active studies of both small, optically active components of the atmosphere of Venus, and the space and time variability of the structural parameter fields are required. In connection with this, the problem of the cloud cover of Venus, to consideration of which we now turn, occupies a special place.

II. Clouds

1. Introduction

The interest in studies of the Venusian clouds, which has existed for a long time, has been due to various reasons, but the main one is the effort to establish the nature of the formation of the global, uniform cloud cover, which, for optical methods, remained only the possibility of study of the layer of the atmosphere above the clouds. To uncover the regularities of formation of the clouds of Venus requires determination of their chemical composition, microstructure and vertical macrostructure, study of the characteristics of atmospheric circulation and other factors. Presently available information on the composition and structure of the clouds has been obtained mainly from ground optical measurement data (data on the spectral brightness and polarization), with the exception of the measurements of the vertical illumination profile by means of Venera-8. Interpretation of the measurements of brightness and polarization of Venus in the visible and near infrared regions of the spectrum is based on the use of the theory of radiation transmission in an absorbing and scattering gaseous medium, containing suspended aerosol particles, the dimensions of which are greater than (or comparable to) the wavelength. Extensive literature has been devoted to discussion of the theory of radiation transmission, and we here confine ourselves only to references to the monographs of R.M. Goody [99], V.Ye. Zuyev [24], K.Ya. Kondrat'yev [132,133], V.V. Sobolev [53] and Ye.M. Feygel'son [60]. /26

Generally speaking, clouds can be either the product of condensation of gaseous components of the atmosphere, or the result of the blowing away and transport of minute dust particles into the atmosphere. If the former is true, the clouds should be localized in a specific layer of the atmosphere, where there are conditions favorable for condensation [100,49]. In the second case, a dust cloud can fill the entire atmosphere, right up to the level of its upper boundary. In view of the high temperatures and pressures near the surface of Venus, the presence of diverse gaseous components, which can form a condensate layer in the free atmosphere, can be suggested. Therefore, precisely for this reason, there is such a large number of hypotheses, which propose various alternate versions of cloud composition. Since scarcely any direct measurements of cloud composition have yet been made (excepting the measurements of water vapor and ammonia concentrations aboard the Venera spacecraft), the main arguments in favor of a given hypothesis still are the data of ground spectroscopic measurements and theoretical considerations, based on radiation transmission theory. Among the important problems connected with this question is the problem of formation of the spectral lines and interpretation of the brightness phase curve measurement data, which make possible study of the vertical structure of the cloud cover.

2. Vertical Structure of Cloud Cover

Without dwelling on the history of theoretical research on the formation of spectral lines, as well as the dependence of the equivalent line width on phase angle, which were of very great im- /27
portance in the interpretation of spectroscopic observations (an exhaustive report on these problems can be found in the works of V.V. Sobolev [50-52]), we direct attention only to a brief characterization of the results of recent work on these questions. A recent series of the most detailed studies is that of G.E. Hunt [115-118], who demonstrated, first and foremost, the unsatisfactory nature of models of a uniform and isotropically scattering atmosphere. The use of such a model does not permit either the observed phase relationship or the spectral line profiles to be correctly described. The development of an adequate theory is possible, only on the basis of taking account of the vertical (gravitational) heterogeneity of the atmosphere and a correct theory of transmission, in which the actual (elongated) scattering indicatrix and the multiplicity of scattering are taken into account.

An interesting result of the first of the studies of G.E. Hunt [115] was the discovery of the fact that, in the case of a CO_2 line of average intensity (typical of the λ1048.8 nm band) and clouds with strongly anisotropic scattering, the equivalent line width decreases monotonically with increase in phase angle, only in the event the phase effect is determined by the clouds. If the gas component is predominant, with phase angles of over 120°, an increase in the equivalent width occurs with increase in phase angle , i.e., the "reflecting layer" effect is observed. Such a phenomenon is characteristic of weak absorption bands (for example, 782.0, 788.3 mm), but it is of a different nature.

G.E. Hunt [116] constructed a model of spectral line formation in the atmosphere of Venus (see also Y. Fouquart [94]), based on the assumption that the pressure at the level of the primary cloud layer tops is 0.2 atm and temperature 240°K and, at the cloud base level, 8 atm and 450°K. Calculations by this model were carried out for a monodisperse cloud, with various particle sizes and indexes of refraction. The calculation results show that the growth curves for reflecting and scattering atmosphere models are parallel (with the exception of the case, when the square root principle is valid for weak lines). This means that a simple model of a reflecting layer, in which scattering and absorption by the cloud particles are not taken into account, can be quite suitable for the interpretation of spectroscopic measurements (determination of the effective pressure, etc.), if the sections of the growth curves under consideration for both models coincide.

Analysis of the calculation results has shown that the clouds of Venus cannot be a single layer, since, in such a case, a monotonic increase in the equivalent width should be observed for the lines of the weak carbon dioxide bands with phase angle, which actually does not occur. If it is assumed that a stratospheric haze /28
layer (50-6 mb level), with 1 μm radius particles at a concentration of 10 cm^{-3}, is located above the basic cloud layer, the equivalent width initially increases in the 0-90° phase angle interval, and it then sharply decreases (the results under consideration are associated with the 782.0 nm line, which has an intensity of $7 \cdot 10^{-8} cm^{-1} (cm\text{-}atm)^{-1}$. At a 20 cm^{-3} particle concentration, the normally observed decrease in equivalent width with increase in phase angle occurs. Thus, it can be concluded that a haze layer of low optical thickness is located above the basic cloud layer of Venus (Fig. 4).

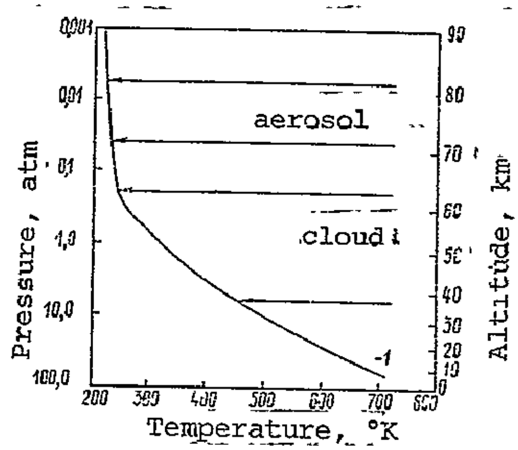

Fig. 4. Schematic vertical structure of cloud cover of Venus (1. vertical temperature profile).

The results obtained by G.E. Hunt [115-117] showed that only study of the equivalent width phase curves of the weak spectral lines permits the vertical structure of the cloud layer of Venus to be found (neither contour lines nor spherical albedo are sufficiently informative, in this sense). The effect of the optically thin aerosol layer on the level of formation of lines is detected most distinctly, at phase angles of over 110°. In this case, the absorption lines form at higher levels than with a single layer cloud. The most decisive indicator of the existence of the stratospheric aerosol layer is the presence of a section of increase in equivalent width with increase in phase angle. If this section is absent, an isolated aerosol layer evidently does not exist in such a case (the aerosol extends right up to the upper boundary of the basic cloud layer). In the light of the results obtained, it would be extremely important to carry out measurements of the phase dependence of the equivalent width, from an artificial /29 satellite of Venus or in the flyby mode of an unmanned interplanetary spacecraft.

Having noted that the data on the phase variations of brightness of Venus in the 782.0 and 788.3 nm carbon dioxide bands were interpreted by G.E. Hunt as indicating a two layer cloud cover, D.L. Regas et al [173,174] noticed that such a conclusion was made, by means of comparison with the results of calculations of the phase brightness curves for a heterogeneous atmosphere model, with or without an aerosol layer above the dense cloud cover of Venus. In this case, the increase in equivalent width with increase in phase angle from 0 to 90° was interpreted as the unequivocal result of the existence of a two layer cloud structure. In connection with this conclusion, the possibility of interpretation of the decrease in equivalent width at small phase angles, as the result of the effect of a "rear" lobe of the scattering indicatrix, which appears at small phase angles and can be considered as an analog of the scattering indicatrixes of terrestrial water clouds [109], was discussed in work [173]. Since there is such an effect, D.L. Regas et al [173] think that the conclusion that there is a two layer cloud structure of Venus, based on analysis of the phase brightness curves, cannot be considered conclusive. For a more nearly correct solution of the problem, calculation of the phase curves is required, with account taken of the detailed structure of the scattering indicatrix.

In disagreeing with these objections, G.E. Hunt [118] emphasized that calculations of back scattered radiation, with allowance for the vertical heterogeneity of the atmosphere and scattering indicatrixes for Mie particles, showed that: 1. the characteristic spectrographic features of scattered ratiation do not depend on such details of the scattering indicatrix as the glory, rainbow, etc; 2. the shape of the phase curves for a carbon dioxide atmosphere depends on the vertical structure of the Venusian clouds. This disputes the objections against the conclusions that there is a two layer cloud structure, based on the assumption of the effect of the "rear" lobe of the scattering indicatrix. The conclusion that there is at least a two layer structure of the cloud cover is in agreement with both calculation results and brightness and polarization measurement data.

L.P. Whitehill and D.E. Hansen [200] continued the discussion of factors which determine the "inverse phase effect," having recalled that observation of the equivalent carbon dioxide absorption line widths in the atmosphere of Venus disclosed a decrease in equivalent width with decrease in phase angle, at small phase angles [204,205]. Thus, for example, the equivalent width near 782.0 nm decreases by 10-30%, at phase angles of 0-30°. Although these data are not completely reliable, because of variations in the equivalent width from day to day which are comparable in magnitude, they were used, nevertheless, for wholly definite conclusions as to the vertical cloud structure of Venus. /30

As was noted earlier, the calculations showed that, if the layer of the Venusian atmosphere above the clouds is considered uniform and isotropically scattering, there should be a monotonic increase in the absorption line equivalent width with decrease in phase angle. Therefore, it should be considered that the "inverse phase effect" in the region of small phase angles is due to anisotropic scattering or vertical heterogeneity of the atmosphere (to the presence of "secondary" cloud layers), or to both of these factors. If, however, anisotropic scattering does not cause the inverse phase effect, it can be considered that it is due to vertical heterogeneity of the atmosphere.

In connection with the conflicts noted, L.P. Whitehill and D.E. Hansen [200] undertook calculations of the dependence of the equivalent absorption line width on phase angle for a uniform cloud model, with particles, the characteristics of which (shape, index of refraction and size distribution) were taken from polarimetric measurement data. The scattering indicatrix on which the calculations were based was calculated for wavelength 782.0 nm, on the assumption that the index of refraction is real and equals 1.43 and that the particle size concentration distribution function n(r) corresponds to the formula

$$n(r) = \text{const}\, r^{\frac{1-3b}{b}} e^{-\frac{r}{ab}}, \qquad (1)$$

where a=1.05 μm, the mean effective radius; b=0.07.

The existence of two secondary backscattering maxima in the 150-180° scattering angle range is characteristic of the scattering indicatrix under consideration (the peak at 160° corresponds to the "rainbow" and, at 180°, the "glory").

The results of calculations made by the doubling method were averaged over the illuminated part of the planet, and they primarily indicate the presence of the inverse phase effect, due to the specific nature of the Mie scattering indicatrix, expressed by the existence of the backscattering maxima (Fig. 5). The phase curves so distinctly reproduce the characteristics of the indicatrix, that this permits formulation of the inverse problem of determination of the scattering indicatrix from measurement data of the equivalent line width phase curves. The day-to-day variability of the equivalent width and the effect of heterogeneity of the atmosphere of comparable magnitude, however, seriously complicate the solution of this problem. Therefore, the statement of this reverse problem is hardly of practical promise. Since the scattering in indicatrix is fairly well known, it is more advisable to study the vertical structure of the atmosphere, from the data on the equivalent line width phase curves, although, in this case, the problem of taking account of the day-to-day variability remains. Evidently, from this point of view, the use of contour line data is the most promising. /31

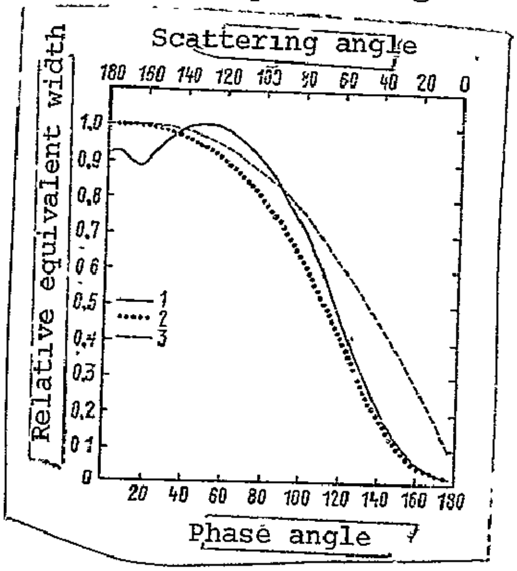

Fig. 5. Relative equivalent width of spectral lines (Lorentz profile) vs. phase angle; albedo for single scattering in center of line $\omega_0 = \frac{1}{1+0.1}$ corresponds to a line of moderate intensity; 1. Mie indicatrix for index of refraction n=1.43; 2. averaged Hansen-Greenstein indicatrix, without secondary "back" scattering maximum; 3. isotropic scattering.

N. Fukuta [95] noted that infrared absorption spectroscopy, based on analysis of the rotational and vibrational-rotational bands, is an especially effective method of study of the composition of planetary atmospheres, in the transparency windows of the terrestrial atmosphere. For interpretation of the resulting data, there is great importance in the selection of an adequate model of the atmosphere, which describes the characteristics of formation of the absorption lines. As has been noted, two models are presently used, based on the assumption that there is either a scattering cloud layer (in this case, the lines are formed in the layer above the clouds), or the passage of radiation into the cloud layer and formation of lines, due to scattering in the clouds.

In analyzing the conditions of the Venusian atmosphere, N. Fukuta showed that, in the presence of clouds in the form of condensate, it is important to consider the three following factors: 1. exchange of cloud components with the layer above the clouds, due to convection (this results in the chemical composition of the clouds and the layer above the clouds being the same); 2. the distribution of the gaseous components between the gas phase and the condensate, depending on the solubility of the gases; 3. Loss of "characteristic" molecules in the condensed phase, due to dissociation. Consideration of available data leads to the conclusion that the formation of HCℓ and HF lines under the atmospheric conditions of Venus takes place, either in the layer above the clouds, if it is considered that the cloud particles are in the liquid phase, or in the scattering layer of clouds, if it is ice (in this case, all the HCℓ in the cloud can only be in the gas phase). /32

In summarizing the results of theoretical studies devoted to the problem of spectral line formation and interpretation of the equivalent line width phase curves, it should be stated that the occurrence of an equivalent width minimum at small phase angles may be due to both the effect of the multilayer nature of the cloud cover of Venus, and to the indicatrix effect. However, there is no doubt that the conclusion of the two layer nature of the clouds drawn by G.E. Hunt [116] should be considered authentic, since the data of other observations, which will be discussed later, give evidence in favor of this conclusion. The authors of [179] expressed the hypothesis that the existence of a dust layer at high altitudes in the atmosphere of Venus was possible.

The studies of spectral line formation permit the effective pressure in the line formation layer to be determined. It is natural to assume that, in a strongly scattering atmosphere, the formation of weak spectral lines occurs at greater depths than strong lines. L.D. Young [204] studied the conditions of line formation at various phase angles, from the equivalent width measurements of the rotational lines of the carbon dioxide band in the atmosphere of Venus, in the 782.0-1217.7 nm wavelength range (the band intensity varies from 0.16 to 170 $cm^{-1}/km \cdot atm$), on the assumption that the mean rotational temperature is 240°K.

The measurement data were interpreted in work [204], based on the use of two methods: 1. a reflecting layer model with a Voigt line profile; 2. a scattering layer model with a Lorentz profile. The reflecting layer calculations showed that the effective pressure, which determines the line formation level, decreases with increase in line intensity (the 1.05 μm band forms at a level, where the pressure is approximately three times higher than in the case of the 1.2 μm band). The scattering layer model gives initial results, but less difference in pressure (approximately half) at the levels of formation of the 1.05 and 1.2 μm bands. The effective pressure decreases with increase in phase angle from 26° to 164°.

The question of the effective pressure in the line formation layer has caused discussion, in connection with the use of measurements of radiation of the equatorial and polar regions of Venus, in the carbon dioxide bands in the near infrared region of the spectrum, to justify the conclusion that there are variations of the cloud top altitude. G.E. Hunt and R.A. Schorn [121] showed that such a conclusion actually has no basis.

3. Chemical Composition, Microstructure and Optical Properties

One of the most characteristic features of the cloud cover of Venus (and, therefore, of the entire planet) is its high albedo in the visible region of the spectrum of 78% [120], which is comparable with the albedo of thick cumulus clouds onthe earth or the snow cover of the polar caps. Of course, the high albedo of the /33 clouds of Venus indicates their great optical thickness and considerable vertical extent. Measurements of the rotational temperature of the carbon dioxide band, in the 700-2000 nm wavelength interval, result in a stable value of about 240°K, which corresponds closely to the effective temperature found from the outgoing thermal radiation, and it indicates uniformity of the cloud cover. The radio refraction data of Mariner-5 [93], as well as interpretation of the phase curves by G.E. Hunt (see Section 2), led to the conclusion that, above the primary cloud cover, the tops of which are located at about the 240 mb level, there is a semiopaque haze layer, which reaches the ∿5 mb level. It is possible that the cloud cover of Venus has a multilayer structure [142-144].

The albedo of Venus changes as a function of wavelength. A decrease is observed towards the ultraviolet (wavelengths less than 350 nm) and infrared (λ∿3000 nm) regions of the spectrum. Therefore, one way of determination of the composition of the Venusian clouds was to compare their albedos with the analogous properties of terrestrial clouds and artificial media (under laboratory conditions). In this connection, data on the optical constants of water and ice [24,184], as well as calculations of cloud albedos [15,35,111], are of great importance.

3.1 Cloud Albedo

Upon analyzing available data on the spectral brightness of terrestrial water and ice clouds and comparing them with the reflection spectrum of Venus, K.Ya. Kondrat'yev and O.I. Smoktiy [34] noted a general similarity of the spectral albedo curves, which makes the water nature of the clouds of Venus probable. Broad adsorption bands near 1500 and 2000 nm and a very weak reflection at wavelengths over 2700 nm are characteristic of the reflection spectrum of ice clouds on the earth. These features are slightly different in the spectrum of Venus, obtained by M. Bottema et al [71,72] from a balloon, because of the effect of strong absorption by carbon dioxide in the Venusian atmosphere. This does not permit a definite conclusion to be drawn that the clouds are ice.

One possibility of obtaining an idea of the nature of the clouds of Venus is to compare the measured and calculated reflection spectra. As the authors of [34] noted, a similar method can be used to estimate particle dimensions (generally speaking, the microstructure). /34

D.L. Regas et al [174] interpreted the spectra of Venus in the 1050 nm region of the carbon dioxide band and the 818.9 nm water vapor line, by comparing the measured and calculated spectra, based on the use of a heterogeneous, isotropically scattering model of the atmosphere, with structural parameters taken from preliminary Mariner-5 and Venera-4,5 and 6 data. It was found that, if the Venusian clouds are a great thickness of absorbing dust, their tops should be located above the 0.09 atm level. If, however, they are a layer of absorbing condensate, their tops are above 0.065 atm. By their scattering properties, the upper part of the clouds of Venus are similar to cirrus or stratus clouds. Calculation of the absorption in the 818.9 nm water vapor line, assuming an isothermal temperature of 240°K above the 0.25 atm level and the clouds to be of an icy nature, gave values considerably in excess of those observed. It can be concluded from this that the clouds of Venus are not purely ice.

Since review of the Mariner-5 data [93] resulted in a significant change in the structural parameters of the atmosphere (the new data indicate, in particular, the possibility of formation of a water cloud at the 58 km level with a mixing ratio for water vapor of 10^{-2}, measured by the Venera spacecraft), the authors of [174] undertook a revision of the interpretation of the ground measurements of the atmospheric spectrum in the 1050 nm band and in the 822.6 nm water vapor line (the observations were made 20-24 October 1967, at a phase angle of 102°). The data which characterize the dust cloud model, in the cases of minimum and maximum cloud top altitudes, are presented in Table 5.

TABLE 5. DUST CLOUD PARAMETERS

Parameter	Minimum cloud top altitude	Maximum cloud top altitude
Pressure at cloud top level (atm)	0.10	10^{-3}
Optical thickness with isotropic scattering	4400	1290
Photon path length at 0.2 atm level (km)	0.65	1.5

As is evident, similar clouds should have a large optical thickness. The single scattering albedo is 0.9966 in the case under consideration, and it completely excludes the possibility of the passage of solar radiation through the clouds (the illumination measurements aboard Venera-8, which will be discussed later, undoubtedly contradict this). If the effect of anisotropic scattering is taken into account, the photon path lengths proves to vary within 0.11-0.25 km. This corresponds rather closely to terrestrial cirrus and stratus clouds. /35

The results of calculations for purely scattering condensate

ORIGINAL PAGE IS
OF POOR QUALITY

clouds, with optical thickness 9.9, are presented in Table 6. This table indicates the possible range of altitudes within which condensate clouds can exist.

TABLE 6. PARAMETERS OF CONDENSATE CLOUD LAYER

Parameter	Minium cloud top altitude	Maximum cloud top altitude
Pressure at cloud top level (atm)	0.034	10^{-3}
Pressure at cloud bottom level (atm)	0.47	0.91
Temperature at cloud bottom level (°K)	282	330
Photon path length at 0.2 mb level (km)	0.8	1.6

A comparison of Tables 5 and 6 leds to the conclusion that the photon path length is approximately the same in both cases.

Data of observations in the 822.6 nm line are in agreement with calculations, if variability of the bulk mixing ratio of water vapor within 1.5-4.8 10^{-5} is assumed and the possibility of the existence of an upper cloud layer of a water solution of hydrochloric acid in the 10-16 mb layer is assumed (optical thickness of cloud is 0.5), i.e., in the cold "trap" zone at an altitude of 80 km, found upon review of the Mariner-5 data. A thicker lower cloud layer of unknown composition is under the upper layer.

D.L. Regas et al [174] criticize the two layer cloud model like that proposed by G.E. Hunt, since it imposes too strong limitations, either on the nature of the condensate in the lower cloud, or on the nature of transmission of radiation in the upper troposphere of Venus. The latter is determined by the fact that such a two layer model assumes too short a photon path length with aniso- /36
tropic scattering, of 0.01 km at the 0.2 atm level. This corresponds to the case of terrestrial cumulus clouds, and it is of little likelihood. Thus, according to [174], the hypothesis of the presence of clouds made of hydrochloric acid solution, located either above the aggregate of condensation clouds, or above the extended dust cloud, leads to the best agreement with the spectroscopic data. A combination of condensation and dust cloud layers also is possible. However, the possibility of the presence of clouds consisting of a sulfuric acid solution must be analyzed.

to an altitude of 65 km. Since an appreciable temperature difference is observed at the 61 km level (the temperature here is about 260°K, and the pressure is 240 mb), it can be suggested that the upper boundary of the lower cloud layer is located at this level.

In the opinion of D.G. Rea [171], spectroscopic data on the composition of the Venusian atmosphere enables it to be considered that the most likely components of the upper cloud layer can be H_2O, HCℓ and HF. The aggregate of polarization and reflection and emission spectra measurements leads to the conclusion that the upper cloud layer apparently consists of liquid drops of HCℓ-H_2O solution (the polarization measurements are in agreement with the assumption of the presence of spherical droplets of about 1000 nm radius, which have an index of refraction 1.45±0.02 at a wavelength of 550 nm).

It is difficult to express definite judgements on the composition of the lower cloud layer, but it is clear that none of the cloud layers can consist of ice crystals since, in this case, the water vapor content above the clouds would have to significantly exceed that observed (however, it is not excluded that crystalline water can be a secondary component of the upper cloud layer).

Despite the successful direct measurements, by means of the Venera series unmanned interplanetary spacecraft and indirect Mariner spacecraft data, as well as numerous theoretical studies, the problem of the chemical composition of the clouds of Venus remains unsolved. Many substances have been proposed as probable components of the Venusian clouds, but the concept that the clouds consist of water (in the liquid or solid phase), iron or ammonium chlorides, dust or mercury compounds has dominated in recent years.

As B. Hapke [113] noted, analysis of the polarization measurements has convincely shown that the cloud particles are spherical (thus, in all likelihood, liquid), have a comparatively monodispersed microstructure (radius about 1000 nm) and have an idex of refraction of 1.45±0.02. In this connection, an emission spectrum of Venus in the 200-1600 nm range, which illustrates the following features of the generation of emissions, is presented in work [113]: absorption by clouds in the UV and visible regions of the spectrum, as well as strong absorption by the cloud particles in the 300-500 nm interval. /38

In the opinion of B. Hapke [113], available observation data exclude a large part of the possible components of the Venusian clouds listed above. If the Venera spacecraft data on the comparatively high water vapor concentration are confirmed, it is completely likely that the clouds are water. The low albedo of the 300-500 nm interval can occur, with a considerable concentration of OH_3^+ ions, which is possible in the presence of hydrochloric acid at a concentration of about 25% (as is known, spectroscopic data indicate the existence of HCℓ in the atmosphere of Venus).

The question of the existence of ice in the clouds of Venus has been very widely discussed in numerous studies, but the conclusions have always been contradictory. The contradictory nature of the conclusions as to cloud composition even appears in works of the same authors. Thus, for example, D. Rea and B. O'Leary [172] rejected the hypothesis of water clouds, having explained the characteristics of the spectral path of the brightness of Venus in the near IR region of the spectrum by the effect of carbon dioxide. However, two years after this, B. O'Leary [160] came to a completely different conclusion. D. Rea [171] presents other concepts. B. O'Leary examined photometric observation data at the Kitt Peak observatory, in the period around inferior conjuction in 1969, which indicate the existence of an anomalous increase in brightness (by approximately 0.07 star magnitude), at a phase angle of 158°. This corresponds to the direction, in which the halo should occur (the halo usually is observed as a ring under earth conditions, located at an angular distance of 22° from the sun or moon). The angular width of the brightness maximum is approximately 3° (the width of the halo band is 2-3° under earth conditions). This kind of result was obtained at all 5 wavelengths (450, 550, 700, 850 and 1050 nm) at which observations were carried out.

B. O'Leary interprets the results obtained as the halo phenomenon, indicating the existence of hexagonal ice crystals in the upper portion of the Venusian clouds. The possibility of such an interpretation is determined by the similarity of the observed phenomenon and the terrestrial halo. In particular, in accordance with the dependence of the index of refraction of ice on wavelength, there is a location dependence (angular radius) of the halo on wavelength.

D.G. Rea [171] considered that a review of the radio transillumination data on the atmosphere of Venus from Mariner-5 led to the conclusion that the vertical temperature profiles on the night and day sides are identical and that there is a fine vertical profile structure in the 60-90 km altitude range, with a characteristic minimum at the 81-82 km level. The latter circumstance, together with observation data on the transit of Venus over the solar disc, /37
permits the hypothesis to be expressed that there is an upper cloud layer at an altitude of 81 km (pressure 3 mb), which is at a temperature of 175°K. As has been noted, the presence of such a layer also was found, based on analysis of the phase variations of the band intensity in the carbon dioxide spectrum and the carbon dioxide line profiles.

Meanwhile, the thickness of the layer has not been successfully determined, but it is clear that its optical thickness cannot be great, since radiation in the near IR region is capable of penetrating it to deeper layers of the atmosphere. Interpretation of the observation data on the fine structure of the carbon dioxide spectrum in the near IR region indicates that the temperature at the band formation level is about 250°K (±5-10°K). This corresponds

If the cloud particles are drops of hydrochloric acid solution about 1000 nm in size, there should be very slightly expressed 1500 and 1900 nm water bands (the lack of these bands in the spectrum of Venus is the main argument against the hypothesis that the clouds are water). The addition of hydrochloric acid decreases the freezing point of the drops to 200°K. This makes the existence of crystalline clouds on Venus very much less likely than on the earth.

None of the observed components of the atmosphere of Venus has noticeable absorption in the 300-600 nm interval, which causes the yellow color of the clouds. This absorption possibly is caused by condensation nuclei, which are the products of volcanic eruptions or soil erosion and are particles of iron compounds (the Fe^{3+} ion has strong absorption bands in the 200-400 nm wavelength region). A 6 M $HC\ell$ solution containing 1.7 moles of dissolved $FeC\ell_3$ per liter of solution has an index of refraction of 1.45, i.e., it can be suggested that the clouds consist of drops of "dirty" hydrochloric acid. Highly accurate measurements of the spectrum of Venus in the UV wavelength region are necessary for a more reliable substantiation of this suggestion.

R.A. Hanel et al [107] recorded the emission spectra of Venus in the 700-2500 nm range at McDonald observatory. After eliminating the effect of the atmosphere of the earth (by means of determination of the intensity ratio in the spectra of Venus and the moon), they found an abundant fine structure. This structure permits identification of a whole series of carbon dioxide lines, as well as a depression around 900 cm^{-1}, which was ascribed to the effect of the cloud layer particles.

As has been noted, one important component of the Venusian clouds may be mercury compounds. J.F. Potter [164] analyzed the /39
correctness of this hypothesis, from the point of view of its correspondence to the high albedo of the planet. Different models of this kind of cloud cover lead to the conclusion that it should develop in the upper layers of the atmosphere and consist of mercury drops. However, such clouds should strongly absorb and, consequently, have a low albedo. Therefore, it should be suggested that the albedo of the planet is due to a higher layer of clouds, which consists of $Hg_2C\ell_2$. It is possible that there is a still higher layer above this layer, which consists of hydrochloric acid $HC\ell$-H_2O

J.F. Potter [164] calculated the albedo of this kind of cloud system, for the purpose of estimating the correspondence of the results obtained and observation data. These calculations were made, on the assumption of the absence of a reflecting layer above the primary layer of mercury clouds, for wavelength 626.4 nm (Venus is the brightest at this wavelength, with an albedo of 0.94) but, with allowance for a reflecting layer located below, with cloud drop radii of 10, 100 and 1000 nm (the complex index of refraction is 2.21-5.60). The addition of strongly reflecting upper story cloud layers led to the conclusion that, if the drop radius of the mercury cloud is not over 2500 nm, the mercury content in the primary cloud should not exceed 10^{-3} $g \cdot cm^{-2}$.

Upon turning again to discussion of the problem of the composition of the clouds of Venus, R.G. Prinn [165] proceeded from the fact that, according to available data, the upper part of the visible clouds of Venus is at a temperature of about 250°K and that their tops are located near the 200 mb (63 km) level, but it is difficult to fix its location distinctly. Polarization measurements of the sunlight reflected by the clouds resulted in an estimate of particle radius on the orderof 1100 nm and an index of refraction of 1.44 at the 50 mb level. Evidently, intermittent, weak haze layers, noted on photographs in UV light, are at about the 10 mb level.

In connection with the detection of water vapor and hydrochloric acid in the atmosphere of Venus, the hypothesis was expressed that the upper haze layer consists of drops of concentrated hydrochloric acid, which can form at a temperature of about 198°K, corresponding to a pressure of 20 mb. In this case, it was assumed that the mixing ratio for water vapor is 10^{-4} at the cloud top level. However, recent observations have shown that, even inside the primary mass of clouds, the mixing ratio apparently is a total of 10^{-6}. In such a case, hydrochloric acid and water vapor can condense only above 88 km (pressure 1 mb, temperature 160°K), in the form of ice crystals and solid hydrogen chloride $HCl \cdot 3H_2O$.

The very small water vapor mixing ratio means either predominance of similar conditions in the entire atmosphere of the planet, /40
or the existence of highly hygroscopic cloud materials, which cause a low water vapor content in the visible part of the atmosphere of Venus. It was noted earlier that hydrochloric acid drops have an index of refraction of 1.44, and the hypothesis of clouds consisting of such drops is in agreement with measurement data of the IR spectrum of Venus. The water vapor tension above such drops is so small, that it permits a mixing ratio on the order of 10^{-6} to be explained.

Spectroscopic observations led to the conclusion that there is a very low concentration of sulfur containing gases in the Venusian atmosphere. However, it was shown that this was due to rapid photochemical dissociation of such gases (primarily carbonyl sulfide COS) in the upper atmosphere (the dissociation time is on the order of 10^3-10^5 sec). This leads to the formation of a sulfuric acid drop aerosol, by means of photooxidation of SO_2, in the presence of O_2 and small amounts of H_2O.

Thus, it can be proposed that the visible clouds of Venus are an extended haze of sulfuric acid drops, the scale height of which exceeds the scale height of the gaseous atmosphere [189,202,207]. It was shown in a recent work of A.T. Young [203] that the best agreement with the measured IR emission spectrum of Venus is obtained, if it is assumed that the cloud particles consist of a water solution of sulfuric acid, the concentration of which slightly exceeds 75%. In such a case, the water vapor mixing ratio should be 10^{-6} (lower limit) and 10^{-7} for carbonyl sulfide and sulfur dioxide (upper limit). This agrees well with observation data. There should be no discontinuities in the cloud layer, only if the dynamics of the atmosphere do not cause mixing of the entire cloud layer in a time less than a few days. In such circumstances, the water vapor mixing ratio can increase to 10^{-4}, and a thin haze layer of hydrochloric acid drops can form above the primary mass of clouds. The presence of sulfur in the cloud particles may subsequently be detected by X-ray fluorescence measurements from unmanned interplanetary spacecraft.

In summarizing studies of the chemical composition of the clouds of Venus, the spottiness and disagreements of present concepts (more accurately hypotheses) on this question should again be emphasized. Besides water, ice, dry ice, water solutions of hydrochloric and sulfuric acids and mercury compounds, the following have been proposed as components of the Venusian clouds: carbon suboxide C_3O_2 [136], ferrous chloride hydrate $FEC\ell_2 \cdot 2H_2O$ [137], sodium chloride [122], formaldehyde [201], hydrocarbons [128], hydrocarbon amides [176], water polymers [87], ammonium nitrite NH_4NO_2, calcium and magnesium carbonates and $NH_4C\ell$ [142]. The interpretation of the Venus polarization measurements made a definite /41
contribution to ordering the results obtained.

3.2 Polarization of Sunlight Reflected by Clouds

One of the most effective methods of study of cloud particle sizes, determination of their optical properties (complex index of refraction) and composition is interpretation of polarization measurements of the light of Venus [50-53,82,130]. Some estimates of particle radius and index of refraction, obtained from polarization observations, were mentioned above. They all lead to approximately the same result. The average particle radius is about 1000 nm, and the index of refraction is significantly greater than that of water (1.4-1.7). Thus, for example, J.E. Hansen and A. Arking [110], having calculated polarization at wavelengths of 365, 550 and 990 nm, with allowance for multiple scattering and nonmonodispersed particles (with an average radius of 1100 nm), found the best agreement with the measured values at indexes of refraction of 1.46, 1.45 and 1.44, respectively. Very precise calculations of the dependence of polarization on phase angle (the case of a spherical atmosphere, models of single layer and multilayer cloud cover), made by G.W. Kattawar et al [130], with the use of the Monte Carlo method, reached the conclusion that the average particle size is about 1000 nm and the index of refraction varies from 1.45 to 1.6. Absorption is appreciably displayed, only at a wavelength of 340 nm, for which the particle albedo is 0.977.

In a recent work, J.E. Hansen and J.W. Hovenier [112] summarized the polarization studies of Venus and undertook new comparisons of the results of theoretical calculations of the degree of polarization with observation data, with the intention of determining cloud particle sizes and their index of refraction. The calculations were done for clouds, the microstructure (particle size distribution) of which is given by formula (1). Since parameters a and b of this formula can be considered as effective values of the particle radius and variability of radius, respectively, both of these quantities are basic parameters, which determine the degree of polarization. Two other parameters are the index of refraction n and coefficient f_R, the contribution of Rayleigh scattering (the ratio of the coefficients of Rayleigh and aerosol scattering). The polarization phase curves were calculated for wavelengths 365, 550 and 990 nm, to which particle albedos of 0.98427, 0.99897 and 0.99941, respectively, correspond. With such single scattering albedos, the spherical albedos of the planet are 0.55, 0.87 and 0.90. Cosα (α, scattering angle), which characterizes the scattering indicatrix, is 0.761, 0.713 and 0.715, respectively. /42

The calculations of J.E. Hansen and J.W. Hovenier showed that polarization at 550 nm is most sensitive to particle size and changes rather strongly, as a function of the index of refraction. The calculation results, compared with all available polarization observation data, illustrating the variability of the polarization phase curves vs. particle size, are presented in Fig. 6. The polarization maximum at phase angles around 20° reflect the position of the primary rainbow, and the maximum at ∿155° corresponds to anomalous diffraction. It follows from the Fig. 6 data that, if the index of refraction is 1.44±0.015, the best agreement with observation results occurs with an effective radius (parameter a)∿1050±100 nm and radius /43 variability (parameter b) 0.07±0.02. Data of a similar comparison for other wavelengths confirm this conclusion, relative to the cloud microstructure.

Since the index of refraction can change as a function of wavelength, calculations were carried out, in order to analyze the sensitivity of the phase curves to the index of refraction at all 3 wavelengths under consideration.

At wavelengths on the order of 1000 nm, the observed polarization of Venus is negative at all phase angles. This is caused by the comparability of particle sizes and wavelengths in this wavelength range. At λ=990 nm, the polarization phase curves are very sensitive to both particle size and index of refraction (Fig. 7). Therefore, measurements at this wavelength are very informative, from the point of view of determination of the corresponding parameters. In particular, they result in n=1.43±0.015.

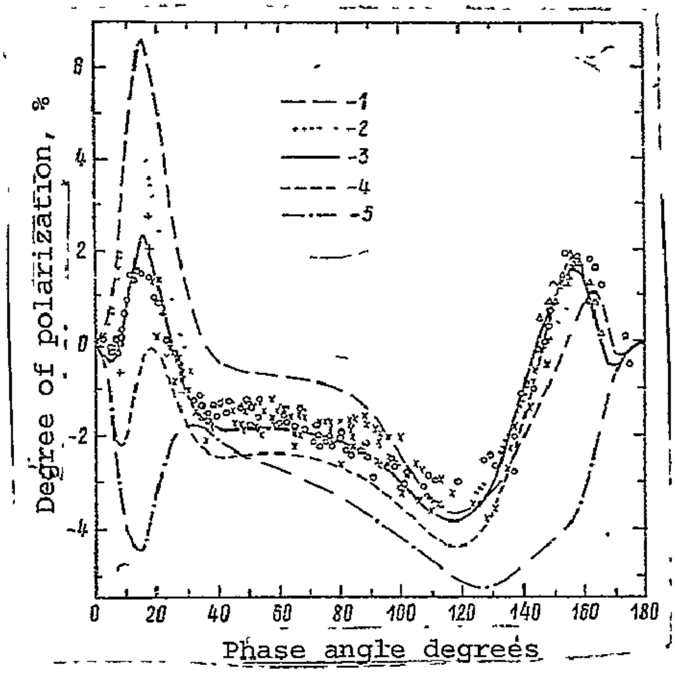

Fig. 6. Degree of polarization of solar radiation reflected by Venus at 550 nm vs. phase angle from measure-measurement (circules, crosses, triangles) and calculation data (and these and other data are associated with the entire illuminated portion of the disc of the planet); calculations were done for index of refraction n-1.44 and parameters b=0.07 and f_R=0.045: 1. a=1500 nm; 2. a=1200 nm; 3. a=1050 nm.

In the UV region of the spectrum (λ=365 nm), polarization is less sensitive to the cloud microstructure than in the visible and near IR ranges, but it permits a highly precise determination of the index of refraction, due to the presence of a strong polarization maximum in the zone of the primary rainbow. The best correspondence with observations results in n=1.46±0.015. /44

Observations of polarization in the UV region of the spectrum also are informative, from the point of view of estimation of the contribution of Rayleigh scattering in the clouds and above the clouds. Here, the degree of polarization depends essentially on the value of f_R, and comparison of calculations with observations results in the best agreement with f_R=0.045. The authors of [112] showed that, in the case of the uniform atmosphere model, the pressure inside the clouds p_1, at a depth corresponding to unit optical thickness, $p_1 \approx 1.16\ f_R$, i.e., it is about 50 mb.

Analysis of the observation results at other wavelengths than the 3 considered above, in the same 340-1000 nm range, by J.E. Hansen and J. W. Hovenier [112], confirmed the conclusions obtained. There also are some observation data for the 1250-360 nm interval, but they are scanty and insufficiently reliable. However, it is significant that negative polarization was invariably observed at all phase angles, for wavelengths of 1250, 1650 and 2000 nm, primarily positive polarization at 2200 nm and only positive polarization for λ=3600 nm. Just such a course should be expected of the spectral relationship of polarization, in the case of particles with an effective radius of about 1000 nm. Consequently, these data are in agreement with the conclusions indicated above.

Since interpretation of the polarization observations definitely indicate that the index of refraction of the Venusian cloud particles is 1.44±0.015 at λ=550 nm, and vary from ~1.46 at λ=365 nm to ~1.43 at λ=990 nm, there is a basis for an opinion on the possible cloud composition. By attempting to use the spectral relation of the index

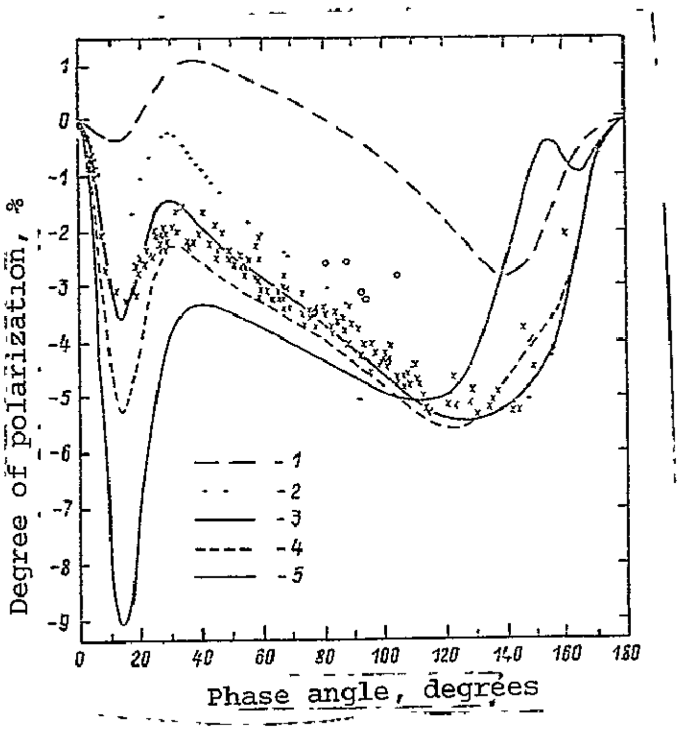

Fig. 7. Degree of polarization of solar radiation reflected by Venus at 990 nm vs. phase angle, from measurement data (circles, crosses) and calculations; calculations were done for parameter b=0.7: 1. n=1.33 (a=800 nm); 2. n=1.40 (a=1000 nm); 3. n=1.43 (a=1050 nm); 4. n=1.45 (a=1100 nm); 5. n=1.50 (a=1200 nm).

of refraction, obtained from observations, for this purpose, J.E. Hansen and J.W. Hovenier showed that, in the visible region of the specturm $\frac{n^2+2}{n^2-1} \sim \lambda^{-2}$. Since J.E. Hansen and A. Arking [110] showed that none of the cloud composition hypotheses proposed before 1970 satisfy the polarization measurement data, the most probable current hypotheses were chosen. As is evident from Fig. 8, neither the carbon suboxide C_3O_2 hypothesis, nor the hydrochloric acid solution hypothesis [143-145] agree with observations. It should be considered most probable that the clouds of Venus consist of drops of concentrated (~75%) sulfuric acid solution. Obviously, these drops should have a spherical shape. /45

The surprising uniformity of the microstructure and optical properties (index of refraction) of the Venusian clouds, as well as the small variability in particle sizes, which is completely opposite to what is observed in the case of the cloud cover of the earth, attracts attention. Thus, for example, parameter b for earth clouds varies from ~0.05 to ~0.30. However, if we turn to the data for the stratospheric aerosol layer (Yunge layer), located at the ~50 mb level, b~0.06-0.08. This permits a definite analogy to be seen between the upper part of the cloud cover of Venus, which is responsible for the polarization of light (polarization is determined mainly by the effect of multiple scattering in a layer of optical thickness ~1), and the stratospheric aerosol layer of the earth [123], of which a high sulfuric acid content also is characteristic [197].

Since the polarization measurements permit a decision only on the composition of the upper cloud layer, the existence of cloud layers of a different composition than that substantiated in work [112] is completely probable. Even the highly convincing arguments of J.E. Hansen and J.W. Hovenier as to the composition of the upper part of the visible cloud cover of Venus cannot be considered as

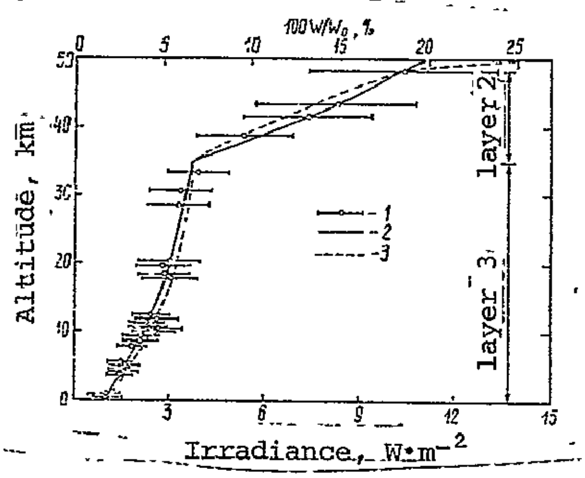

Fig. 8. Vertical profile of illumination from upper hemisphere: 1. Venera-8 measurement data; 2,3. calculation results for models 1,2, respectively (see Table 13); W_0. extra-atmospheric light flux.

completely unequivocal. Although these authors reject the "dirty hydrochloric acid" model of B. Hapke [113], mentioned above, it should be considered that other combinations of cloud composition are possible, which satisfy the available, comparatively limited volume of observation data. Of course, data of direct measurements of microstructure and chemical composition of the clouds of Venus at different levels will be decisive. There is no doubt that measurements of the angular brightness distributions and polarization for various narrow spectral intervals in the range from the UV to IR regions of the spectrum could be of great importance. Thus, the main question as to the microstructure, composition and vertical and horizontal heterogeneities of the clouds of Venus remains largely open. In particular, it formerly was unclear why there is a persistent, continuous global cloud cover on Venus, while instability and horizontal heterogeneity are characteristic features of the cloud cover on the earth (some considerations on this question were expressed in the work of J.T. Bartlett and G.E. Hunt [69]). /46

3.3 Cloud Formation Conditions

Recent studies of the formation of clouds of various planets have concentrated on the question as to whether or not they consist of binary mixtures of drops, for example, drops of NH_3-H_2O solution on Jupiter, HCl-H_2O or H_2SO_4-H_2O solutions on Venus.

According to previously proposed theories, liquid solutions in drop form, in the cases under consideration, are formed as soon as the partial pressure of each component reaches the saturated vapor pressure above the liquid. However, such a situation can only occur in the presence of condensation nuclei, as is well known from study of the formation of terrestrial water clouds. If "uniform, heteromolecular nucleation" occurs (when there are no condensation nuclei), the appearance of drops of condensate is possible, only in the event the partial pressure of each component significantly exceeds saturation.

D. Stauffer and C.S. Kiang [193] proposed a theory and performed calculations of uniform, heteromolecular nucleation, which characterize the threshold values of the partial pressures of NH_3, HCl, H_2SO_4 and C_2H_5OH vs. relative humidity, at which the formation of drops of the corresponding solution occurs, in case condensation nuclei are lacking. The calculation results showed that, under the atmospheric conditions of Jupiter, the lower boundary of NH_3-H_2O solution clouds should be at an altitude of about 40 km (where the temperature exceeds 400°K) and not at 10-25 km, as follows from calculations which assume the presence of condensation nuceli. A similar ~20 km upward shift of the cloud bottoms occurs on the outer giant planets, Uranus and Neptune. Calculations for a new model of the atmosphere of Jupiter, proposed by S.J. Weidenschilling and J.S. Lewis [199], resulted in the conclusion that, in this case, the cloud bottoms should be shifted still higher, to the region of below 0°C temperatures, for which the theory under consideration cannot be considered sufficiently reliable. /47

If it is assumed that the clouds of Venus consist of drops of hydrochloric acid solution, the calculations of D. Stauffer and C.S. Kiang lead to the conclusion that it is impossible for clouds to form at the 60 km level, with a temperature around 0°C, even with the high water vapor content which corresponds to the Venera spacecraft data. With a mixing ratio of 0.01% (spectroscopic data), the formation of HCl-H_2O clouds at this level is impossible, even in the presence of dust (condensation nuclei). These conclusions make the hypothesis that the clouds of Venus consist of drops of sulfuric acid solution more likely.

If the Venusian clouds are made up of sulfuric acid solution in a layer where H_2SO_4 production is at a maximum, calculations by the theory of uniform, heteromolecular nucleation do not find changes in the cloud bottom altitude from the case when the presence of condensation nuclei is assumed, but they indicate a greater duration of the cloud formation process.

The vertical structure of the cloud cover is of great importance. If, for example, the clouds of Venus encompass the entire mass of the atmosphere, beginning at the surface of the planet, the drops of the cloud layer located below can serve as condensation nuclei for the layers of the atmosphere located above it. This means that condensation can occur at practically zero supersaturation, as occurs with a dusty atmosphere. At both Jupiter and Venus (with a high water vapor content), NH_3-H_2O and HCl-H_2O solution clouds form at a relative humidity close to that which corresponds to the nucleation of pure water. Therefore, precise measurements of the water vapor content, and not that of NH_3 or HCl, are very much more important to solution of the cloud composition problem. The results of calculation for a C_2H_5OH-H_2O mixture and laboratory measurement data have turned out to be in good agreement. This indicates the reliability of the calculation method mentioned. For a more confident prediction of the cloud formation conditions in the atmospheres of various planets, more reliable data are required on the water vapor content, as well as further laboratory experiments, for the purpose of testing the accuracy of the calculation methods.

III. Greenhouse Effect

Naturally, the discovery of the high surface temperature of Venus and the presence of a cloud cover over the entire planet caused great interest in discussion of the greenhouse effect of the cloud cover, as the main factor responsible for the high surface temperature. /48

1. Theoretical Calculations

If the Milne-Eddington approximation for the conditions of a "gray" atmosphere which is in radiant equilibrium is used, it is easy to estimate the optical thickness of the atmosphere τ_∞, in which the greenhouse effect of the atmosphere ensures the observed surface temperature T_S, based on the following relation [124]:

$$T_s = \frac{F_\infty \left(2 + \frac{3}{2}\tau_\infty\right)}{2\sigma}, \tag{2}$$

where F_∞ is the outgoing thermal radiation; σ is the Stefan-Boltzmann constant. On the assumption of a 77% albedo for Venus, we obtain F_∞=1.6 erg·cm^{-2}·sec^{-1}. This results in τ_∞=60 for T_S= 600°K, and τ_∞=113 for T_S=700°K. Such optical thicknesses of the atmosphere are completely likely, and this makes the greenhouse effect hypothesis quite plausible. A similar conclusion is confirmed by the results of more precise calculations, which take into account the selectivity of radiation transmission in the atmosphere of Venus. In connection with this, we note that, as follows from available observation data of the spectral distribution of the outgoing thermal radiation of Venus [107] and theoretical calculations [29-33], the outgoing radiation spectrum has a complex fine structure. Therefore, the "gray" atmosphere approximation can be acceptable, only for the roughest errors. Another important circumstance, which sometimes is not taken into account [45], is that the layer of the Venusian atmosphere above the clouds has a significant effect on the production of the outgoing radiation [8].

The effective temperature, determined from the average amount of solar radiation absorbed by Venus, is 237°K. In the absence of an atmosphere, the surface temperature of the planet should be identically this value. Since the actual surface temperature is about 700°K, the atmosphere of Venus should cause an unusually large greenhouse effect, reaching 450-500°K (in the case of the earth, this effect is about 35° and, of Mars, about 7°). G. Ohring [158, 159] analyzed the possibility of the existence of such a greenhouse effect, by using the condition of equality of the solar radiation absorbed by the planet (a fixed value) and the outgoing thermal radiation, calculated with the known stratification of the atmosphere, but a variable surface temperature (to achieve equality with the absorbed radiation). With consideration of the composition of the Venusian atmosphere, according to Venera-4 and Mariner-5 data, calculations were carried out for the following models of the atmosphere (without accounting for cloud cover): /49

Composition of atmosphere	100% carbon dioxide
Vertical temperature gradient in troposphere	9 degrees·km^{-1}
Pressure at tropopause level	0.4, 0.2, 0.0 atm
Vertical temperature gradient in stratosphere	isothermal
Water vapor mixing ratio	10^{-3}, 10^{-4}, 10^{-5}
Pressure at surface of Venus	20, 65 atm
Albedo of planet	0.73

The transmission functions on which the calculations were based were obtained, by means of extrapolation (with the use of the "strong line" approximation) of laboratory measurement data, associated with pressures not exceeding several atmosphere. The calculations showed that, with a surface pressure of 65 atm and a mixing ratio of 10^{-3}, the surface temperature reaches 600-650°K, which is in accordance with observation data. This value of the mixing ratio is considerably higher than that which spectroscopic measurements give. However, it can be considered that these results concern the upper layers of the atmosphere of Venus.

Thus, on the basis of only taking account of the carbon dioxide and water vapor emissions (at high surface pressure), the observed surface temperature of Venus can be explained by the greenhouse effect. The effect of such factors as cloud cover, the aerosol component of the atmosphere and induced pressure transitions can only increase the greenhouse effect.

G.M. Strelkov [54,55] reached similar conclusions as to the validity of the greenhouse effect hypothesis. In order to test the hypothesis that the high surface temperature of Venus is due to the greenhouse effect, G.M. Strelkov [54,44] calculated the radiant energy transport to the lower (below the clouds) part of the atmosphere of the planet, with the parameters of the Venusian atmosphere from Venera-5 and Venera-6 data (surface pressure and temperature were assumed to be 90 atm and 750°K) taken into account. The integral thermal radiation fluxes were obtained, on the basis of calculation of the fluxes for five transparency windows of the atmosphere: 825-1325, 2025-2175, 2526-3425, 3975-5125 and 5525-7025 cm^{-1}. The calculations showed that the primary portion of the radiation transport is in the 1700 and 2200 nm transparency windows. /50

The magnitude of the radiation flux changes little with altitude, and it is not over 0.3 of the outgoing radiation. This is evidence of transformation of the convective energy transport in the part of the atmosphere of Venus beneath the clouds. In the layer of the atmosphere directly adjoining the surface, convective heat transfer is hampered, and heat transport is due to turbulent and radiant heat exchange. Analysis of the heat balance equation of the surface shows that the greenhouse effect provides surface heating to the observed values of about 700-750°K. The average daily heat loss of the surface due to turbulent heat exchange should be 50-90% of the incoming solar radiation.

A correct analysis of the greenhouse effect requires careful accounting for the effect of all optically active components of the atmosphere on radiation transport. In this connection, I.J. Eberstein et al [91] made laboratory measurements of the transmission functions of CO, HCℓ and SO_2, in order to study the possible contributions of these gases to the greenhouse effect observed in the atmosphere of Venus.

The main difficulty in using laboratory measurements is the necessity to change over to transmission values in the case of a heterogeneous medium. This can be done, if the laboratory measurements are represented in the form of a power function of the logarithm of the transmission vs. content of the radiation adsorbing substance and total pressure (the latter is determined in the sense of the effective pressure, calculated with allowance for the efficiency of collisions of molecules of different gases).

A Perkin-Elmer 621 spectrometer with a diffraction grating, which permits coverage of the 200-4000 cm^{-1} wave number region (2500-50000 nm). The spectral width of the slit is 20 cm^{-1}. The gas cuvette, with cesium iodide windows, is 10 cm long (part of the measurements were made with a 400 cm long cuvette). Studies of the spectra of the gases mentioned above was carried out in a mixture with pure nitrogen or dry carbon dioxide. Measurements were made, both with constant pressure of the absorbing gas (with change in total pressure), and with constant total (but not effective) pressure, but with variation of the pressure of the absorbent. All measurements were made at room temperature and a pressure range from $0.79 \cdot 10^{-2}$ to 0.79 atm.

At the pressures and absorbing gas content used, appreciable absorption was observed only in the region of the basic vibrational bands (with the exception of one case), where a very small popula- /51
tion of the upper vibrational levels was detected at room temperature. Therefore, the measurements were confined to the basic bands: 2143 cm^{-1} CO; 2886 cm^{-1} HCℓ; 1361, 1151, 519 cm^{-1} SO_2 and 2499 cm^{-1} SO_2 combination band. The experimental data (in the transmission region from 5 to 95%) are well described by the exponential relation of the logarithm of the transmission function mentioned above.

A comparison of the results of specially performed direct calculations of transmission for the 2143 cm^{-1} carbon monoxide band with the experimental data revealed good agreement. This comparison again confirmed the validity of the exponential relation, but it pointed out the danger of extrapolation of this relation, both to very small and to large transmission values.

With the use of the results obtained for estimates of the contribution to the greenhouse effect under the conditions of Venus, it can be considered that the effect of absorption by the component under consideration is significant, if the averaged optical thickness exceeds 1 above the 1 atm pressure level. In accordance with this criterion, I.J. Eberstein et al [91] calculated the required content of the gases under consideration, with the use of laboratory data on their quantitative absorption characteristics for the maximum absorption sections. In all cases, with the exception of the 2143 cm^{-1} carbon monoxide band, the required gas content considerably exceeds that observed. However, even the effect of carbon monoxide on the greenhouse effect cannot be significant, since carbon dioxide, which is dominant in the atmosphere of Venus, absorbs strongly in the region of the basic band of this gas. Concerning sulfur dioxide, which has strong absorption around 1361 and 1151 cm^{-1}, its effect does not appear, due to the low concentration. Since the spectroscopic data on composition concern the upper layers of the atmosphere of Venus, it is possible that future direct measurements will introduce corrections into the results which concern estimates of the factors causing the greenhouse effect.

The phenomenon of the greenhouse effect can be of great importance, from the point of view of the evolution of the atmosphere of Venus [163,170]. Thus, for example, owing to the greenhouse effect, disappearance of a water shell which initially surrounded the planet could occur. If the planet is sufficiently close to the sun, much water should evaporate from the hypothetical ocean into the atmosphere. This results in the greenhouse effect condition, an increase in surface temperature and complete evaporation of the water. Such an "expelling" greenhouse effect can explain why the conditions on the surface and in the atmosphere of Venus are so different from those on the earth (as to the low water vapor content of the atmosphere of Venus, this can be explained by its /52
destruction, as a result of photodissociation during the billions of years of evolution of the atmosphere).

In order to analyze the conditions of evolution of the greenhouse effect on Venus, J.B. Pollack [163] calculated the outgoing thermal radiation and albedo, with the selectivity of radiation transmission taken into account, and on the assumptions that the planet is covered with an ocean and that the greenhouse effect is due only to the water vapor content of the atmosphere. Calculations of the surface temperature under various cloud conditions (degrees of cloud cover of 50 and 100%), as a function of the incoming solar radiation flux, were carried out for a structure and composition of the atmosphere, selected by analogy with the conditions of the terrestrial atmosphere. However, the pressure at the surface varies from 0.1 to 10 atm, and the acceleration of gravity was assumed to be that of Venus (888 $cm \cdot sec^{-2}$).

Values of 0.39 and 0.33 $cal \cdot cm^{-2} \cdot min^{-1}$ were obtained for the albedo and outgoing radiation, respectively, calculated for earth conditions. This sufficiently satisfactorily agrees with known values and, consequently, it confirms the correctness of the calculation method. The calculation results, which characterize the dependence of the outgoing radiation and fraction of solar radiation absorbed by the planet on surface temperature (the calculations are for zero 50% cloud cover), were used to determine the equilibrium surface temperature, from the condition of equality of the absorbed radiation and outgoing radiation and subsequent plotting of surface temperature vs. insolation beyond the atmosphere. It turned out that, with 50% cloud cover, the insolation on Venus is now so high, that is should ensure complete evaporation of the hypothetical ocean (with a surface temperature of approximately 500°K. In turn, that means that, as a result of desorption of carbon dioxide, it will accumulate in the atmosphere. With half the extraatmospheric insolation, which corresponds to conditions on earth, the surface temperature turns out to be very much less, which produces conditions for the existence of liquid water.

Based on 100% cloud cover on Venus and the assumption of the insolation which occurred 4.5 billion years ago (30% less than now), the surface temperature turns out to be rather moderate (permitting the presence of water), in connection with the fact that, with 100% cloud cover, a strong increase in the albedo of the planet occurs with increase in surface temperature. These conditions are preserved, even with an increase of insolation to the modern level. Therefore, it can be suggested that there was partial cloud cover on Venus in the past.

It is possible that, during the evolution of Venus, accompanied by the loss of water, life could have adapted to existence in the upper, more moderate part of the atmosphere, when the loss of water occurred. Therefore, J.B. Pollack considers it premature to write Venus off, as a planet which is not of biological interest. /53

2. Direct Measurements Aboard Venera-8 Spacecraft

Measurements of the illumination, by means of the photometer (cadmium sulfide photoresistor) installed aboard Venera-8, which could function at ambient temperature and pressure of up to 500°C and 100 atm, respectively, are of exceptionally great importance, for analysis of the conditions of development of the greenhouse effect. The photometer permitted, for the first time, measurement of the illumination from the upper hemisphere in the 500-800 nm interval, at various altitudes in the atmosphere of Venus during the parachute descent of the spacecraft (the parachute occupied about 1% of the field of view of the photometer), on 22 July 1972. The measurement data were processed by V.S. Avduyevskiy et al [68], with account taken of the temperature dependence of the photometer sensitivity (according to preflight calibration data). The use of the onboard calibration results of the photometer indicated an increase in its sensitivity in flight. This required the introduction of a correction of 12%. The error of measurement of the light flux was approximately ±30%.

The vertical illumination profile in the 0-50 km altitude range (Fig. 8) indicates a sharp change in illumination at an altitude of about 32 km. Above this level, a very much stronger increase in illumination is observed with altitude. This permits it to be considered that the lower boundary of the cloud layer is located near an altitude of 32 km. The height of the sun above the horizon at the time of measurement was 5.5±2.5°, which corresponds to extraatmospheric illumination (with allowance for the spectral sensitivity of the photometer) of 65±35 $W \cdot m^{-2}$ (by using recent data on the extraatmospheric spectral distribution of solar radiation, A.A. Lacis and J.E. Hansen [139] obtained 55±25 $W \cdot m^{-2}$). Since the illumination measured at an altitude of about 48.5 km was approximately 10 $W \cdot m^{-2}$, this means that approximately a sevenfold attenuation of the light by the overlying atmosphere occurred (according to the data of [139], fivefold). The illumination decreased another three times in the 50-32 km layer and three times again, in the layer between the 32 km level and the surface.

Thus, the illumination measurement data indicated a vertical heterogeneity of the atmosphere. The upper measurement point 48.5 km) corresponds to a temperature of 329°K and a pressure of 1.09 atm. If the cloud top altitude is determined from the level to which an optical thickness of 1 corresponds, this corresponds to the 50±25 mb level [112]. In the case under consideration, the 50 mb level corresponds to an altitude of about 68 km [139]. The attenuation of solar radiation is at a maximum in the layer between the cloud tops (65-70 km) and an altitude of about 48 km, and it is at a minimum in the atmosphere located below 32 km. /54

According to the data of V.S. Avduyevskiy et al [68], which are in agreement with measurement data, calculations of the vertical illumination profile in the 0-32 km layer showed that the attenuation of light in this layer is due mainly to molecular scattering (the scattering coefficient exceeds the Rayleight scattering coefficient by not over 30%, the single scattering albedo is greater than 0.99, and the surface albedo is in the 0-0.6 range). Attenuation above 32 km may be caused by aerosol scattering and absorption. Although a comparatively small part of the extraatmospheric solar radiation flux reaches the surface of

Venus (about 1.8%), even this is enough to ensure considerable illumination at the surface level (compared with earth conditions) and maintenance of a high temperature in the lower part of the atmosphere. The resulting illumination data, thus, do not contradict the hypothesis of the "greenhouse" mechanism of heating of the atmosphere of Venus.

A.A. Lacis and J.E. Hansen [139] carried out a detailed comparison of the illumination data under consideration with theoretical calculation results, for two three layer models of the atmosphere. In this case, they took quite accurate account of the multiplicity of scattering (see also optical characteristics data in work [5]). A comparison with calculation data for a uniform atmosphere model indicated complete nonconformity of this model with observation data, but it resulted in satisfactory agreement with observations and the use of a two layer model, with the boundary of the layers at the 35 km level. This determined the selection of the three layer models, the parameters of which are indicated in Table 7. The layer boundaries were fixed at altitudes of 35 km and 48.5 km. Of course, the lack of measurement data above 48.5 km introduces uncertainty into selection of the parameters for the calculations. However, it was found that the lack of in- /55
formation on the characteristics of the clouds in the lower layers of the atmosphere are of still greater importance.

TABLE 7. OPTICAL PARAMETERS OF VENUS ATMOSPHERE MODELS ($\tilde{\omega}_c$ -- CLOUD PARTICLE ALBEDO, τ_c -- OPTICAL AEROSOL THICKNESS OF LAYERS, A_s -- ALBEDO OF UNDERLYING SURFACE)

Model 1				Model 2			
Layer	$\tilde{\omega}_c$	τ_c	Absorption	Layer	$\tilde{\omega}_c$	τ_c	Absorption
1	0,997565	18,9	9,98%	1	1,0	8,4	0,0
2	0,999999	561	~0	2	0,97328	4,4	8,62%
3	0,999999	517	~0	3	—	0,0	0,0
	$A_s = 0,995$		0,02%		$A_s = 0,6$		1,38%

Test calculations and their comparison with illumination measurement data led to the conclusion that the following are the most likely ranges of optical parameters of the upper layer: $8 \lesssim \tau_c \lesssim 19$ and $1 \gtrsim \tilde{\omega}_c \gtrsim 0.9976$. The lack of information on the optical parameters of the lower layer complicates the unambiguity of selection of these parameters to the strongest degree. Calculation results for two extreme models (see Table 7) are reproduced in Fig. 8. In both cases, the disagreement with measurement data does not go beyond the measurement error.

In the case of model 1, practically all the solar radiation is absorbed by the upper layer (i.e., above 48.5 km). The vertical illumination profile in the two lower layers is well described, by assuming almost conservative scattering ($\tilde{\omega}_i$=0.999999) and a very large aerosol optical thickness (τ_i=1078). Thus, in this case, such a solution is completely satisfactory, when $\tilde{\omega}_i \to 1$ and $\tau_i \to \infty$.

The complete lack of absorption by the upper layer is characteristic of model 2. The absorption is concentrated in the middle layer. Absorption of solar radiation by the underlying surface is about 1.4%.

An attempt to use a ten layer model showed that still better agreement with observations can be achieved, but the possible variations of the optical parameters of the clouds remain approximately the same as for the three layer model. Thus, for example, the optical thickness of the entire atmosphere can vary within $3 \lesssim \tau_c \lesssim \infty$. It should be noted here that all the estimates of optical thickness presented above are associated with the case of isotropic scattering. To take anisotropy into account, a correction factor of 3.3 should be introduced. Consequently, the optical thickness of the entire atmosphere $\tau_i \gtrsim 10$. The albedo of the underlying surface at the landing point $A_s \gtrsim 0.6$. This is unexpected, since a lower albedo should be expected for granite type materials. Besides, it should be emphasized that estimates of the albedo depend critically on the accuracy of measurements at the very lowest point.

Thus, a detailed comparison of illumination measurements with calculation results, for various optical models of the atmosphere, lead to the conclusion that the aerosol structure of the atmosphere of Venus should be at least three layered. The measurement data of illumination from only the upper hemisphere permits the establishment of only the extremely broad limits of possible variability of optical thickness, and they do not make it possible to unambiguously decide on the vertical distribution of the absorption of solar radiation by layers.

The Venera-8 data are very valuable for estimating the penetration of solar radiation into the atmosphere, but a whole series of important questions remain unanswered. In particular, they do not contradict the greenhouse effect hypothesis, but they cannot be used to confirm it. It will be important subsequently to undertake measurements of the vertical profiles of the ingoing and outgoing radiation fluxes, in both broad and narrow wavelength intervals, through the entire atmosphere, including the cloud and haze layers located above the primary cloud cover. A necessary supplement to this kind of measurement has to be measurements of the angular and spectral distribution of brightness and polarization, from unmanned interplanetary spacecraft operating as artificial Venus satellites. /56

Although the results reported above are basically evidence in favor of the greenhouse effect hypothesis, the validity of this hypothesis cannot yet be considered completely proven. As D.M. Hunten and R.M. Goody noted [124], three factors which complicate consideration require further discussion: 1. matching of the exceptionally great optical thickness of the atmosphere to infrared radiation with the necessity of fairly high transmission of solar radiation; 2. accounting for the effect of heat transport by free and forced convection; 3. accounting for turbulence and large scale atmospheric circulation. We now turn to consideration of these factors.

IV. Atmospheric Circulation

The data on the structural parameters of the Venusian atmosphere considered above indicate that the lower part of it is in a state of convective equilibrium. Precisely this circumstance is the most important, in constructing current theoretical models of the thermal conditions and general circulation of the atmosphere. However, before consideration of these models, we turn to discussion of the existing collection of observation data on the winds on Venus. This kind of data was primarily obtained, on the basis of many years of ground based observations of the patterns of nonuniformity of the cloud cover in the UV region of the spectrum. Such observations were recently continued, by obtaining UV images of Venus from Mariner-10. Finally, observations of the descent and drift of the Venera spacecraft brought in important information on the winds at various altitudes.

1. Four Day Circulation

1.1. Observation Data

The cloud cover of Venus prevents determination of the angular velocity of rotation of the surface of the planet from telescope ob- /57
servation data. Observations of indistinct, grayish heterogeneities, concerning which it was proposed that they are visible through random clearings of the atmosphere from sections of the solid surface, have led in the past to many erroneous determinations of the period of rotation, from 1 to 225 days. As was noted earlier, only the radio astronomy measurements of recent years have reliably established the retrograde rotation of Venus, with a sidereal period of 243 days (the synodic period is 117 days).

However, the heterogeneities of the cloud cover, observed in photographs obtained in the UV region of the spectrum and having, as a rule, a Y or Ψ shape, permit the nature of the atmospheric motion to be traced from the displacement of these heterogeneities.

C. Boyer [73,74] examined systematic UV photographs of Venus, made with the aid of the 260 mm refractor in Brazzaville (4° S. Lat.), which found a four day rotation of the heterogeneities near the equator, at the very start of these observations. The proposal was then expressed that rotation of the atmosphere was observed in this case. Further observations confirmed this conclusion and disclosed that the rotation is retrograde. Analysis of photographs, obtained by means of the 600 mm and 1 m telescopes in the Pic-du-Midi observatory resulted in the same conclusion. The synodic period of rotation was 3.995 days (this corresponds to a velocity of 112 $m \cdot sec^{-1}$). This concerns the rotation of the upper layers of the atmosphere, at an altitude of about 80 km. A detailed analysis of the rotation rates of different heterogeneities, during a time on the order of several days, brought out the specific characteristics of rotation of the Y and Ψ shaped heterogeneities. In particular, the rotation rate depends on the location of the heterogeneities, and it changes from -50 to -140 $cm \cdot sec^{-1}$.

An analysis of the 300 best UV photographs of Venus, obtained at the Meudon observatory in 1966-1969, carried out by J. Nikander and C. Boyer [156], found a retrograde rotation of these heterogeneities, with a period of 4.0±0.5 days. This leads to an estimate of the upper limit of the wind speed on the order of 740 $km \cdot hour^{-1}$, if it is assumed that the clouds are at an altitude of 95 km, with respect to the "radar" surface (planetocentric radius is 6052 km). The corresponding minimum speed is 320 $km \cdot hour^{-1}$. The reality of this rotation of the upper atmospheric mass was demonstrated independently by M.B. Guinot [106], from Doppler measurements, as well as measurements by means of a Fabry-Perot reference, in the 550-570 nm wavelength interval. The agreement of these data, which result in a rotation period of 4.3±0.4 days, with the results of photographic analysis is excellent. Thus, the rapid rotation of /58
the upper atmosphere of Venus, which evidently reflects a complex planetary circulation of the atmosphere, can be considered reliably established.

Systematic photography of Venus in the UV was undertaken, within the framework of an International Planetary Patrol Program. J. Caldwell [75] examined data for the period from June 1970 to 20 September 1970, obtained at three observatories (Lowell in Arizona, Mauna Kea in the Hawaiian Islands and the Republican Observatory in South Africa). The maximum film sensitivity was around 360 nm with a transmission band width of 70 nm. A series of 14 photographs usually was made, with 1 sec intervals between pictures. On a good night, up to 200 photographs were successfully obtained, of which the best were selected for processing.

Analysis of the photographs confirms the previously established existence of retrograde rotation (circulation) of the upper atmosphere of Venus. The direction of rotation and its period were found from the movement of clearly recorded details of the cloud cover. In particular, a distinctive Y shaped structure was observed many times, during a long period of observation from 21 June to 1 August. This permitted the synodic period of rotation of 4.4±0.2 days to be determined (this corresponds to a sidereal period of 4.50 days). The value obtained differs significantly from other estimates but, of course, it concerns only the observation period under consideration. The observed changes in structural detail shapes of the cloud cover can be interpreted as due to the transient nature of the atmospheric circulation on Venus.

In particular, time variability of the cloud rotation period is possible (its cause may be changes in altitude of the "ultra-violet" clouds). This makes differences in the rotation period completely natural. A few changes in the latitude variations of the Y shaped structure do not permit a decision to be made on the presence of a latitude effect of the rotation period. However, it is clear that the period is fairly constant, with changes in latitude of the center of the structure reaching 20°. Analysis of the data considered shows that, sometimes, an upper story cloud cover located still higher can mask the "ultra-violet" structure of the cloud cover located under it.

In connection with some disagreement on the results of determination of the rotation period of the upper layers of the atmosphere of Venus, by means of analysis of characteristic details of the cloud cover in photographs of Venus taken in UV, A.H. Scott and E.J. Reese [188] carried out an reanalysis of this kind of photographs. The initial material was 1600 photographs, obtained at the observatory of the University of New Mexico on 830 dates, in the period between 29 September 1963 and 29 May 1971.(the maximum film sensitivity is at a wavelength of 370 nm). Primarily Y shaped structures were used as characteristic details of the cloud cover. Determination of the rate of movement of characteristic details in from 2 to 8 hours, in the 10° N. Lat.-15° S. Lat. latitude band, gave an average retrograde rotation sidereal period of 4.57±0.37 days, with variations from 3.5 to 6.8 days (this corresponds to speeds of from -127 to -66 $m \cdot sec^{-1}$). /59

Another method of determination of the rotation period is the measurement of the interval between appearances of a characteristic detail after one or more revolutions. For this purpose, photographs, divided into time intervals of from 3 to 12 days, were analyzed. Such an analysis led to the conclusion that periods of 4.05±0.01 and 4.59±0.02 days are predominant (from the data of 67 pairs of photographs). This corresponds to speeds of -110.2±0.3 and -97.2±0.5 $m \cdot sec^{-1}$. In 85% of the cases, the latitudes of pairs of characteristic details were located no more than 10° from the equator and, in the remaining cases, no more than 20°. A search for persistent characteristic details of the cloud cover showed that their lifetimes rarely exceed 20 days and usually are much shorter. The details were distributed fairly randomly over the disc of the planet. The averaged sidereal period of rotation, from all observation data for 8 years, was 4.0654 ± 0.001 days. It is noted that this period should be acknowledged as fictitious, since it is due to the commensurability of the apparent 4 day rotation period of the atmosphere of Venus and the period of rotation of the earth, which was developed by determination of the period of rotation of the atmosphere from the data of observations from one point.

Observations of persistent cloud cover details of Venus, found in photographs in the UV region of the spectrum, brought out that the periods of rotation of these details, 4.0 and 4.6 days, predominate over intermediate periods. This contradicts previously obtained results, which may be subject to significant errors, due to the comparability of the period determined and the period of rotation of the earth. In connection with this, R.F. Beebe [70], based on statistical analysis of available data, showed that the effect of comparability of the periods excludes the possiblity of reliable determination of the rotation period of the upper atmosphere of Venus, from observation data of the frequency of recurrence of details from a single station. If cloud cover details have relatively short lifetimes and have periods of from 3.5 to 5.0 days, the observer finds a large number of details with a period of about 4.0 days. The histogram method previously used for determination of the rotation period contains this type of systematic error.

Although the measurement of displacements of characteristic cloud cover details for determination of the rotation period are /60 less accurate, generally speaking, than the identification of repeating details, the use of this method is preferable, since it permits the use of all details which can be measured. To increase the duration of the observation period and increase the accuracy of the results, observation data from more than one point must be used. This also permits information to be obtained on the variability of speed over the disc of the planet and, on the whole, it makes the results more reliable.

An important indicator of atmospheric circulation is thermal maps of Venus, which can be plotted, based on the use of ground observation data. In this connection, A.P. Ingersoll and G.S. Orton [125] analyzed the thermal maps of Venus in the 8000-14000 nm wavelength interval, which were obtained about 10 years ago (the spatial resolution of these maps, plotted for different phase angles of the sun, is about 1/30 of the diameter of the planet), for the purpose of study of characteristics of the general circulation of the Venusian atmosphere, based on study of the horizontal heterogeneities of the radiation field. It is assumed that the radiation in this wavelength interval is produced at the cloud top level and, therefore, it characterizes its temperature and altitude.

Horizontal heterogeneities of the radiation field can be caused by three factors: 1. "by darkening" (decrease in intensity) towards the edge of the disc, connected with the effect of the atmosphere above the clouds, where the temperature decreases with altitude; 2. by change in temperature and altitude of the cloud tops, depending on the phase angle of the sun; 3. by the effect of variability of the general circulation of the Venusian atmosphere and instrument noise (accuracy of determination of the relative radiation values is about 2%). Correspondingly, the horizontal heterogeneities of the radiation field can be presented in the form of a set of three components (the method of separation of the radiation into components has been described). The first of them ("limb") was analyzed in detail earlier but the other two still have not been studied in detail. Therefore, examination of the "sun dependent" component permitted interesting new results to be obtained.

The authors of [125] showed that the spatial distribution of this component is nearly symmetrical about the equator. There is a tendency for the radiation intensity to decrease towards the poles. This probably is due to the decrease in sun height with increase in latitude. In both the northern and southern hemispheres, the minimum radiation intensity is observed at the middle and high latitudes, near the morning terminator, apparently at a small distance from the edge of the thermal charts obtained. The radiation maximum was found at the equator, and it is located somewhat to the east of the antisolar point. Three broad ridges of relatively high radiation intensity go out from the maximum zone, one /61
of which goes westward along the equator and the other two, to the northeast and southeast (in the northern and southern hemispheres, respectively). Displacement of the two latter ridges to the east indicates that horizontal exchange (transport of momentum from high latitudes towards the equator) probably is an important factor in ensuring the existence of the equatorial maximum of zonal momentum, which is connected with the 4 day circulation of the atmosphere of Venus.

The existence of a tendency for a decrease in radiation ("cooling") towards the poles can be interpreted as the result of the effect of rotation of the planet on circulation between the equator and the pole, and not of the subsolar and antisolar points (in the latter case, equality of the temperatures at the poles and near the terminators should be expected).

It should be noted that a basic factor in the ambiguity of interpretation of the results obtained is the impossiblity of distinguishing changes in radiation (brightness temperature) caused by a horizontal heterogeneity and a change in altitude of the radiating layer. To eliminate this heterogeneity, it was important to obtain synchronous "multispectral" radiation charts for different wavelengths (from the UV to the IR regions of the spectrum).

1.2 Theory

Thus, the observations of a whole series of authors, carried out in recent years, have discovered the rapid rotation of the upper atmosphere of Venus, in a direction opposite to the rotation of the planet. The moving clouds are located at about the 5 mb level, which corresponds to an altitude above the solid surface of the planet of approximately 80 km. According to the data of A.J. Scott and E.J. Reese [188], the sidereal period of rotation is 4.50 ±0.02 days, and it corresponds to an equatorial tangential velocity of 98 $m \cdot sec^{-1}$ (the equatorial tangential velocity of the surface is a total of 1.8 $m \cdot sec^{-1}$).

C.B. Leovy [141] has noted that the stability of the large scale structure of the upper layer of cloud cover during several revolutions indicates a rotation similar to the rotation of a solid, at least in the ±30° latitude band. There are data, which indicate that the retrograde rotation covers the entire atmosphere, right down to the top of the primary layer, which is near the 240 mb level (approximately 60 km). Doppler observations of the motion of Venera-8 indicate the existence of retrograde zonal winds of lesser magnitude, up to an altitude of 20 km, but the lack of a zonal component of the wind below 10 km. Very low wind speeds in the lower layers of the atmosphere also have been found from Ven- /62
era-4 and -7 data (see further on).

In connection with the 4 day circulation found, several attempts were made to explain it. P.J. Gierasch [96] drew attention to the fact that the laboratory experiments of G. Schubert and J.A. Whitehead [186] detected the development of strong zonal motion during rotation of a heat source under a circular container with mercury. If the motion of this heat source is compared to the motion of the sun in the sky of Venus, it can be suggested that a similar mechanism is the cause of a 4 day rotation. The plausibility of such a hypothesis was confirmed in the work of G. Schubert et al [187], by some calculations carried out in the Bussinex approximation and two dimensional flow.

The authors of [187] analyzed the problem of the flow of a liquid produced by travelling heat waves in a layer of liquid, bounded top and bottom by horizontal unsupported and rigid surfaces, respectively. Two types of boundary conditions were used here: 1. assigned variations of temperature at the upper boundary and fixed temperature at the lower boundary; 2. assigned variations of the heat flow at the upper boundary and heat insulation (absence of thermal conductivity) at the level of the lower boundary. It was shown that, depending on the value of the Prandtl number $P = \nu/k$ (ν is the coefficient of kinematic viscosity; k is the coefficient of thermal diffusion), movement in the layer under consideration is in a straight line (which coincides with the direction of movement of the heat wave) or retrograde.

The critical value of the Prandtl number $P_c(S)$, which determines the transition from one circulation regimen to another, depends on parameter $S=\omega h^2/\nu$ (ω is the angular frequency of the heat wave h is the depth of the layer). The circulation is forward at $P=P_c(S)$ and vice versa. Since the retrograde circulation occurs only at small Prandtl numbers, the existence of this kind of 4 day circulation in the upper atmosphere of Venus should mean that through at least the upper atmosphere of the planet, it corresponds to small (considerably less than 1) Prandtl numbers. The latter indicates that thermal diffusion is not due to turbulence, but to another process. Radiation heat transport apparently dominates in the upper atmosphere of Venus.

The atmosphere of Venus is deep and compressible, radiating and three dimensional. This requires a more correct theory than that mentioned above. In particular, it is important to consider that the transport of energy in the atmosphere of Venus is due (at least partially) to radiation and to find out the consequences of this. It also requires an answer to the question, at what level in /63 the deep radiating atmosphere should thermally dependent motion originate. It is far from mandatory that it be the level where the main fraction of solar radiation is absorbed.

In connection with the circumstances noted, P.J. Gierasch [96] carried out approximate calculations, which characterize the role of radiation as a heat transport factor, without consideration of the effect of viscosity and thermal conductivity. It is assumed that the lower boundary of the layer of the atmosphere under study (stratosphere), considered as a solid surface, is at the cloud top level (200 mb) and has a constant temperature of 245°K (it is evident that the thermal inertia of the atmosphere of Venus is very large). Estimates have been made, which show that the radiation time constant (relaxation time) at the lower boundary level is about 1 Venusian day, and that it decreases with altitude above this boundary. These estimates were used for an approximate representation of the radiant heat influx in the heat influx equation, through deviation of the temperature of the atmosphere from the radiant equilibrium temperature and radiation time constant.

Solution of the system of equations of the problem, including a heat influx equation simplified in the manner indicated and the equation of motion (in the hydrostatic approximation), leads to a scheme of development of convective cells, which originate as a result of inhomogeneities of the temperature (correspondingly, density) field. The average zonal velocity increases rapidly with altitude and, at fairly high altitudes at the subsolar point, a heating region develops. A thermal wave with a 4 day period has an amplitude of 4.5°K, and it should occur at the 40 mb level (the amplitude of the change in radiant equilibrium temperature at this level is 40°K. P.J. Gierasch [96] emphasized the provisional nature of the model he proposed and the limitations on its possibilities of description of atmospheric motions near the equator.

In continuing discussion of the dynamic aspects of the 4 day circulation, R.E. Young and G. Schubert [206] called attention to the fact the observations in the zone around the morning terminator indicate the existence of zonal transport in the direction of the subsolar point, while there is transport in the opposite direction in the region of the evening terminator. This means that the observed motions are not in agreement with the model of circulation in the form of Hadley cells.(in such a case, transport should always take place from the subsolar to the antisolar point). There are some data, which indicate a latitudinal dependence of the rotation period, increasing to six days in the 6-15° latitude belt. Spectroscopic measurements in the 550-570 nm region have also recorded the existence of retrograde rotation, with a period of 4.3±0.4 days, /64
but later measurements of the Doppler shift of carbon dioxide spectral lines resulted in a transport rate on the order of 100 $m \cdot sec^{-1}$. There are other data, which indicate strong winds in the upper atmosphere of Venus. In connection with this, the question arises as to whether the intensive zonal flow extends to deeper layers of the atmosphere. Estimates of the frictional stress, which should arise at the surface in this case, show that such a possibility is excluded.

R.E. Young and G. Schubert [206] have discussed in detail three mechanisms, proposed to explain the zonal circulation of the upper atmosphere: 1. the "moving flame" hypothesis (based on accounting for the phase lag of heating of the upper layers of the atmosphere in the upward propagation of heat from below); 2. nonlinear instability of convection with respect to the average wind shear (see R. Thompson [196]) and 3. tidal forces. In all these cases, the correctness of estimates depends significantly on the nature and magnitude of the diffusion of momentum in the upper atmosphere. Although even the question of the nature of the diffusion (laminar or turbulent) is controversial at present, it is most natural to assume that there is turbulent viscosity)(cofficient of diffusion on the order of 10^3-10^4 $cm^2 \cdot sec^{-1}$), if it is considered that there is small scale turbulence in the four day rotation zone.

According to [206], the effect of tidal forces as a generator of the 4 day circulation can be significant, only on the condition of laminar diffusion of momentum. A theory of convection, unstable relative to the average wind shear, can explain the development of an average flow rate on the order of 100 $m \cdot sec^{-1}$, but the necessary conditions for development of such an instability still have not been determined sufficiently definitely. Here, the direction of trans-port depends on the initial conditions, and retrograde and forward movement have the same probability, in this respect. However, it is possible that the simultaneous action of the "moving flame" mechanism can cause an initial retrograde motion, which is then reinforced by the effect of instability. The stability of stratification of the atmsophere above 60 km is an important factor, which contributes to generation of the retrograde motion as a result of the "moving flame" mechanism.

Thus, attempts to explain the results of observations of the 4 day circulation have been reduced primarily to the hypothesis of the presence of a traveling solar heating wave, which provides vertical transport of momentum, or instability, connected with vertical thermal shear due to the circulation system from the subsolar to the antisolar points. C.B. Leovy [141] noted, however, that one important circumstance was overlooked here, concerning the atmospheric circulation on Venus. While there is an insignificantly small meridional atmospheric pressure gradient at the surface of Venus (as the Venera spacecraft data indicate), but a small decrease in average temperature is observed from the equator to both poles, the isobar surfaces at high altitudes should reveal an equatorial "bulge." The pressure gradient forces caused by it can only be equalized by an excessive centrifugal force, which gives rise to the increasing rotation with altitude. /65

The estimates made by C.B. Leovy show that, to ensure the geocyclostrophic balance mentioned, a 3°K difference in the average equator-pole temperatures is sufficient, which is fully acceptable. Yet the question still needs an answer, as to how the vertical rotation rate distribution arises and how differential rotation can be maintained, despite the counterstimulating effect of turbulent and molecular viscosity with vertical wind shear.

S.B. Leovy thinks that, in any planetary atmosphere with an equatorial thermal "bulge," caused by heating, but without a barocline or barotropic instability due to slow rotation of the planet or damping, excess rotation should develop, which coincides in sign with the rotation of the upper layers of the atmosphere of the planet. In particular, the "superrotation" of the upper layers of the terrestrial atmosphere apparently is a manifestation of this effect.

2. Mariner-10 Spacecraft Data

The discovery of the 4 day circulation of the upper layers of the atmosphere of Venus caused great interest in study of the atmospheric circulation from unmanned interplanetary spacecraft. In connection with this, in development of the television equipment of

Mariner-10, intended primarily to obtain images of the surface of Mercury, the possibility of obtaining UV photographs of Venus also was provided for (Mariner-10 was launched towards Venus and Mercury on 3 November 1973). The television equipment (two alternately operating cameras), similar to that used earlier in Mariner-9, was improved, primarily by means of widening the transmission band of the communications lines from 16 to 117.6 kilobits·sec^{-1}. This permitted the use of the onboard memory to be avoided and images to be transmitted in real time. The substitution of new optics (with 1500 mm focal length) and the use of a set of light filters permitted images to be obtained at wavelengths of 355.0, 474.0, 482.0, 512.0, 578.0 and 358.0 nm)(the last light filter was polarizing). The field of view is 0.36°x0.48°. Each television image, recorded in 42 sec, consists of 700 scanning lines with 832 "points" along the line. The discrimination of 256 brightness levels was possible (with the maximum high spatial resolution of 4.5'' and a signal-to-signal noise ratio of 20:1). Therefore, the use of contrast enhancement methods permits very small brightness contrasts to be distinguished (right down to a brightness variation of less than 1%). /66

As B.C. Murray et al reported [154], a total of about 3400 high quality images, with a resolution of about 130 km (this is approximately twice as good as the highest resolution achieved by ground observations), were recorded in 8 days. The images obtained through blue and orange filters disclose only very weak brightness contrasts, and they still have not been thoroughly analyzed. Therefore, only the UV images and a portion of the photographs with the orange filter associated with the edge of the disc of the planet have been examined.

B.C. Murray et al [154] have analyzed a series of ultraviolet images, which indicate the existence of the following heterogeneities of the cloud cover: 1. small scale (100-150 km) "specks" at the subsolar point of the equatorial zone (Fig. 9a, 10);[3] 2. jet shaped (with minimum distinguishable width of 10-20 km) and striated structures at high latitudes in both hemispheres (Fig. 9b, 11, 12); 3. strongly diverging flows around the subsolar point, symmetrical about the equator (Figs. 11,12). Large light and dark formations on the order of 1000 km in size, the contrast between which is about 30%, have an abundant fine structure with characteristic dimensions of up to 10 km. The lifetimes of individual formations in the ±50° latitude range vary from 2 to 12 hours.

The variability and brightness of the cloud cover of Venus in the UV region of the spectrum undoubtedly reflects characteristics

[3]The author thanks Dr. B.C. Murray for kindly providing the originals of the photographs in Figs. 9-13.

of the general circulation of the atmosphere in the upper troposphere and stratosphere. In this case, the observed strong dependence of brightness on wavelength evidently is due to variations in the absorption capacity of the clouds, but not their microstructure, and the time pattern of individual formations probably indicates the formation or dissipation of cloud condensate, but not dust or photochemical reaction products. However, since the cloud composition remains unknown, conclusions as to the nature of the wind field, obtained from the pattern of heterogeneity of the cloud cover, should be considered preliminary.

The images, obtained in a period of 8 days in February 1974, reveal a circulation in the upper troposphere and stratosphere of /67
Venus, which has a high degree of symmetry in both hemispheres, relative to the axis of rotation of the planet, at an angular velocity which increases with latitude to 2 days at a latitude of 50° (Figs. 11, 12). Observation of the zonal transport near the equator confirms the presence of the 4 day retrograde circulation and indicates the existence of several slightly noticeable zonal bands less than 100 km wide. Analysis of images of Venus, obtained 4 days after the nearest approach, disclosed the presence of a distinct Y shaped /68
structure at the equator, similar to that repeated observed earlier from the earth, which also indicates the existence of the 4 day circulation.

The presence of a cellular structure of the cloud cover, similar to that presented in Fig. 10, is characteristic of the subsolar zone of the equatorial belt. Analysis of high resolution image mosaics shows that the largest and less distinctly expressed cells (500 km) have dark edges and that some of them have the shape of polygons. Their lifetime apparently does not exceed a few hours. The inner portion of the large cells has a fine structure. Several smaller cells (∿200 km) also were found, which move along with the wind and change noticeably in two hours. The equatorial convection zone, which continually evolves in the region of the subsolar point (following the movement of the sun), extends about ±20° in latitude and at least 80° in longitude. Interaction is observed between this convection zone and the average zonal flow.

Flows in the form of bright bands, similar to the terrestrial jet streams, encircle Venus with meridional spirals (extending 200-300° in longitude), which fuse with a clear, prominent circumpolar /69
band ("ring") of clouds, at a latitude of about 50° (Figs. 11, 12). /70
Anlaysis of high resolution image mosaics shows that, towards the equator, smaller "jets" and, sometimes, circular "loops" adjoin the spirals mentioned. This indicates the presence of horizontal wind shear and turbulence. At least two systems of spiral flows, particularly distinctly expressed at latitudes of ±30°, are observed in each hemisphere (one flow system is symmetrical about the equator).

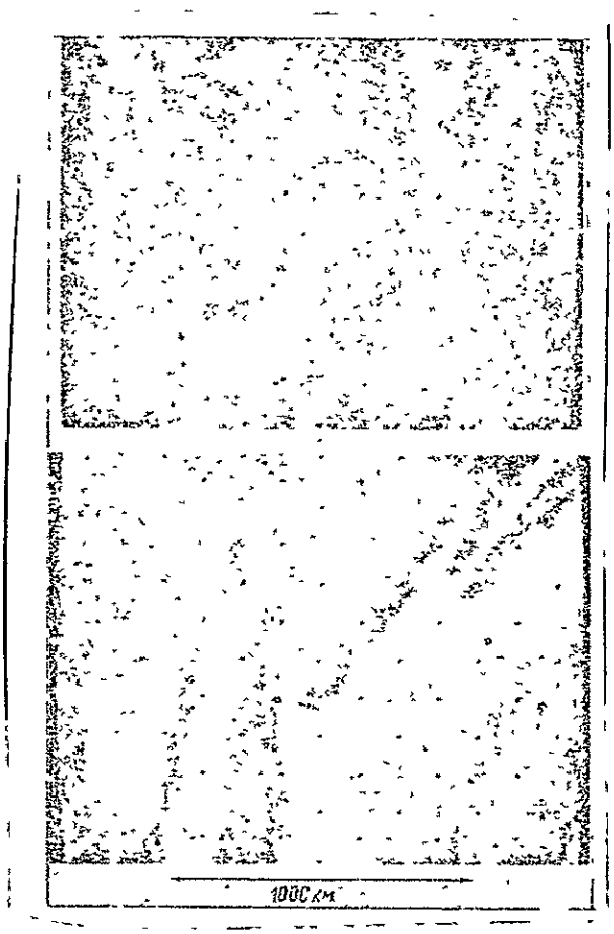

Fig. 9. Fine scale structure ("spots") of cloud cover near equator (a); large scale bands ("jets") of cloud cover at high latitudes (b); the black dots (here and on succeeding photographs) are marked on the screen of the television tube, used for the elimination of geometric distortion.

These flows disclose neither any signs of instability on a global scale, nor structures similar to terrestrial cyclonic vortexes.

Analysis of successive images of the 4-day period, which characterizes the pattern of cloud cover in the latitude band from +40° to -50°, indicates the complex nature of the distribution of heterogeneities of the cloud cover. Estimates of the zonal transport rate in the equatorial belt (outside the subsolar zone) result in a value of ∿100 $m \cdot sec^{-1}$ and the disclosure of retrograde circulation. This is in complete agreement with the conclusions of ground based observations. However, it is noted that the small scale heterogeneities do not always participate in this transport. Transport also is predominantly zonal at high latitudes.

No appreciable meridional motion was found at low latitudes but, at higher latitudes (30-50°), a ∿10 $m \cdot sec^{-1}$ component towards the pole is observed. Very faint cloud belts parallel to the equator were noticed in some of the mosaics. Sometimes, 3-4 such belts, the width of which is less than 100 km, are noted in the ±20° latitude belt. These belts apparently move rapidly around the planet in the direction of the general motion, and they sometimes cross the latitude circles. There is no doubt of the existence of a dynamic interaction of the strong zonal flow and convection zones in the subsolar region. Dark formations are found in some mosaics, which can be interpreted as evidence of the existence of bow shaped waves, generated by interaction with a "soft" obstacle (Fig. 11). These "waves" move relative to the obstacle, in distinction from true waves of this type. They are symmetrical about the equator, they extend to at least ±30° latitude, and they evidently exist in pairs.

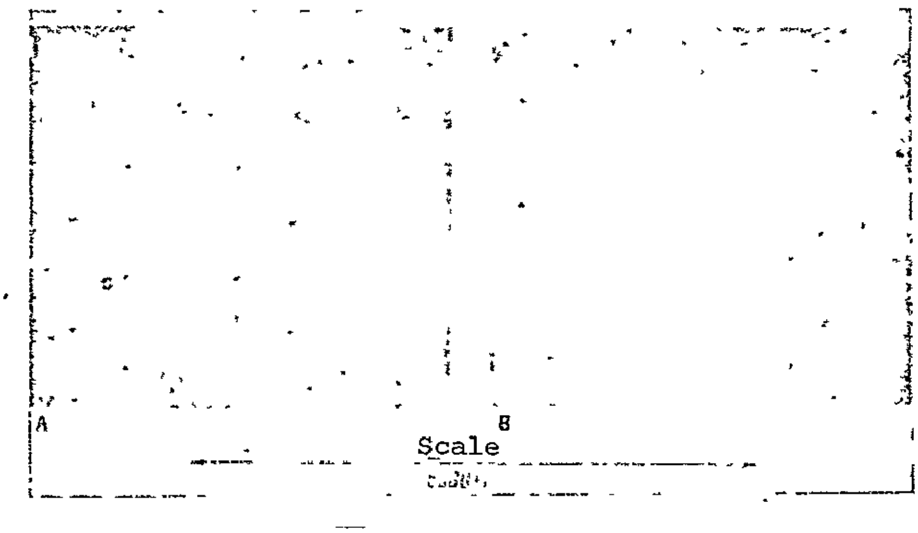

Fig. 10. Television images of cloud cover near subsolar point, obtained at 2 hour time interval. The stability of large cells (around 280 km), indicated by the arrow, and variability of the smaller cells (170 km) on the right (east) side of the image attract attention.

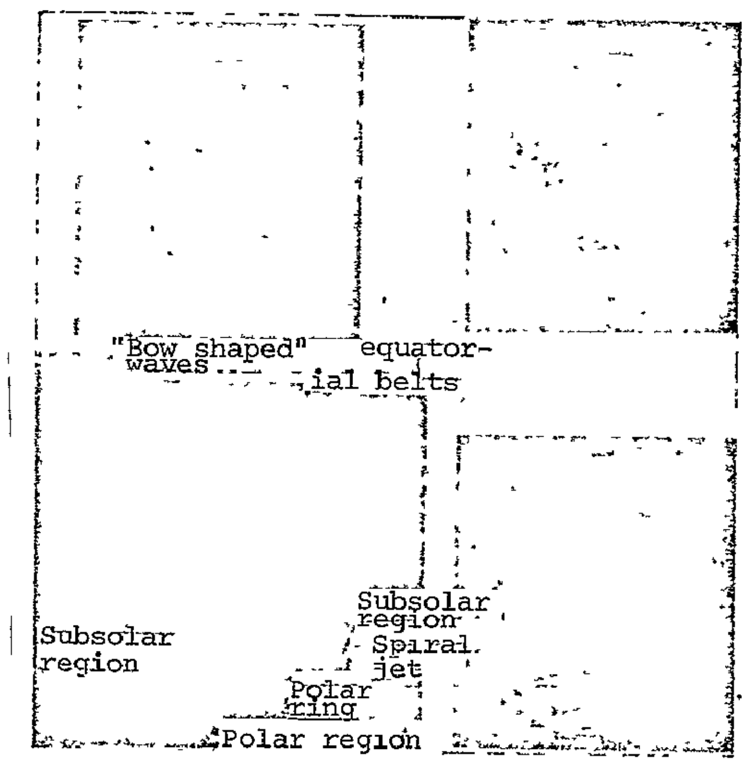

Fig. 11. Basic features of global cover reflecting regularities of general circulation of the atmosphere.

Fig. 12. Series of global television image mosaics at 7 hour intervals, showing stability of large dark and light formations in 14 hour period; dimensions of these formations, indicated by arrows, are about 1000 km.

The circumpolar cloud belts are the most distinct large scale structural characteristics of the cloud cover. Thus, for example, the south polar ring covers a latitude belt 10-15° wide, with the southern boundary near 50° S. Lat. (Figs. 11, 12). A similar ring apparently exists in the northern hemisphere (the sighting geometry did not permit the corresponding observations to be made). The entire polar region possibly is a vortex, "fed" by the meridional flow from the equatorial belt (small scale vortex like jets are ob- /71
served at the edge of the polar cap).

Analysis of images of the edge of the disc of Venus (see Fig. 13) brought out the existence of a multilayer haze structure above the cloud layer (near the 10 mb level and above), with layers up to 1 km thick. The presence of the multilayer haze indicates great stability of the atmosphere at the corresponding levels. The vertical turbulent mixing coefficient here is probably the same or less than observed in the stratosphere of the earth, where there is a similar layered haze structure. The results obtained are in agreement with the current model, which assumes the presence of a haze layer of optical thickness $\sim$2 in the 20-50 mb level range, above a dense cloud cover (cloud tops at the 200 mb level).

In study of possible physical factors of the general circulation
of the atmosphere, the unexpectedly great effect of the subsolar /72
zone on the global circulation attracts attention. Direct measurements of the temperature, wind and other parameters in the equatorial and polar regions, as well as measurements of the microstructure and cloud particle composition, are very important for solution of this problem. There is no doubt that the theoretical considerations as to the nature of the 4 day circulation, reported in the preceding section, require significant reexamination, in the light of the Mariner-10 data.

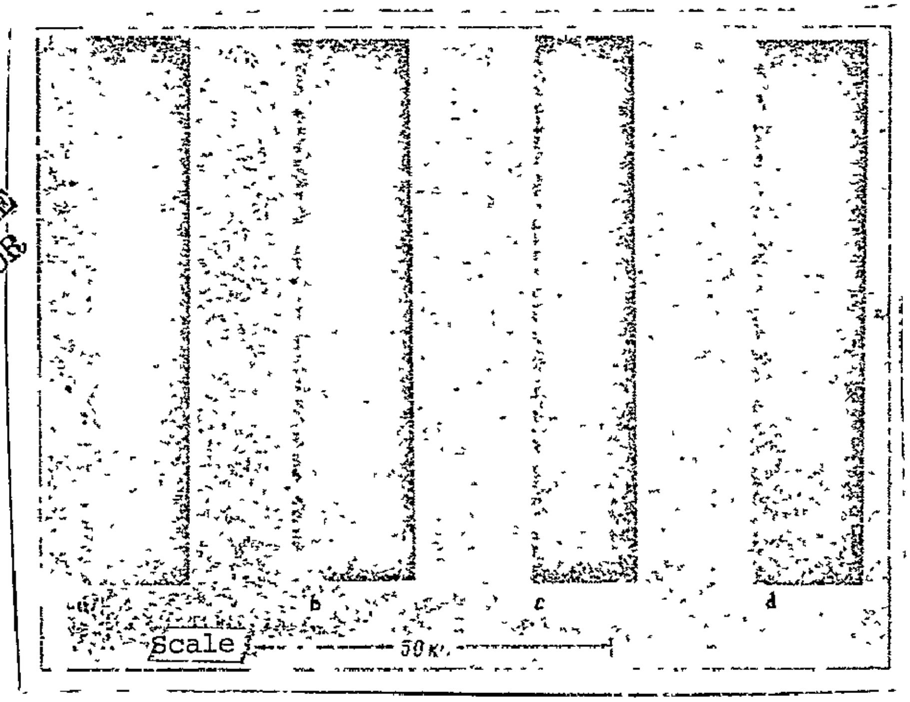

Fig. 13. Images of edge of disc of Venus: a,b. images of edge of disc near equator obtained through orange filter (578.0 nm); c, d. images of edge of disc near 22° N. Lat. obtained through orange (c) and UV (d, λ=355.0 nm) filters; the lower boundaries of the layers of the atmosphere under consideration are at approximately no lower than the 90 mb and 10 mb levels for the orange and UV filters, respectively.

3. Venera Spacecraft Data

All the results of observation of the atmospheric circulation considered above concern the layer of the atmosphere above the primary cloud cover. Only the measurements carried out by means of the Venera spacecraft first permitted an idea to be compiled, as to the pattern of the layers of Venus below the clouds, based on experiment. Measurements of the thermodynamic parameters of the atmospheres from Venera -4,5,6 and 7, discussed by V.V. Kerzhanovich et al [25,26,131], made it possible to estimate the upper limit of vertical velocities and to perform studies of the velocity field and turbulence in the atmosphere of Venus, based on the use of data on the descent pattern of the interplanetary spacecraft.

The method of determination of wind speed is based on consideration of the fact that the radial component of the wind velocity V_R can be found, as the difference in the radial descent rate of the spacecraft from Doppler measurements and the calculated rate of descent, obtained with allowance for the mutual motions and rotations of the earth and Venus, as well as the descent rate of a parachute under calm atmospheric conditions. The latter estimate was made, with the use of two independent methods, one of which was based on analysis of the descent pattern of a parachute and the other, connected with the use of vertical pressure and temperature profile measurements. The basic factors, on which the reliability of solution of the problem depend, are errors in localization of the point of entry of the interplanetary spacecraft into the atmosphere, the dynamics of the parachute-spacecraft system and the frequency stability of the onboard crystal oscillators.

After determination of the radial velocity, it is easy to calculate the vertical and horizontal components of the velocity which are equal to $V_R \cos\delta$ and $V_R \sin\delta$, respectively, where δ is the angle between the earth-Venus direction and the local vertical in the descent area of the spacecraft. In the cases of Venera-4-7, $\delta \lesssim 15°$ and, for Venera-8, $\delta \sim 38°$. This makes the data of the latter spacecraft more convenient for determination of the horizontal velocity component (more precisely, that part of the horizontal velocity which corresponds to the direction from the subsurface point to the landing point of the descent vehicle). The locations of the landing points and subsurface points of the Venera spacecraft are presented in Fig. 14 [150]. /73

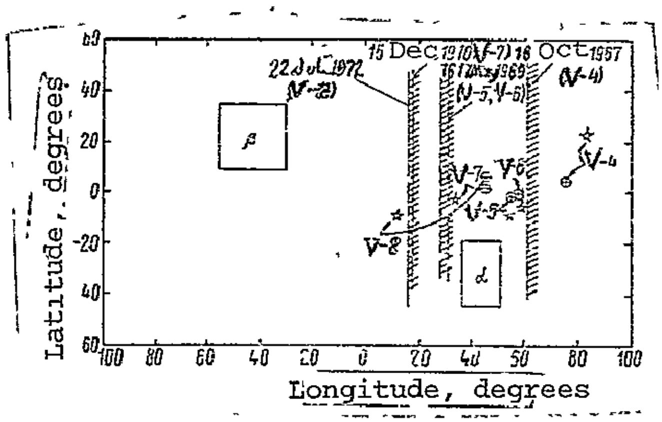

Fig. 14. Location of landing points (stars) and subsurface points (circles) of Venera spacecraft; vertical lines with cross hatching define the location of the morning terminator, with the cross hatching on the dark (night) side of the terminator: the letters α and β mark high radio wave albedo zones.

Analysis of available measurements permitted determination of the vertical and horizontal components of the wind speed from the Venera-4 and 7 data, and of only the vertical component from the Venera-5 and 6 data. All the data concern the night side of the planet (4-5 a.m. local Venus time). The considerations expressed in work [131] show that the space scale of the inertial range of isotropic turbulence on Venus is wider than on the earth. If the turbulence is considered isotropic, this means that the magnitudes of fluctuation of the vertical and horizontal wind speed components differ by $(4/3)^{1/2}$ times. With an average descent rate of 3 m·sec^{-1}, the characteristic turbulence scale at altitudes of 40-55 km is 100-200 m. The root mean value of the vertical velocity fluctuations is practically constant, at 0.28-0.32 m·sec^{-1} (Venera-5), 0.24-0.28 m·sec^{-1} (Venera-6), and it does not exceed 0.5 m·sec^{-1}. The low fluctuation magnitude indicates weakness of the convective currents. Below 40 km and right down to the surface (Venera-7), no turbulence was detected.

According to Venera-4 data, the wind speed reaches 40-50 m·sec^{-1}. However, no wind was recorded below 40 km. The Venera-5 and 6 Doppler data discovered a very slow change in wind speed during the entire descent, without appreciable turbulence (the wind speed does not exceed 3-15 m·sec^{-1}). Processing of the Venera-7 data resulted /74
in speeds of 5-14 m·sec^{-1} at altitudes of 38-53 km. The wind speed was zero below 38 km. In the layer from the surface to the 3.5 km level, the wind speed increases monotonically from 0 to 2.5 m·sec^{-1} (the maximum is 5 m·sec^{-1}). The vertical speed at an altitude of 3.5 km is 0.5 m·sec^{-1}, with a maximum of 1 m·sec^{-1}. It should be noted that an indirect method of estimation of vertical speeds in planetary atmosphere was recently proposed by S.S. Zilitinkevich [21]). With allowance for the spacecraft structural characteristics and variations in the radio signal during landing, it was found that the resilience of the soil is 2-80 kg·cm^{-2}.

The vertical profile of the horizontal wind speed components from all existing data, obtained by M.Ya. Marov et al [150], is shown in Fig. 15. In the case of Venera-8, the azimuth of the subsurface point is about 115° (see Fig. 14), and the positive speed indicates the presence of a wind from the night to the day sides, i.e., coinciding with the direction of rotation of the planet. Of course with the availability of only measurement data of the projections of the horizontal speed vector from the subsurface point to the landing point, it is impossible to determine the zonal and meridional components of the speed. If the horizontal velocity vector is directed along a latitude circle, to change from the values presented in Fig. 15 to the actual zonal velocity, a coefficient of ~1.1 must be introduced. The measurement data are in agreement with the assumption of the meridional velocity, if a coefficient of ~2.4 is introduced.

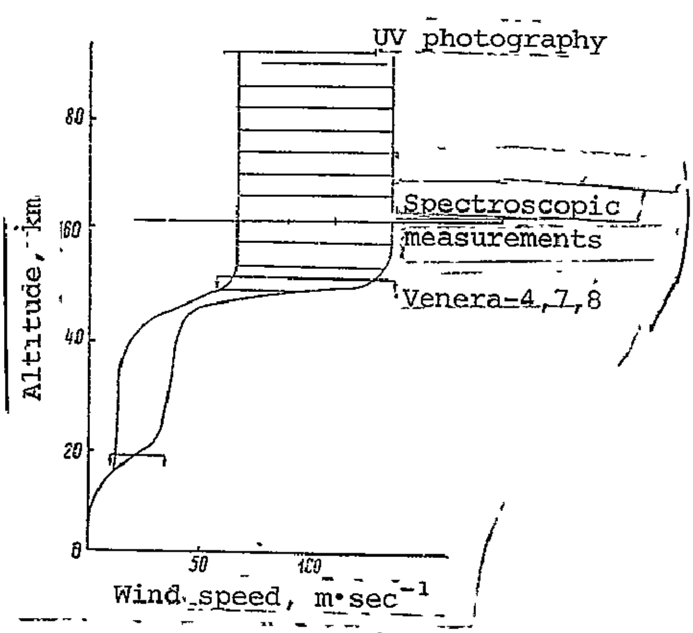

Fig. 15. Vertical profile of horizontal velocity components (in the direction from the subsurface point to the landing point) from Venera spacecraft data and indirect measurements.

Examination of Fig. 15 shows that the wind speed increases from 0-0.5 m·sec^{-1} at the surface of the planet to 100-1400 m·sec^{-1} at altitudes above 48 km, but that it does not change direction. The wind is practically constant, at 30-36 m·sec^{-1}, in the 20-40 km layer. A slight wind is characteristic of the lower part of the troposphere (0-10 km). The fact that, according to Venera-8 data, much stronger winds than were obtained previously are observed in the 20-40 km layer attracts attention. According to the Venera-7 data, the wind speed in this layer is not over 5 m·sec^{-1}, but the Venera-4 observations, concerning an almost meridional direction, gave a horizontal component of nearly zero, but with an error of about 12 m·sec^{-1} [131]. Data on the horizontal wind component could not be obtained from the Venera-5 and 6 data, since these spacecraft landed very close to the subsurface points. In consideration of the low wind speed at the surface of Venus, M.Ya. Marov et al [150] expressed the hypothesis that there is a low dust concentration in the lower layers of the atmosphere and slight wind erosion. /75

4. Numerical Modeling of Atmospheric Circulation

The successful development of research for the purpose of numerical modeling of the general circulation of the atmosphere of the earth, and the accumulation of considerable direct measurement data on the composition, structural parameters and wind have created a basis for carrying out theoretical work in recent years, for the purpose of numerical modeling of the general circulation of the Venusian atmosphere.

It can perhaps be considered that the beginning of modern research on the atmospheric circulation on Venus was the well-known work of R.M. Goody and A.R. Robinson [104]. A theory of circulation in the deep layers of the atmosphere was proposed in this work, based on the hypothesis that solar radiation is completely absorbed in the upper layers of the atmosphere (above the level of the primary cloud cover), and that the heat sources and sinks are the subsolar and antisolar points, respectively. A schematic

representation of the asymmetrical circulation produced here is shown in Fig. 16. If it is assumed that the solar radiation penetrates into the clouds (as follows from the Venera-8 data) and is absorbed in the entire mass of the atmosphere, within the framework of the theory under consideration, the circulation scheme remains as before, but the equatorial belt and the polar latitudes become the heat sources and sinks, i.e., the circulation becomes meridional, in the form of the Hadley circulation cells observed in the tropics of the earth. P. Stone [194] generalized the circulation model of R.M. Goody and A.R. Robinson to the case of accounting for the effect of the boundary layer of the atmosphere. He also showed that the /76
effect of the Coriolis forces can become significant on such a slowly rotating planet as Venus, only with a characteristic length on the order of 10^5 km. Since such a scale onsiderably exceeds the radius of Venus, this means that the Coriolis forces have no effect on the Venusian atmospheric circulation.

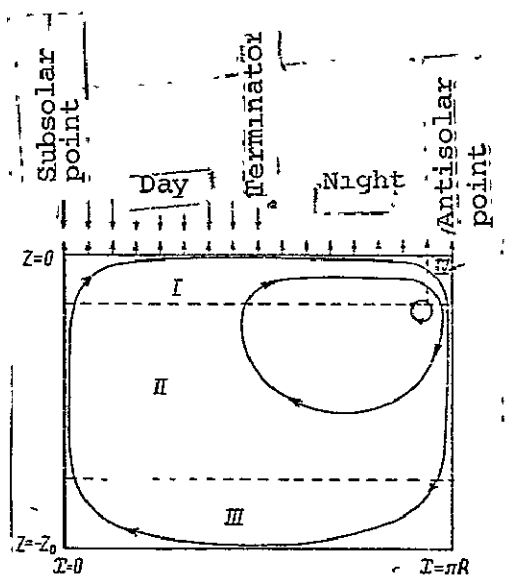

Fig. 16. Schematic representation of deep circulation on Venus (z is the vertical coordinate, R is the radius of the planet); the arrows symbolically represent the incoming solar radiation and outgoing longwave radiation: I. upper boundary layer; II. inner region; III. Lower boundary layer; IV. mixing region.

The circulation model of R.M. Goody and A.R. Robinson results in a wind speed on the order of 30 $m \cdot sec^{-1}$ in the narrow upper boundary layer and very slow circulation (slight winds) in the deep layers of the atmosphere. The vertical temperature gradient in the inner region and lower boundary layer should be adiabatic. This means that there is intensive mixing in these layers of the atmosphere. S.L. Hess [114] expressed, however, the hypothesis that turbulence decreases at great depths, where radiant equilibrium possibly predominates. However, this hypothesis clearly contradicts the work of V.S. Avduyevskiy et al [67], in which it was shown that the use of calculation data on the vertical radiation flux profiles for calculation of the vertical temperature distribution with radiant equilibrium results in a very large superadiabatic temperature gradient in the lower layers of the atmosphere. This indicates the necessity for the generation of intensive convection, /77 to ensure thermal equilibrium. Based on the use of hydrodynamics equations for a compressible gas, with Rayleigh numbers of not over 10^6, a theoretical model of convection in the atmosphere of Venus is examined, on the assumption of the existence of convective cells with a characteristic dimension which corresponds to the height of the uniform atmosphere. The maximum vertical speed of convective motion is 1.5 $m \cdot sec^{-1}$, but it can reach 10 $m \cdot sec^{-1}$ in the case of turbulent flow.

A whole series of studies, devoted to the synthesis of a theory of the vertical temperature profile [14,192,177,159], have led to the conclusion that there is mixing in the troposphere of Venus. The simple circulation model developed by R.M. Goody and A.R. Robinson is of interest, in the sense that it makes it possible to explain the factors which dictate the existence of a continuous, global cloud cover on Venus [69].

The first attempts at numerical modeling of the atmospheric circulating on Venus were made in recent years, in the spirit of similar works on the atmosphere of the earth, and which reproduced a three dimensional global circulation pattern. An exhaustive cycle of work in this area has been performed by S.S. Zilitinkevich A.S. Monin et al [22,23], D.V. Chalikov, A.S. Monin et al [79].

In this cycle of works, based on the use of the complete system of hydrodynamics equations (the so-called "primitive" equations), the continuity and heat inflow equations for a two layer model (the atmosphere is divided into two layers of the same mass), in the quasi-static approximation, numerical modeling of the general circulation of Venus was first accomplished. Based on this system of equations, the latitudinal (u) and meridional (v) components of the horizontal velocity vector and potential temperature (θ) and pressure at the surface of the planet (P) were determined. With such data available, the temperature T, geopotential Φ and the analog of the vertical velocity component $\frac{\partial \sigma}{\partial t}$ ($\sigma = P/P_s$) can be calculated.

ORIGINAL PAGE IS OF POOR QUALITY

This system of equations was solved, with horizontal turbulent mixing and radiant heat influx taken into account. The coefficient of horizontal turbulent mixing was determined by means of Richardson's law, on the assumption that the dissipation of kinetic energy is $0.2 \cdot 10^{-4}$ $m^2 \cdot sec^{-3}$. The radiation fluxes were calculated by the method of V.V. Sobolev [53]. The albedo of the planet was assumed to be 0.76, in which it was assumed that 20% of the absorbed solar radiation is due to absorption by the atmosphere and 80%, by the surface of the planet. The incoming solar radiation is determined by $S_0/4$, where the solar constant S_0=3.8 $cal \cdot cm^{-2} \cdot min^{-1}$. The heat radiation /78 of the surface is completely absorbed by the lower layers of the atmosphere (thus, the vertical heat transport in the primary mass of the atmosphere is determined by the effect of large scale motions and convection). The vertical flows of momentum and heat in the boundary layer, as well as the surface temperature, were determined by the method of A.S. Monin and S.S. Zilitinkevich [152]. "Convective adaptation" ("adaptation" to an adiabatic vertical temperature gradient) was used in the free atmosphere, if hydrostatic instability developed.

A special study showed that the basic features of planetary circulation remain constant, with variation in the number of points of a three dimensional network within rather broad limits. This indicates the global nature of the circulation and the absence of such large scale disturbances as cyclones and anticyclones. The larger part of the calculations was carried out with horizontal steps of about 2200 km (80 points on the sphere), during 160 earth days, as well as with 1500 km steps (168 points) for 90 days. A state of rest was the initial state, with 80 atm pressure at the surface level and 700°K potential temperature (for the entire atmosphere).

The calculations showed that the average kinetic energy per unit mass increases, only during the first 30 days, reaching a stable value of 14.5 $m^2 \cdot sec^{-2}$ (with small variations about this value), which corresponds to a wind speed of $\sim$5.5 $m \cdot sec^{-1}$. This means that, even in the case of such a massive atmosphere as the Venusian, with its tremendous dynamic and thermal inertias, numerical experiments can be limited to calculation in a comparatively short segment of time ("accelerating" the atmosphere from a state of rest to dynamic equilibrium conditions takes about 1 month), during which fairly stable circulation is established (though it should be noted that this theoretically important conclusion requires further confirmation, based on more realistic numerical modeling).

The calculations, carried out in the greatest detail for a network of 80 points, permitted the variability of circulation to be studied, during complete Venusian solar days (about 117 earth days). Since there is no time of year on Venus, the data of these calculations characterize the time changes of the fields of the horizontal and vertical components of wind speed, temperature, atmospheric pressure, radiation and turbulent heat flows, tangential stress (friction) and surfaces. The Venusian circulation is almost symmetrical about the equator, and its source is the temperature difference of the night and day sides of the planet (there is practically no equator-pole temperature difference). Circulation symmetry, either with respect to the axis of rotation (similar to the earth), or to the solar-antisolar point axis is not observed. The zone of maximum heating noticeably "lags" behind the subsolar point, and it is located near the evening terminator, while the coldest region is observed near the morning terminator (in a certain sense, this is similar to the temperature minimum in the early morning hours in the daily temperature variation on the earth). /79

The temperature field calculation showed that the temperature differences at different points reach 2.5°, and that the average surface temperature difference of the day and night hemispheres is a total of 1°. The amplitude of pressure variation at the surface is 80 mb (the average pressure on the day side is 28 mb less than on the night). The main circulation characteristics are the winds toward the heating zone in the lower part of the atmosphere, where rising and spreading of the air towards the cold region occur (Fig. 17). The typical wind speed is about 5.5 $m \cdot sec^{-1}$, i.e., approximately half that on the earth (10 $m \cdot sec^{-1}$). However, since the air density on Venus is about 50 times higher, the wind pressures are 10-15 times greater than on the earth. The kinetic energy per unit mass in the northern and southern hemispheres is the same, but it is almost twice as much on the day side (18 $m^2 \cdot sec^{-2}$), as on the night side (11 $m^2 \cdot sec^{-2}$). The latitudinal movements correspond to approximately twice the kinetic energy of the meridional movements. The mean zonal circulation is very slightly expressed. Its kinetic energy is three orders of magnitude less than the energy of nonzonal movements. A characteristic feature is intensive vertical movements (Fig. 17). The maximum vertical speed reaches several $cm \cdot sec^{-1}$. /80

Heating of the lower part of the atmosphere on the day side is caused mainly by turbulence ($5.3 \cdot 10^{-7}$ $degree \cdot sec^{-1}$), and cooling of the upper atmosphere, by radiation ($2.4 \cdot 10^{-7}$ $degree \cdot sec^{-1}$). There are no local heat inflows in the lower layers of the night hemisphere, but there is radiation cooling in the upper atmosphere ($3.4 \cdot 10^{-7}$ $degree \cdot sec^{-1}$). The entire Venusian atmosphere is in a state of convective mixing.

A comparison of the calculation results mentioned above for the greenhouse model of the atmosphere, with calculation data

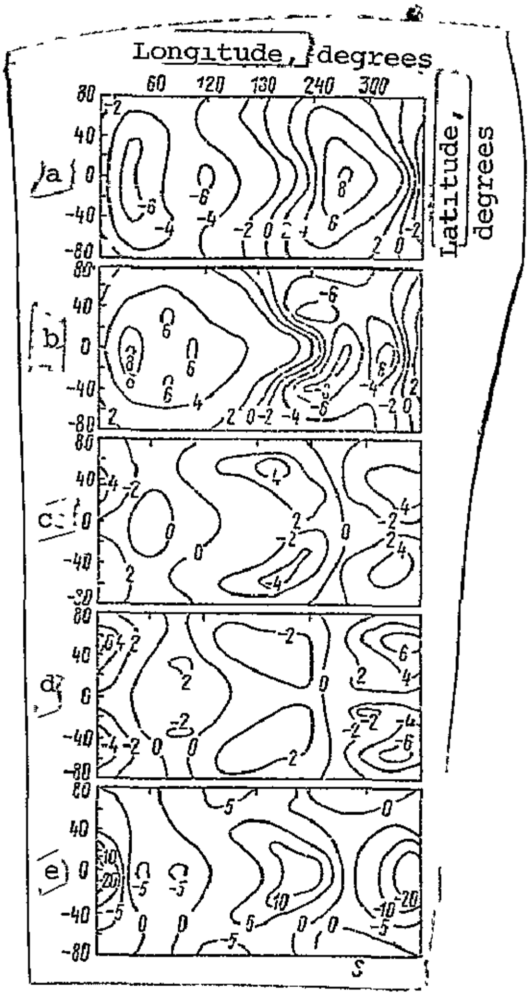

Fig. 17. Wind field on day 140 from numerical experiment data (the letter S marks the location of the subsolar point): a and b, latitudinal, c and d. meridional velocity components ($m \cdot sec^{-1}$) at lower and upper levels; e. analog of vertical velocity $d\sigma/dt$ (10^7 sec^{-1}) at level $\sigma=p/p_s=0.5$ (positive values correspond to downward motions and negative, upward).

assuming that all the solar radiation is absorbed by the upper layers of the atmosphere (Goody-Robinson model), did not reveal significant disagreements. But, the greenhouse model evidently reflects reality more adequately. The authors of [79] note close coincidence of estimates of the average wind speed and temperature difference of the hemispheres, made by G.S. Golitsyn [16], based on considerations of similarity theory and numerical modeling data. In this sense, there also is a definite qualitative correspondence of the numerical modeling results under consideration with Venera spacecraft measurements, although the sketchiness of the space network of the model does not permit, for example, a vertical wind profile which would be similar to that observed (Fig. 15) to be obtained. The assumption that 80% of the solar radiation is absorbed by the surface of the planet is clearly in disagreement with the Venera-8 data.

Similar numerical modeling of the atmospheric circulation on Venus, based on the use of a terrestrial circulation model, developed by A. Kasahara and W.M. Washington [129], was undertaken by T. Sasamori [182]. By disregarding rotation of the planet (and, consequently, the effect of Coriolis forces), as well as the revolution of Venus around the sun (i.e., by keeping heating due /81
to absorption of solar radiation constant over time), T. Sasamori analyzed the two dimensional circulation on a sphere, in a plane which contains the subsolar and antisolar points. Analysis of the role of optically active gaseous components of the atmosphere in the absorption of solar radiation led to the conclusion that the basic factor in the horizontal heterogeneity of the radiation heating

of the atmosphere should be absorption by carbon dioxide, with water vapor of secondary importance (if it is assumed that the mixing ratio for water vapor is 10^{-3}). The calculations showed that the ratio of the solar radiation reflected by the clouds to that transmitted can be assumed to be 8:2, since this results in a completely reliable albedo of 0.73 (7 and 20% of the radiation is absorbed by the atmosphere above and below the clouds, respectively). From the condition of balance of the absorbed solar and outgoing longwave radiation, it was found that the balance is best observed, with a cloud top altitude of 64 km. This corresponds to a pressure of ∿200 mb (it is assumed that the thickness of the cloud layer is small compared to the altitude scale). Since the mass of the atmosphere above the clouds is small (about 0.2% of the total mass), it turns out that the differential (along the horizontal) radiation heating is strongly concentrated in and above the clouds. The coefficient of horizontal turbulent diffusion is assumed to be 10^{10} $cm^2 \cdot sec^{-1}$, and values of 10^5 and 10^6 $cm^2 \cdot sec^{-1}$ have been used for the coefficient of vertical diffusion.

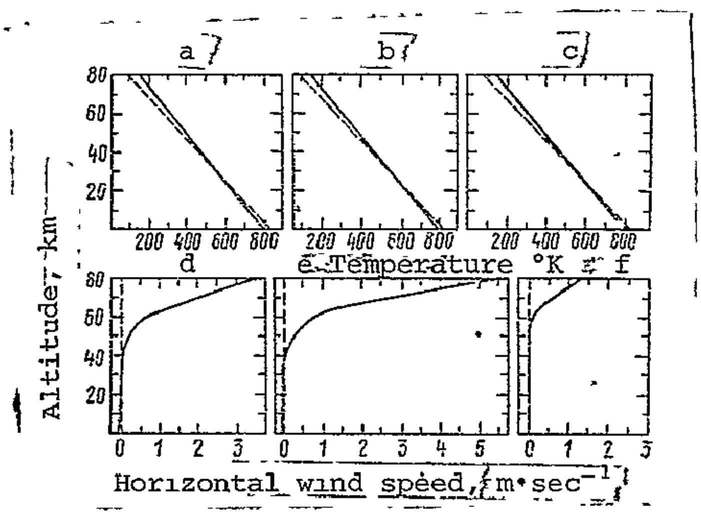

Fig. 18. Vertical temperature profiles (Fig. 19a, b, c) and horizontal wind speed components (Fig. 18 d, e, f) from calculation data on day 80: a. subsolar point (angular coordinate reckoned from subsolar point, ϕ=0°); b. terminator (ϕ=90°); c. antisolar point (ϕ=180°); d. ϕ=45°; e. ϕ=90°; f. ϕ=135°.

T. Sasamori used an eight layer model of the atmosphere (layers 10 km thick) and horizontal steps 10° wide (1067 km). Calculations of the radiant heat influx were done with vertical steps of 2 km. In view of the great thermal inertia of the Venusian atmosphere, arbitrary pressure and temperature fields were not used as the initial distributions of these quantities, but values in agreement with Venera-4 and Mariner-5 measurements. In accordance with this, initial, uniform pressure (109.3 atm) and temperature (304°K) fields were assumed at the surface, and the vertical gradient was assigned as adiabatic (initial wind speed everywhere is zero). Numerical modeling, based on the use of a correspondingly simplified system of equations of motion, continuity and heat influx, showed that the "start-up" time of the atmosphere is about one month, after which there are only slight oscillations of the horizontal wind component, with a period of 4-5 earth days. Vertical temperature and wind profiles at certain characteristic points, obtained on day 80, are presented in Fig. 18 (the initial distributions /82 are depicted by a dashed line). Positive velocities correspond to the direction from the subsolar point to the antisolar point.

As is evident, the vertical temperature distribution, which initially was neutral (adiabatic), turns out to be mildly stable (the vertical temperature gradient is somewhat less than adiabatic). There is practically no horizontal temperature gradient. An increase in velocity with altitude is characteristic of the vertical wind profile but, even at high altitudes, the wind, nevertheless, remains light, in contrast to the Venera-8 data (Fig. 17). Of course the numerical modeling results do not reveal anything similar to the four day circulation, since the sun is fixed "motionless." Near the surface of the planet (ϕ=45 and 90°), very light winds toward the subsolar point are noted.

Three dimensional fields of the horizontal ρV (Fig. 19a) and vertical $\rho\omega\frac{\Delta y}{\Delta z}$ (Fig. 19b) components of momentum, as well as the momentum vector field (Fig. 19c) on day 80 are shown in Fig. 19. They graphically characterize the characteristics of the planetary circulation. The vertical component of momentum increases $\Delta y/\Delta z$ times (Δy, Δz are the steps along the horizontal and vertical coordinates, respectively). On the left side of Fig. 19b, to save space in the recording, the zeros are dropped (thus, for example, 26 means 0.26, etc). The length of the arrows in Fig. 19 is proportional to the momentum $\rho|\vec{V}|$. As is seen from Fig. 19c, the atmospheric circulation from the subsolar (ϕ=0°) to the antisolar /83 (ϕ=180°) points has only slight asymmetry, compared with the result for the model of R.M. Goody and A.R. Robinson (Fig. 16). The maximum positive horizontal component of momentum is at about the 45 km level, near ϕ=80°, and the maximum (by modulus) negative component is observed near the surface (Fig. 19a). The maximum value of the ascending component of momentum at the subsolar point is approximately twice that of the descending component at the antisolar point. Fig. 19 b and c do not show that very narrowly localized, so-called mixing region, near the upper boundary above the antisolar point (region IV in Fig. 16), where both vertical and horizontal turbulent diffusion are of equal significants to maintenance of the stationary state of the atmosphere, and the speed of downward movement reaches 10 $m \cdot sec^{-1}$ (according to P. Stone [194] only 0.5 $m \cdot sec^{-1}$). However, the extent of the downward movement zone at the antisolar point on the surface, characteristic of the model of P. Stone [194], is found in Fig. 19b,c.

The study of the distribution of the radiation balance of the "underlying surface-atmosphere" system, carried out by T. Sasamori [182], showed that the balance is positive in the interval from the subsolar point to $\phi \approx 70°$, and that it becomes negative at $\phi > 70°$. /84
These data are in good agreement with the distribution of energy transport by atmospheric motions. Thus, it can be concluded that

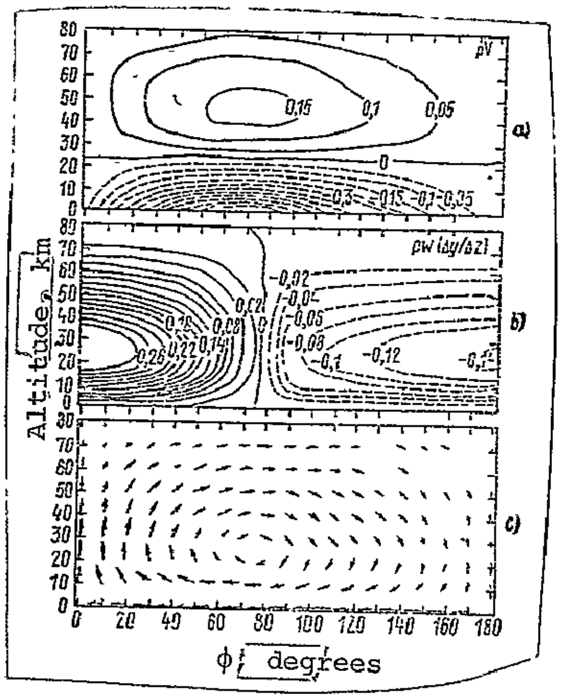

Fig. 19. Vertical section of fields of horizontal (a) and vertical (b) components of momentum ($g \cdot cm^{-2} \cdot sec^{-1}$), as well as the momentum vector (c), from day 80 calculation data.

the stationary state of the atmospheric circulation on Venus is determined by the balance between the differential radiant heat influx and the heat influx due to energy transport by atmospheric motions.

Since the duration of the solar days on Venus is 117 earth days, this means that the solar heating "waves" travel along the solar equator at a rate of ~ 4 m$\cdot$sec^{-1}. In this connection, T. Sasamori [182] undertook calculations of the horizontal velocity component field at the surface and at the 80 km level in the plane of the equator, on the assumption that solar heating is fixed at a specific subsolar point or travels at the speed mentioned (accordingly, the subsolar and antisolar points travel). In both cases, the results proved to be similar, from which it follows that a quasi-stationary hydrodynamic state is established in the atmosphere, with a small phase lag behind the traveling heat source. Thus, it can be concluded that the atmospheric circulation on Venus is a bipolar circulation between the subsolar and antisolar points, which travels along the solar equator at a rate of ~ 3 m$\cdot$sec^{-1}. This conclusion agrees with the results of the work of R.M. Goody and A.R. Robinson [104] and of P. Stone [194], but there is no doubt that it contradicts both numerous observation data of the four day circulation, and the complex pattern of motion of the atmosphere above the clouds, found from the Mariner-10 data [154].

Still another attempt at numerical modeling of the atmospheric circulation on Venus was undertaken by E.K. de Rivas [175], who also used the two dimensional approximation (on a sphere). However, the calculations were done, with the use of nonuniform spatial grids, for adequate consideration of the boundary layers. Two limiting cases were considered here: 1. the planet does not rotate, and the position of the subsolar point is fixed; 2. rotation of the planet is taken into account, but it is assumed that the effect of the daily variation in heating, due to absorption of solar radiation, is negligibly small (the amount of heating is averaged over the Venusian solar day). Two approaches were used for solution of the problem in each of these cases: 1. the Bussinex approximation (density is unchanged and the effect of radiation is not taken into account, since it is assumed that the transport of heat is due only to turbulent diffusion and large scale advection); 2. "quasi-Bussinex" approximation (density stratification and radiation transmission in the "gray" approximation are taken into account).

The caculations of E.K. de Rivas showed that the use of the Bussinex approximation leads to results similar to those obtained by Goody and Robinson, but weak descending movements are observed in the larger part of the night side and not only near the anti-solar point (this agrees with the conclusions of T. Sasamori [182]). However, if density stratification is taken into account in the case when solar radiation is absorbed near the cloud tops, large scale circulation is limited to the upper layers of the atmosphere during the entire period ($4 \cdot 10^7$ sec) of numerical modeling. It is possible that, over a longer time (on the order of 10^9 sec), the circulation penetrates into the inner part of the atmosphere but, on the other hand, the calculations lead to the conclusion that the long wave radiation is due to the high stability of the lower layers of the atmosphere, in the absence of the penetration of solar radiation into these layers. /85

If it is assumed that solar radiation penetrates into the mass of the atmosphere, to the extent that 6% of the incoming radiation reaches the surface of the planet at the equator, the combined effect of the deeper circulation and the greenhouse effect can explain the presence of adiabatic stratification. As a result of symmetrical solar heating (Bussinex approximation with rotation taken into account), forward circulation Hadley cells develop in both hemispheres, with small retrograde circulation cells near the poles. The transport of momentum towards the pole, which occurs in the upper atmosphere, gives rise to a wind shear in zonal transport, with a maximum rate of retrograde transport of about 10 $m \cdot sec^{-1}$ at the level of the top of the atmosphere.

In discussing the first three dimensional (two layer) model of global circulation on Venus, developed by S.S. Zilitinkevich et al [22,23], leading to bipolar circulation between the morning and evening terminators, which are the coldest and warmest points in the case under consideration, E.K. de Rivas noted that lack of consideration of rotation of the planet in this model and the insufficient spatial resolution, especially along the verticals, makes it impossible to use this kind of model for comparison with the results he obtained.

In concluding the discussion of the results of numerical modeling of the atmospheric circulation on Venus, it should be stated that all the models proposed give a wind field pattern, which turns out to be considerably simplified, compared with what observations disclose. It can be acknowledged that such a situation is completely natural, since only the first steps have been taken on the way to development of a theory of the Venusian atmospheric circulation.

5. Upper Atmosphere

Brief information on the upper atmosphere of Venus was presented above (see Sections 2,3). Therefore, here, we limit ourselves to only references to the surveys of T.M. Donahue [88], J. Dubach et al [89], R.G. Prinn [167] and the comprehensive works of R.E. Dickinson [83-86], and mention of some interesting results, from the point of view of the interaction of the upper and lower layers of the atmosphere. /86

As was noted by D.M. Hunten and R.M. Goody [124], a specific characteristic of the carbon dioxide of the upper atmosphere of Venus (like Mars) is the fact that the carbon dioxide turns out to be slightly dissociated, even at great altitudes. Such stability of carbon dioxide is in sharp contrast to the conditions of the upper atmosphere of the earth, were the dissociation of molecular oxygen by solar radiation is so intense that, even at altitudes over 90 km, atomic oxygen is dominant. Nevertheless, no convincing explanation has yet been given of the fact that zones of predominance of CO and O, as dissociation products of CO_2, have been found on Venus. Another interesting result, obtained from the Mariner-5 data, is that the concentration ratio of deuterium and normal hydrogen is about 1. If this is correct, it should be of great importance from the point of view of the theory of evolution of the atmosphere by dissipation of light atoms.

D.J. Strickland [195] carried out calculations of the emission intensities in the 130.4 and 135.6 nm atomic oxygen lines, for the upper atmosphere of Mars and Venus. The Mariner-6, 7 and 9 measurements disclosed that, under Mars conditions, the relative density of atomic oxygen at the ionospheric F1 maximum level (about 135 km) is 0.5-1%. According to current concepts, the situation on Venus is similar. Since reliable information on the oxygen content of the upper atmosphere is of great importance to understanding the regularities of structure and dynamics of the atmosphere, the question of calculation of the intensities of the emissions under consideration becomes highly urgent.

Venera-4 and Mariner-5 measurements have not disclosed 130.4 nm emissions in excess of the threshold sensitivity of the sensors. However, subsequent rocket measurements have recorded unexpectedly high intensities of 130.4 and 135.6 nm emission, which amount to from 3.0 to 5.7 kilorayleighs. Precisely this convinced D.J. Strickland to undertake calculations of the emission intensities. The selected model of the atmosphere of Venus is characterized by the fact that atomic oxygen is considered to be uniformly mixed through the atmosphere and that its concentration is 1%, at the level for which the total CO_2 concentration in the atmospheric column is $4 \cdot 10^{16}$ cm^{-2}. Resonance scattering of solar photons for the 130.4 nm triplet and dissociative excitation in the case of the 135.6 nm emission, as well as excitation of oxygen by photoelectrons in both cases, are considered to be possible sources of the excitation of emissions. /87

The calculation results for Mars conditions found good agreement with the Mariner-9 data, according to which the average brightness intensity at wavelengths of 130.4 and 135.6 nm are 330 and 50 kilorayleighs, respectively (the calculated values are 350 and 60 kilorayleighs). The calculations for Venus diverge sharply from the rocket measurement data mentioned above. This indicates that the intensity ratio of the 130.4 and 135.6 emissions is approximately 2. This ratio is achieved, with an oxygen concentration of 0.05% and emission intensities of about 0.4 and 0.2, which are approximately an order of magnitude less than measured.

Since the intensity of the emission increases very slowly with increase in oxygen concentration, the 5.7 kilorayleigh level (130.4 nm) is not reached, even with a concentration of 10%. By varying the parameters used for the calculations, full agreement with experiment could not be reached. Therefore, possible additional sources of energy causing the emission were discussed: transfer of the energy of ions, excitation by the solar wind and luminescence unconnected with atomic oxygen. It was shown that the first two factors are insignificant. Therefore, all that is left is to propose the existence of an additional, unidentified source of emission. It also is possible that the atomic oxygen content in the Venusian atmosphere is greater than on Mars, reaching the 10% level.

One fundamental problem is the study of the factors which determine the heating conditions of the upper layers of the atmosphere of Venus. R.E. Dickinson [83-86] studied the situation in detail, in the Venusian stratosphere and mesosphere (see Fig. 1).

The Venusian mesosphere is heated mainly by absorption of solar radiation in the carbon dioxide vibrational-rotational bands, centered at wavelengths of 1200, 1400, 1600, 2000, 2700 and 4300 nm. The basic cooling mechanism is radiation in the 1500 nm carbon dioxide band. It can be expected that there should be a considerable daily variation in temperature in the mesosphere of Venus. Since absorption in the near infrared region of the spectrum has little sensitivity to temperature, calculations of the temperature relations of the horizontal variations in cooling in the 1500 nm band are causing particular interest.

R.E. Dickinson [86] calculated the horizontal variability of infrared heating in the mesosphere, as well as the adjacent layers of the stratosphere and the lower thermosphere, on the assumption that there are no horizontal temperature changes (the basic specific method of calculation is calculation of deviations from LTE, local thermodynamic equilibrium). The calculations revealed very large radiation heating values at the subsolar point, of about 1000° in earth days, in the layer from 10^{-3} to 10^{-4} mb. A strong increase in function of the source of the 1500 nm band also was found in the 10^{-4}-10^{-5} mb layer, which accounts for disturbance of LTE, with increase in absorption in the near infrared region. This results in a strong dependence of radiation cooling on the zenith distance of the sun (this dependence is at a maxmimum at the mesopause level, $8 \cdot 10^{-5}$ mb, which corresponds to 122 km). Therefore, cooling in this layer of the atmosphere compensates approximately half of the heating. /88

R.E. Dickinson expressed the hypothesis that the strong horizontal variability of radiation heating at the 10^{-3} mb level cannot be completely compensated by adiabatic cooling, in the absence of horizontal temperature change. Therefore, it should be considered that radiation in the 1500 nm band should vary horizontally by a factor of approximately two and the temperature, by 20°K. Horizontal temperature variations are negligibly small at levels below 0.1 mb. In connection with the conclusions noted, there is great interest in highly accurate measurements of the infrared radiation of the mesosphere of Venus and thermal sounding of the mesosphere from such measurements.

Numerical hydrodynamic models of the thermosphere of Venus have led to the conclusion that the temperature difference from day to night in the upper thermosphere is about 500°, which is approximately 300° less than is obtained, without accounting for atmospheric movements. Absorption of solar radiation on the day side gives rise to circulation, with ascending movement on the day and descending on the night sides, with an amplitude of over 1 $m \cdot sec^{-1}$ and with horizontal velocities up to several hundred $m \cdot sec^{-1}$ away from the subsolar point.

Since experimental studies of the upper atmosphere of Venus from unmanned interplanetary spacecraft still are in the very initial stage, it is evident that continuation of such studies is of primary importance to the further development of the theories of processes occuring in the upper atmosphere, as well as in study of interactions of the upper and lower layers of the atmosphere.

6. Prospects of Experimental Meteorological Investigations

The results discussed above indicate the primary urgency of investigation of the nature of the clouds, the vertical heat balance profile and its components, as well as the atmospheric /89 circulation and properties of the surface of the planet. As to the cloud problem, data on their chemical composition, microstructure, optical properties, vertical and horizontal macroinhomogeneities and cloud cover patterns are necessary for its solution. In this connection, study of the dense, hot lower layers of the atmosphere is of great importance (their chemical composition, temperature and wind fields and other characteristics). Understanding of the interactions of the atmosphere with the underlying surface is impossible, without the availability of reliable information on the mechanical, physical and chemical properties and optical characteristics of the Venusian soil. Finding the regularities of the general circulation requires both very much more extensive observational data on circulation regularities, and fairly complete information on the energetics of the atmosphere. In this connection, studies of the small, optically active gas and aerosol components of the atmosphere, study of the conditions of turbulent diffusion and convection, etc., should occupy an important place. The problems of the upper atmosphere include an extensive group of questions.

As was noted by D.M. Hunten and R.M. Goody [124] (see also [209]), Soviet and American unmanned interplanetary spacecraft, operating in the fly-by mode of artificial satellites, as well as descent vehicles, are among the possible means of investigation. Sounding balloons drifting in the atmosphere can be released from the descent vehicles. It is evident that the main tasks of the descent vehicles and sounding balloons should be direct measurements, which is most important, and of the Soviet and American unmanned interplanetary spacecraft, the satellites can be used to determine various parameters of remote display methods. There is no doubt that ground optical and radioastronomical studies have to play a serious role in the future.

References

1. Avduyevskiy, V.S. et al, "Temperature, pressure and density of the atmosphere of Venus from Venera-4 unmanned interplanetary spacecraft measurements," Doklady AN SSSR 178/2, 310-313 (1968).

2. Avduyevskiy, V.S., M.Ya. Marov and M.K. Rozhdestvenskiy, "Results of measurement of parameters of atmosphere of Venus aboard Soviet Venera-4 spacecraft," Kosmich. issled. 7/2, 233-246 (1969).

3. Avduyevskiy, V.S., M.Ya. Marov and M.K. Rozhdestvenskiy, "Model of atmosphere of Venus from direct measurement data," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, Moscow, 1972, p. 254-261 (1973, 3.62.192).

4. Avduyevskiy, V.S. et al, "Results of direct measurements of illumination in the atmosphere and on the surface of the planet Venus during flight of Venera-8," Doklady AN SSSR 210/4, 799-802 (1973) (1973, 11.62.174).

5. Biryukov, Yu.A., A.S. Panfilov and L.G. Titarchuk, "Estimates of optical characteristics of the atmosphere of Venus, as applied to the task of photographing its clouds and surface," in the collection Kosmich. ikonika [Space Imaging], Nauka Press, Moscow, 1973, p. 106-117 (1973, 7.62.173).

6. Borodin, N.F., and V.I. Os'makov, "Study of Venus by means /90
of interplanetary stations," Vestnik AN SSSR 7, 8-12 (1973) (1974, 1.62.232).

7. Bronshten, V.A., "The nature of Venus," Astronomicheskiy vestnik 1/1, 4-27 (1967).

8. Bunakova, A.M. and K.Ya. Kondrat'yev, "Some characteristics of the outgoing thermal radiation fields of the atmospheres of Venus and Mars," Izv. AN SSSR. Fizika atm. i okeana 9/3, 247-254 (1973).

9. Vetukhnovskaya, Yu.N. and A.D. Kuz'min, "Some results of combined processing of AIS Venera-4 measurements and ground-based radioastronomy and radar measurements," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, Moscow, 1972, p. 359-365 (1973, 2.62.166).

10. Vinogradov, A.P. et al, "Determination of the chemical composition of the atmosphere of Venus by Venera-4 interplanetary station," Doklady AN SSSR 179, 37 (1968).

11. Vinogradov, A.P., Yu.A. Surkov and B.M. Andreychikov, "Studies of the composition of the atmosphere of Venus by interplanetary stations Venera-5 and Venera-6," Doklady AN SSSR 190, 552 (1970) (1970, 5.62.179).

12. Vinogradov, A.P. et al, "Chemical composition of the atmosphere of Venus," Kosmich. issledovaniya 8/4, 578-587 (1970) (RZhG/Fiz., 1970, 12A26).

13. Vinogradov, A.P., Yu.A. Surkov and K.P. Florenskiy, "Study of the chemical composition of the atmosphere of Venus by automatic station Venera-4," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, Moscow, 1972, p. 244-250 (1973, 3.62.193).

14. Ginzburg, A.S. and Ye.M. Feygel'son, "Some optical properties of the atmosphere of Venus and radiant equilibrium conditions," Kosmich. issled. 7/2, 258-265 (1969) (RZhG/Fiz., 1969, 7A54).

15. Glushneva, I.N., "New determination of dependence of albedo of Venus on wavelength in the ultraviolet region of the spectrum," Astron. zhurn. 46/1, 211 (1969).

16. Golitsyn, G.S., Vvedeniye v dinamiku planetnykh atmosfer [Introduction to the Dynamics of Planetary Atmospheres], Gidrometeoizdat Press, Leningrad, 197, p. 104.

17. Golitsyn, G.S. and S.S. Zilitinkevich, "Estimates of the global characteristics of circulation of planetary atmospheres with different hypotheses of the nature of dissipation," Izv. AN SSSR. Fizika atmosfery i okeana 8/8, 785-798 (1972).

18. Goody, R., "Movement of planetary atmospheres," collection of articles Issledovaniya atmosfer Marsa i Venery [Studies of the Atmospheres of Mars and Venus], (transl. from Engl., K. Ya. Kondrat'yev, ed.), Gidrometeoizdat Press, Leningrad, 1970, p. 5-62.

19. Gurvich, A.S., "Radiospectroscopy of the planetary atmospheres by means of AIS," Izv. AN SSSR. FAO 7/10, 1023-1030 (1971).

20. Danilin, V.A., A.N. Kazantsev and A.V. Plotnikov, "Accuracy of determination planetary atmosphere parameters from phase radiooccultation measurements," Izv. VUZ. Radiofizika 16/9, 1405-1408 (1973) (1974, 4.62.174).

21. Zilitinkevich, S.S., "Estimates of vertical velocities in planetary atmospheres," Izv. AN SSSR. FAO 10/4, 411-413 (1974).

22. Zilitinkevich, S.S. et al, "Numerical modelling of the circulation of the Venusian atmosphere," Doklady AN SSSR 197/6, 1291-1294 (1971).

23. Zilitinkevich, S.S. et al, "Numerical experiments on the general circulation of the atmosphere on Venus," XV General Assembly IUGG, Joint Symposium of IMPA/IAGA on Planetary Atmospheres, Moscow, 13 August 1971, 15 pp.

24. Zuyev, V.Ye., Rasprostraneniye vidimykh i infrakrasnykh voln v atmosfere [Propagation of Visible and Infrared Waves in the Atmosphere], Sov. radio Press, Moscow, 1970, p. 496.

25. Kerzhanovich, V.V. et al, "Wind speed and turbulence in the Venusian atmosphere, obtained from Doppler measurement data of the speed of automatic interplanetary stations Venera-4, Venera-5 and Venera-6," Kosmich. issled. 10, 261-273 (1972) (1972, 9.62.169). /97

26. Kerzhanovich, V.V. et al, "Wind speed and some surface characteristics of Venus, obtained by means of AIS Venera-7," Kosmich. issled. 10/3, 390-399 (1972) (1972, 10.62.210).

27. Konashenok, V.M. and K.Ya. Kondrat'yev, Novoye o Venere i Marse [News of Venus and Mars], Gidrometeoizdat Press, Leningrad, 1970, 51 pp.

28. Kondrat'yev, K.Ya. (ed), Issledovaniya atmosfer Venery i Marsa. Sb. statey [Studies of the Atmospheres of Venus and Mars: Collection of Articles], transl. from English, Gidrometeoizdat Press, Leningrad, 1970, 366 pp (1970, 11.62.173).

29. Kondrat'yev, K.Ya., A.M. Bunakova and A.M. Anolik, "Characteristics of thermal radiation of the atmospheres of Mars and Venus," collection Perenos izlucheniya v atmosfere [Transmission of Radiation in the Atmosphere], Leningrad State Univ. Press, 1972, p. 58-60.

30. Kondrat'yev, K.Ya. and V.N. Konashenok, "Theoretical foundations of the meteorology of planetary atmospheres," collection of articles Problemy fiziki atmosfery [Problems of Physics of the Atmosphere], Leningrad State Univ. Press, 1970, No. 8, p. 142-161.

31. Kondrat'yev, K.Ya. and A.M. Bunakova, Meteorologiya Marsa [Meteorology of Mars], Gidrometeoizdat Press, Leningrad, 1973, 62 pp (1973, 8.62.161).

32. Kondrat'yev, K.Ya. and A.M. Bunakova, "Contribution of the atmospheric aerosol to the infrared radiation of planetary atmospheres," collection of articles Problemy fiziki atmosfery [Problems of Physics of the Atmosphere], Leningrad State Univ. Press, Leningrad, 1974, issue 11, p. 3-10.

33. Kondrat'yev, K.Ya., A.M. Bunakova and M.V. Anolik, "Calculation of the outgoing thermal radiation field of the upper atmosphere of Venus," Ibid., p. 11-18.

34. Kondrat'yev, K.Ya. and O.I. Smoktiy, "Possible nature of the clouds in the atmosphere of Venus," collection of articles Problemy fiziki atmosfery [Problems of Physics of the Atmosphere], Leningrad State Univ. Press, Leningrad, 1970, issue 8 p. 11-30.

35. Krekova, M.M. et al, "Possibility of calculation of the spectral albedo of Venus in the near IR range," Kosmich. issled. 11/4, 607-611 (1973) (1974, 2.62.170).

36. Krupenio, N.N. and A.P. Naumov, "Interpretation of radar measurements of Venus in the radio microwave range," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, Moscow, 1972, p. 365-367 (1973, 3.62.199).

37. Kuz'min, A.D., "Radiophysical studies of Venus," Itogi nauki. Radiofizika 1965-1966 [Reviews of Science: Radiophysics 1965-1966], VINITI, Moscow, 1967.

38. Lukashevich, N.L., M.Ya. Marov and Ye.M. Feygel'son, "Interpretation of illumination measurements in the atmosphere of Venus," Kosmich. issled. 12/2, 272-278 (1974).

39. Marov, M.Ya., "Model of the atmosphere of Venus," Doklady AN SSSR 196/1, 67-70 (1971) (1971, 8.62.163).

40. Marov, M.Ya. et al, "Preliminary results of studies of the atmosphere of Venus by means of AIS Venera-7," Kosmich. issled. 9/4, 570-579 (1971)(1971, 12.62.295).

41. Marov, M.Ya., "What is now known of Venus," Priroda 10, 9-20 (1972) (1973, 3.62.190).

42. Mikhnevich, V.V. and V.A. Sokolov, "Model of the atmosphere of Venus from direct temperature and density measurements," Kosmich. issled. 7/2, 220-232 (1969) (RZhG/Fiz., 1969, 7A56).

43. Moroz, V.I., Fizika planet [Physics of the Planets], Nauka Press, Moscow, 1967.

44. Moroz, V.I., "The atmosphere of Venus," Usp. fiz. nauk 14, 317 (1971).

45. Moroz, V.I., "Working model of the atmosphere of Venus," preprint 162, Institute of Space Research Acad. Sci. USSR, Moscow, 1973, 28 pp.

46. Moroz, V.I., V.D. Davydov and V.S. Zhegulev, "Photometric and spectral observations of the planets in the 8-14 μm range," Astron. zhurn. 46/1, 136-146 (1969).

47. Moroz, V.I. and V.G. Kurt, "The atmosphere of Venus (comparison of results of astronomical observations and direct experiments)," Kosmich. issled. 6/4, 576-585 (1968).

48. Naumov, A.P. and G.M. Strelkov, "Theoretical submillimeter radiation spectrum of Venus," Astron. vestnik 4/4, 226-230 (1970). /92

49. Obukhov, A.M. and G.S. Golitsyn, "Estimates of lower boundary and thickness of the cloud layer on Venus," Kosmich. issled. 6/5, (1968).

50. Sobolev, V.V., "Study of the atmosphere of Venus, part I," Astron. zhurn. 41, 1 (1964).

51. Sobolev, V.V., "Study of the atmosphere of Venus, part II," Astron. zhurn. 45, 1 (1968).

52. Sobolev, V.V., "Albedo and intensity of illumination of the surface of a planet having an atmosphere," Astron. zhurn. 46, 419-429 (1969).

53. Sobolev, V.V., Rasseyaniye sveta v atmosferakh planet [Scattering of Light in the Atmospheres of Planets], Nauka Press, Moscow, 1972, 335 pp.

54. Strelkov, G.M., "The hothouse effect in the atmosphere of Venus," Kosmich. issled. 4/4, 581-591 (1966).

55. Strelkov, G.M., "Radiant transport of heat in the subcloud layer of Venus," Izv. AN SSSR. Fizika atm. i okeana 9/2, 311-313 (1971).

56. Surkov, Yu.A. et al, "The cloud layer of Venus," in the collection Ocherki sovrem. geokhimii i analit. khimii [Outlines of Modern Geochemistry and Analytical Chemistry], Nauka Press, Moscow, 1972, p. 17-21 (1973, 3.62.191).

57. Surkov, Yu.A., B.M. Andreychikov and O.M. Kalinkina, "Ammonia content of the atmosphere of Venus from automatic station Venera-8 data," Doklady AN SSSR 213/2, 296-298 (1973).

58. Surkov, Yu.A. et al, "Equipment, experimental technique and basic results of study of gamma radiation of the Venusian surface by automatic station Venera-8," Kosmich. issled. 11/5, 781-789 (1973)(1974, 2.62.169).

59. Surkov, Yu.A. and B.M. Andreychikov, "Studies of Venus by Soviet automatic stations," Zemlya i vselennaya 1, 33-37 (1974).

60. Feygel'son, Ye.M., Luchistyy teploobmen i oblaka [Radiant Heat Exchange and Clouds], Gidrometeoizdat Press, Leningrad, 1970, 230 pp.

61. Sharonov, V.V., Planeta Venera [The Planet Venus], Nauka Press, Moscow, 1965, 252 pp.

62. Avtomaticheskiye planetnyye stantsii [Automatic Planetary Stations], Institute of Space Research, Nauka Press, Moscow, 1973, 279 pp.

63. "Soviet automatons study Mars," Pravda 238(19746), 25 Aug 1972.

64. Arking, A. and J. Potter, "The phase curve of Venus and nature of the clouds," J. Atmos. Sci. 25/4, 617-628 (1968).

65. Avduevsky, V.S., M.Ya. Marov and M.K. Rozhdestvensky, "Model of the atmosphere of planet Venus based on results of measurements made by the Soviet automatic interplanetary station Venera-4," J. Atmos. Sci. 25/4, 537-545 (1968).

66. Avduevsky, V.S., M.Ya. Marov and M.K. Rozhdestvensky, "A tentative model of the Venus atmosphere based on the measurements of Veneras 5 and 6," J. Atmos. Sci. 27/4, 561-568 (1970) (1971, 2.62.175).

67. Avduevsky, V.S. et al, "Heat transfer in the atmosphere of Venus," J. Atmos. Sci. 27/4, 569-579 (1970).

68. Avduevsky, V.S. et al, "Venera 8: measurements of solar illumination through the atmosphere of Venus," J. Atmos. Sci. 30/6, 1215-1218 (1973).

69. Bartlett, J.T. and G.E. Hunt, "Venus cloud cover," Nature Phys. Sci. 238/79, 11-12 (1972).

70. Beebe, R.F., "Ultraviolet clouds on Venus: observational bias," Icarus 17/3, 602-607 (1972).

71. Bottema, M. et al, "Composition of the clouds of Venus," Astrophys. J. 140, 1640-1641 (1964).

72. Bottema, M. et al, "The composition of the Venus cloud and implications for model atmospheres," J. Geophys. Res. 70, 4401-4402 (1965).

73. Boyer, C., "The 4-day rotation of the upper atmosphere of Venus," Planet and Space Sci. 21/9, 1559-1562 (1973). /93

74. Boyer, C., "The four-day rotation of Venus' atmosphere," J. Brit. Astron. Assoc. 83/5, 763-767 (1973).

75. Caldwell, J., "Retrograde rotation of the upper atmosphere of Venus," Icarus 17/3, 608-616 (1972).

76. Campbell, D.B., et al, "Venus: topography revealed by radar data," Science 175, 514-516 (1972).

77. Cess, R.D., "The thermal structure within the stratospheres of Venus and Mars," Icarus 17/2, 561-569 (1972).

78. Cess, R. and T. Owen, "Effect of noble gases on an atmospheric greenhouse (Titan)," Nature 244/5414, 272-273 (1973).

79. Chalikov, D.V. et al, "Numerical experiments on the general circulation of Venus," Tellus 23/6, 483-488 (1971).

80. Chase, S.C., L.D. Kaplan and G. Neugebauer, "The Mariner-2 infrared radiometer experiment," J. Geophys. Res. 68/22, 6157-6169 (1963).

81. Clark, B.G. and A.D. Kuzmin, "The measurement of the polarization and brightness distribution of Venus at 10.6 cm wavelength," Astrophysical J. 142, 23-44 (1965).

82. Coffeen, D.L. and J.E. Hansen, "Polarization studies of planetary atmospheres," in Planets, Stars and Nebulae Studied by Photopolarimetry (ed. T. Gehrels), Univ. of Arizona Press, Tucson, 1973, 83 pp.

83. Dickinson, R.E., "Circulation and thermal structure of the Venusian thermosphere," J. Atmos. Sci. 28/6, 885-894 (1971).

84. Dickinson, R.E., "Infrared radiative heating and cooling in the Venusian mesosphere. I. Global mean radiative equilibrium," J. Atmos. Sci. 29/8, 1531-1556 (1972).

85. Dickinson, R.E. and E.C. Ridley, "Numerical solution for the composition of a thermosphere in the presence of a steady subsolar-to-antisolar circulation with application to Venus," J. Atmos. Sci. 29/8, 1557-1570 (1972).

86. Dickinson, R.E., "Infrared radiative heating and cooling in the Venusian mesosphere. II. Day-to-night variation," J. Atmos. Sci. 30/2, 296-301 (1973)(1973, 10.62.144).

87. Donahue, F.J., "Is Venus a polywater planet?" Icarus 12, 424-430 (1970).

88. Donahue, T.M., "Aeronomy of CO_2 atmospheres: a review," J. Atmos. Sci. 28/6, 895-900 (1971).

89. Dubach, J., R.C. Whitten and J.S. Sims, "The lower ionosphere of Venus," Planet and Space Science 22/4, 525-536 (1974).

90. Dubis, J.J. and S.C. Traugott, "The effect of radiative transfer on shear-flow instability in the atmospheres of Mars and Venus," Icarus 21/4, 496-505 (1974).

91. Eberstein, I.J., B.N. Khare and J.B. Pollack, "Infrared transmission properties of CO_2, $HC\ell$, and SO_2 and their significance for the greenhouse effect on Venus," Icarus 11/2, 159-170 (1969).

92. Fink, U., H.P. Larson, G.P. Kuiper and R.F. Poppen, "Water vapor in the atmosphere of Venus," Icarus 17/3, 617-631 (1972).

93. Fjeldbo, G., A.J. Kliore and V.R. Eschelman, "The neutral atmosphere of Venus as studied with the Mariner V radio occultation experiments," The Astrophys. J. 76/2, 123-140 (1971)(1971, 11.62.184).

94. Fouquart, Y., "Use of Pade approximations for study of the equivalent widths of lines formed in a scattering atmosphere," J. Quant. Spectrosc. and Radiat. Transfer 14/6, 497-508 (1974).

95. Fukuta, N., "Comments on the infrared absorption line formation in cloudy planetary atmospheres," J. Atmos. Sci. 28/8, 1511-1513 (1972).

96. Gierasch P.J., "The four-day rotation in the stratosphere of Venus: a study of radiative driving," Icarus 13/1, 25-33 (1970).

97. Gierasch, P.J. and R.M. Goody, "Models of the Venus clouds," /94
J. Atmos. Sci. 27/2, 224-245 (1970).

98. Goettel, K.A. and J.S. Lewis, "Ammonia in the atmosphere of Venus," J. Atmos. Sci. 31/3, 828-850 (1974).

99. Goody, R.M., Atmospheric Radiation. I. Theoretical Basis, Oxford at the Clarendon Press, 1964, 436 pp.

100. Goody, R.M., "The structure of the Venus cloud veil," J. Geophys. Res. 70, 5471-5481 (1965).

101. Goody, R.M., "Motions of planetary atmospheres," Ann. Rev. Astron. Astrophys. 7, 303-352 (1969).

102. Goody, R.M. "Weather on the inner planets," New Scientist 58/849, 602-605 (1973)(1973, 10.62.145).

103. Goody, R.M. and J.C.G. Walker, Atmospheres, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1972, 150 pp.

104. Goody, R.M. and A.R. Robinson, "A discussion of the deep circulation of the atmosphere of Venus," The Astrophys. J. 146/2, 339-365 (1966).

105. Gray, L.D. and R.A. Schorn, "High-Dispersion Spectroscopic Studies of Venus. I. The Carbon Dioxide Bands Near I Micron," Icarus 8/3, 409-422 (1968).

106. Guinot, M.B. "Measurements of the rotation of Venus," Compt. Rend. 260, 431-433 (1965).

107. Hanel R.A. et al.,"High spectral resolution interferometric planetary observations in the 7-25 µm region," Planetary Atmospheres, Eds. C. Sagan et al., IAU, 1971, p. 44-47.

108. Hansen, J.E., "Absorption-line formation in a scattering planetary atmosphere: a test of van de Hulst's similarity relations," Astrophys. J. 158, 337-349 (1969).

109. Hansen, J.E., "Information contained in the intensity and polarization of scattered light," Goddard Institute for Space Studies, September 1973, 48 pp.

110. Hansen, J.E. and A. Arking, "Clouds of Venus: evidence for their nature," Science 171, 669-772 (1971).

111. Hansen, J.E. and H. Cheyney, "Theoretical spectral scattering of ice clouds in the near infrared," J. Geophys. Res. 74/13 3337-3346 (1969).

112. Hansen, J.E. and J.W. Hovenier, "Interpretation of the polarization of Venus," J. Atmos. Sci. 31/4,1137-1160 (1974).

113. Hapke, B., "Venus clouds: a dirty hydrochloric acid model," Science 175/4023, 748-751 (1972)(1972, 10.62.211).

114. Hess, S.L., "The hydrodynamics of Mars and Venus," in The Atmospheres of Venus and Mars," Gordon and Breach, New York, 1968, p. 109-131.

115. Hunt, G.E., "Formation of spectral lines in a planetary atmosphere. I. Theory for cloudy atmospheres: application to Venus," J. Quant. Spectrosc. and Radiat. Transfer 12/3, 387-404 (1972).

116. Hunt, G.E., "Formation of spectral lines in a planetary atmosphere. II. Spectroscopic evidence for the structure of the visible Venus clouds," J. Quant. Spectrosc. and Radiat. Transfer.12/3, 405-419 (1972).

117. Hunt, G.E., "Formation of spectral lines in a planetary atmosphere. III. The use of analytic scattering diagrams in computations of synthetic spectra for cloudy atmospheres," J. Quant. Spectrosc. and Radiat. Transfer, 12/8, 1023-1028 (1972).

118. Hunt, G.E., "There is evidence for two scattering layers in the Venus atmosphere," J. Quant. Spectrosc. and Radiat. Transfer 13/5, 465-466 (1973).

119. Hunt, G.E., "Pioneer 10: the preliminary results," New Scientist 61/881, 125-127 (1974).

120. Hunt, G.E. and J.T. Bartlett, "The lower Venus atmosphere," Endeavour 32/115, 39-43 (1973)(1973, 5.62.208).

121. Hunt, G.E. and R.A. Schorn, "Height variations of Venusian clouds," Nature Phys. Sci. 233/37, 39-40 (1971). /95

122. Hunten D.M., "The structure of the lower atmosphere of Venus," J. Geophys. Res. 73, 1093-1095 (1968).

123. Hunten, D.M., "Composition and structure of planetary atmospheres," Space Sci. Reviews 12/5, 539-599 (1971).

124. Hunten, D.M. and R.M. Goody, "Venus: the next phase of planetary exploration," Science 165/3900, 1317-1323 (1969) (1970, 3.62.206).

125. Ingersoll, A.P. and G.S. Orton, "Lateral inhomogeneities in the Venus atmosphere: analysis of thermal infrared maps," Icarus 21/2, 121-128 (1974).

126. Jastrow R. and S.I. Rasool (Eds.), The Venus Atmosphere, Gordon and Breach Science Publishers, 1969, 614 pp.

127. Johnson, F.S., "Origin of planetary atmospheres," Space Sci. Review 9, 303-324 (1969).

128. Kaplan, L.D., "Spectroscopic investigation of Venus," J. Quant. Spectrosc. and Radiat. Transfer 3, 537-539 (1963).

129. Kasahara A. and W. Washington, "NCAR global general circulation model of the atmosphere," Mon. Weather Rev. 95, 389-402 (1967).

130. Kattawar, G.W., G.N. Plass and Ch.N. Adams, "Flux and polarization calculations of the radiation reflected from the clouds of Venus," The Astrophys. J. 170, 171-186 (1971).

131. Kerzhanovich, V.V., M.Ya. Marov and M.K. Rozhdestvensky, "Data on dynamics of the subcloud Venus atmosphere from Venera spaceprobe measurements," Icarus 17/3, 659-674 (1972)(1973, 7.62.172).

132. Kondratyev, K.Ya., Radiation in the Atmosphere, Academic Press, New York and London, 1969, 912 pp.

133. Kondratyev, K.Ya., Radiation Processes in the Atmospheres, WMO Monograph No. 309, Geneva, 1972, 214 pp.

134. Krystanov, L.K., S.V. Todorova and L.G. Yuskesselieva, "Can waterdrops and ice crystals be formed in the Venus atmosphere?" Trans. Bulgarian Acad. Sci. 26/6, 759-760 (1973) (1974, 2.62.172).

135. Kroupenio, N.N., "Some characteristics of the Venus surface," Icarus 17/3, 692-968 (1972)(1973, 7.62.171).

136. Kuiper, G.P., "The atmosphere and cloud layer of Venus," Threshold of Space, M. Zelikoff (ed.), New York, Pergamon Press, 1957, 342 pp.

137. Kuiper, G.P., "Identification of the Venus cloud layer," Comm. Lunar Planet. Lab. 101, 1-21 (1969).

138. Kuzmin, A.D., "The atmosphere of the planet Venus," Radio Sci. 5/2, 339-345 (1970)(1971, 2.62.174).

139. Lacis, A.A. and J.E. Hansen, "Atmosphere of Venus: implications of Venera 8 sunlight measurements," Science 184, 979-982 (1974).

140. Lebedev, L. and S. Nikitin, "Investigation of Venus by automatic stations," Sov. Sci. Rev. 1/2, 98-105 (1970)(1972, 8.62.176)

141. Leovy, C.B., "Rotation of the upper atmosphere of Venus," J. Atmos. Sci. 30/6, 1220-1224 (1973).

142. Lewis, J.S., "Composition and structure of the clouds of Venus," Astrophys. J. 152, L79-L83 (1968).

143. Lewis, J.S., "The atmosphere, clouds and surface of Venus," Scientific American 59/5, 557-566 (1971)(1972, 5.62.219).

144. Lewis, J.S., "Composition of the Venus cloud tops in light of recent spectroscopic data," Astrophys. J. 171, L75-L79 (1972).

145. Lewis, J.S., "Refractive index of aqueous HCℓ solutions and the composition of the Venus clouds," Nature 230, 295-296 (1971).

146. McCleese, D.J., J.S. Margolis and G.E. Hunt, "Laboratory simulation of absorption spectra in cloudy atmospheres," Nature Phys. Sci. 233/40, 102-103 (1971).

147. McElroy, M.B., Sze Nien Dak and Yung Yuk Ling, "Photochemistry /96
of the Venus atmosphere," J. Atmos. Sci. 30/7, 1437-1447 (1973).

148. Margolis, J.S., D.J. McCleese and G.E. Hunt, "Laboratory simulation of diffuse reflectivity from a cloudy planetary atmosphere," Appl. Optics, 11/5, 1212-1216 (1972).

149. Marov, M.Ya., "Venus: a perspective at the beginning of planetary exploration," Icarus 16/3, 415-461 (1972)(1973, 2.62.168).

150. Marov, M.Ya. et al., "Venera 8: measurements of temperature, pressure and wind velocity on the illuminated side of Venus," J. Atmos. Sci. 30/6, 1210-1214 (1973).

151. Marov, M.Ya. and O.L. Ryabov, "On reference model of Venus atmosphere," XVII Plenary Meeting of COSPAR Working Group 7, June 1974, Sao Paulo, Brazil, 48 pp., ill.

152. Monin, A.S. and S.S. Zilitinkevich, "On description of micro- and meso-scale phenomena in numerical models of the atmosphere." Tech. Rep. Japan Meteorol. Agency, No. 67, (Proc. WMO/IUGG Symposium on numerical weather prediction, Tokyo, November 26-December 4, 1968), 1969, 1105-1121.

153. Muhleman, D.O., "Interferometric investigations of the atmosphere of Venus," Radio Sci. 5/2, 355-361 (1970).

154. Murray, B.C. et al., "Venus, atmospheric motion and structure from Mariner 10 pictures," Science 183, 1307-1314 (1974).

155. Newell, R.E. and Ch. Boyer, "Seasonal changes in planetary circulations," Planet. and Space Sci. 20/4, 607-612 (1972).

156. Nikander, J. and Ch. Boyer, "Displacement of the clouds of Venus," Nature 277/5257, 477 (1970).

157. Noll, R.B. and M.B. McElroy, "Engineering models of the Venus atmosphere," AIAA Paper, 1973, No. 130, 11 pp., ill. (1973, 8.62.151).

158. Ohring, G., "High surface temperature on Venus: evaluation of the greenhouse explanation," Icarus 11/2, 171-179 (1969).

159. Ohring, G., "Calculations of the atmospheric temperature profile on Venus," Isr. J. Carth. Sci. 22/1, 1-14 (1973) (1974, 2.62.171).

160. O'Leary, B., "Venus halo: photometric evidence for ice in the Venus clouds," Icarus 13/2, 192-198 (1970).

161. Owen, T. and C. Sagan, "Minor constituents in planetary atmospheres: ultraviolet spectroscopy from theorbiting astronomical observatory," Icarus 16/3, 557-568 (1972)(1973, 2.62. 164).

162. Plummer, W.T., Infrared reflectivity of frost and the Venus clouds," J. Geophys. Res. 74/13, 3331-3336 (1969).

163. Pollack, J.B., "A nongray calculation of the runaway greenhouse: implications for Venus' past and present," Icarus 14/3, 295-306 (1971).

164. Potter, J.F., "On mercury clouds in the atmosphere of Venus," Icarus 17/1, 79-87 (1972).

165. Prinn, R.G., "Photochemistry of HCℓ and other minor constituents in the atmosphere of Venus," J. Atmos. Sci 28/6, 1058-1063 (1971).

166. Prinn, R.G., "Venus atmosphere: structure and stability of the ClOO radical," J. Atmos. Sci 29/5, 1004-1007 (1972).

167. Prinn, R.G., "The upper atmosphere of Venus: a review," Phys. and Chem. Upper Atm., Dordrecht-Boston, 1973, p. 335-344 (1974, 6.62.146).

168. Rasool, S.I., "The structure of Venus clouds-summary," Radio Sci. 5/2, 367 (1970)(1971, 1.62.142).

169. Rasool, S.I., R.W. Stewart, "Results and interpretation of the S-band occultation experiments on Mars and Venus," J. Atmos. Sci. 28/6, 869-878 (1971)(1972, 6.62.206).

170. Rasool, S.I. and C.de Bergh, "The runaway greenhouse and the accumulation of CO_2 in the Venus atmosphere," Nature 226/5250, 1037-1039 (1970)(Gph, 1970, 12A28).

171. Rea, D.G., "The composition of the upper clouds of Venus," Review of Geophys. and Space Phys. 10/1, 369-378 (1972) (1972, 9.62.173). /97

172. Rea, D. and B. O'Leary, "On the composition of the Venus clouds," J. Geophys. Res. 73/20, (1968).

173. Regas, J.L. et al., "Does spectroscopic evidence require two scattering layers in the Venus atmosphere?" J. Quant. Spectrosc. and Radiat. Transfer 13/5, 461-463 (1973).

174. Regas, J.L. et al., "An expanded theoretical interpretation of the Venus 1.05 micron CO_2 line and the Venus 0.8226 micron H_2O line," Astrophys. J. 185/1, Part 1, 383-390 (1973).

175. deRivas, E.K., "Numerical models of the circulation of the atmosphere of Venus," J. Atmos. Sci. 30/5, 763-779 (1973).

176. Robbins, R.C., "The reaction products of solar hydrogen and components of the high atmosphere of Venus -- a possible source of the Venusian clouds," Planet. and Space Sci. 12, 1143-1146 (1964).

177. Roeckner, E. and P. Fabian, "Thermal equilibrium calculations of the lower Venus atmosphere," Beitr. Phys. Atmos. 45/3, 230-243 (1972)(1973, 4.62.203).

178. Sagan, C. (Ed.), Planetary Atmospheres, Dordrecht (Holland), Reidel, 1971, XVIII, 408 pp., ill.

179. Sagan, C. and W.W. Kellog, "The terrestrial planets," Annual Rev. of Astron. and Astrophys. 1, 235-366 (1963).

180. Sagan, C. and G. Mullan, "Earth and Mars: evolution of atmospheres and surface temperatures," Science 177/4043, 52-56 (1972).

181. Sagan, C. and J. Pollack, "Anisotropic nonconservative scattering and the clouds of Venus," J. Geophys. Res. 72, 469-477 (1967).

182. Sasamori, T., "A numerical study of the atmospheric circulation on Venus," J. Atmos. Sci. 28/6, 1045-1057 (1971)(1972, 6.62. 209).

183. Saunders, R.S., L.D. Friedman and T.W. Thomson, "Mission planning for remote exploration of the surface of Venus," AIAA Paper, 1973, No. 580, 11 pp., ill.

184. Schaaf, J.W. and D. Williams, "Optical constants of ice in the infrared," JOSA 63/6, 726-732 (1973).

185. Schorn, R.A. et al., "High dispersion spectroscopic studies of Venus II. The water vapor variations," Icarus 10, 98-104 (1969).

186. Schubert, G. and J.A. Whitehead, "Moving flame experiment with liquid mercury: possible implications for the Venus atmosphere," Science 163, 71-72 (1969).

187. Schubert, G., R.E. Young and J. Hinch, "Direct and reverse motion in a layer of liquid: implications for the thermal diffusion in the atmosphere of Venus," J. Geophys. Res. 72/9, 2126-2130 (1971).

188. Scott, A.H. and E.J. Reese, "Venus: atmospheric rotation," Icarus 17/3, 589-601 (1972).

189. Sill, G.T., "Sulfuric acid in the Venus clouds," Comm. Lunar Planet. Lab. 171, 191-198 (1972).

190. Smith, L.L. and S.H. Gross, "The evolution of water vapor in the atmosphere of Venus," J. Atmos. Sci. 29/1, 173-178 (1972).

191. Snyder, C.W., "Meeting review: the upper atmosphere of Venus," Icarus 15/3, 555-557 (1971).

192. Staley D.O., "The adiabatic lapse rate in the Venus atmosphere," J. Atmos. Sci. 27/2, 219-223 (1970).

193. Stauffer, D. and C.S. Kiang, "Cloud base levels for Jupiter and Venus and the heteromolecular nucleation theory," Icarus 21/2, 129-146 (1974).

194. Stone, P., "Some properties of Hadley regimes on rotating and nonrotating planets," J. Atmos. Sci. 25, 644-657 (1968).

195. Strickland, D.J., "The OI 1304 and 1356 A emissions from the atmosphere of Venus," Laboratory for Atmospheric and Space Physics, Univ. of Colorado. Boulder Colo., 1972, 32 pp. (1973, 12.62.268).

196. Thompson, R., "Venus' general circulation is a merrygoround," J. Atmos. Sci. 27, 1107-1116 (1970).

197. Toon, O.B. and J.B. Pollack, "Physical properties of the /98
stratospheric aerosols," J. Geophys. Res. 78, 7051-7056 (1973).

198. Vinogradov, A.P. et al, "The chemical composition of the atmosphere of Venus," Planetary Atmospheres, IAU Symp. No. 40, Springer-Verlag (New York), 1971, p. 3-16.

199. Weidenschilling, S.J. and J.S. Lewis, "Atmospheric and cloud structure of the Jovian planets," Icarus 20, 465-476 (1973).

200. Whitehill, L.P. and J.E. Hansen, "On the interpretation of the 'inverse phase effect' for CO_2 equivalent widths on Venus," Goddard Institute for Space Studies, New York, N.Y., 1973, 21 pp.

201. Wildt, R., "On the possible existence of formaldehyde in the atmosphere of Venus," Astrophys. J.- 92, 247-255 (1940).

202. Young, A.T., "Are the clouds of Venus sulfuric acid?" Icarus 18, 564-582 (1973).

203. Young, A.T., "Venus clouds: structure and composition," Science 183/4123, 407-409 (1974).

204. Young, L.D.G., "Effective pressure for line formation in the atmosphere of Venus," Icarus 13/3, 449-458 (1970).

205. Young, L.D.G., "High resolution spectra of Venus — a review," Icarus 17, 632 (1972).

206. Young, R.E. and G. Schubert, "Dynamical aspects of the Venus 4-day circulation," Planet and Space Sci. 21/9, 1563-1580 (1973).

207. Young, L.D.G. and A.T. Uoung, "Comment on 'The composition of the Venus cloud tops in light of recent spectroscopic data'," Astrophys. J. 179, L39-L43 (1973).

208. "Sideral messengers," Scientific American 230/5, 59 (1974).

209. "1978 Venus probe," Spaceflight 15/11, 428 (1973).

Meteorology of Jupiter

K. Ya. Kondrat'yev and N.I. Moskalenko

II. Cloud Cover. Lower Layers of Atmosphere

A typical feature of the thick atmosphere of the giant planets (Jupiter, Saturn, Uranus, Neptune), the thickness of which is at least 1000 km [14], is the presence of cloud cover. In this connection, Jupiter can be considered as a characteristic example of the planets of this group. V. Khare and C. Sagan [86] have noted that the celestial bodies of the outer part of the solar system are amazingly red. The reflection spectra in the visible and near IR wavelength regions disclose a noticeable decrease in albedo with shortening of wavelength, in observations of the Galilean satellites, the rings of Saturn and the atmosphere of Jupiter, Saturn and Titan. All these red hued objects can be divided into two categories, corresponding to whether they have atmospheres (Jupiter, Saturn, Titan) or not (Galilean satellites, rings of Saturn). In order to explain the colors of the objects of the first category, the authors of [86] carried out laboratory studies of the transmission spectra of a reddish brown polymer, the primary component of which is aliphatic hydrocarbons, in the wavelength interval from 275.0 to 800.0 nm. /119

The measurements disclose a rapid drop in transmission toward the short wavelengths, in the 300.0-520.0 nm range. This corresponds to a type λ^{-2} dependence of optical thickness due to absorption on wavelength. Thus, with an atmosphere containing a large amount of a similar polymer, a monotonic decrease in albedo should occur with decrease in wavelength. If the content of this kind of polymer is low, after some drop in albedo with decrease in wavelength, an increase in albedo should occur, due to Rayleigh scattering. The polymer film thickness in the experiments mentioned was 0.3 ± 0.2 mm, and the maximum crystal size reached 0.15 mm. This results in an estimate of the absorption coefficient on the order of 10^{-3} cm^{-1}. The similarity of the spectral properties and color of the polymer studied to the analogous properties of the clouds of Jupiter, Saturn and Titan prompt the conclusion to be drawn that these clouds consists of substances of the type of polymer under consideration. Of course, further observations are required to confirm this conclusion, especially in the UV, visible and IR regions of the spectrum. /120

It is interesting that the composition of the polymer mentioned is close to the composition of terrestrial Precambrian deposits (in particular, the presence of amino acids is characteristic of both cases). It also is significant that polymers of the type under consideration can be transparent in the 4000-5000 nm interval. This makes observations to great depths practicable in this transparency window, despite the effect of multiple scattering. The polymer possibly is produced in atmospheres, as a result of

UV synthesis processes and, in particular, this could have occurred on the earth in the period of prebiological evolution.

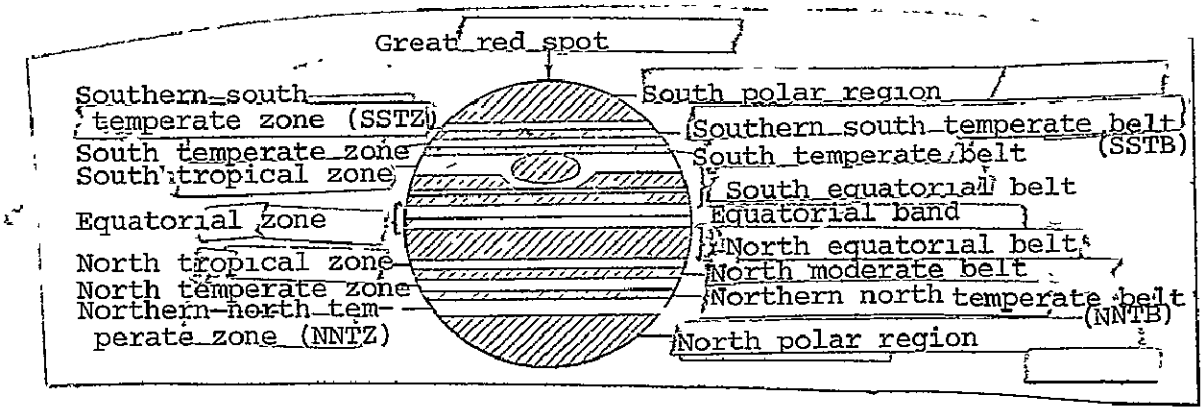

Fig. 2. Schematic representation of cloud cover of Jupiter.

The structure of the global cloud cover of Jupiter has been quite well studied, and it has been described in detail in known monographs [14,22]. A schmatic distribution of the cloud cover with the nomanclature of the belts and zones indicated and the location of the Great Red Spot also indicated, taken from the monograph of V.I. Moroz [14], is represented in Fig. 2.

The present day concepts of the nature and vertical structure of the cloud cover of Jupiter still remain highly contradictory. R.M. Goody [61] illustrated the state of the problem with the following example. If the temperature of the upper boundary of the cloud cover (radiometric data) is assumed to be 160°K and the popular hypothesis that the cloud cover consists of ammonia crystals is used as a basis, the conclusion follows that the ammonia vapor pressure is 2 mm Hg. If the radius of the solid ammonia particles is assumed to be 3000 nm, it is easy to calculate that the scattering coefficient in this case is 10^{-3} m^{-1}. Moreover, according to the data of V.G. Teifel [137-139], interpretation of the measurements of light scattered by Jupiter results in a scattering coefficient on the order of 10^{-7} cm^{-1}. No change whatsoever in the model mentioned is capable of eliminating this discrepancy. Only a hypothesis of a different cloud composition or heterogeneities of their vertical structure can turn out to be promising. /121

The question of the vertical structure of the cloud cover on Jupiter is of great interest. W.B. Street [127] analyzed this question, from the point of view of the phase equilibrium conditions in heterogeneous systems, which the planetary atmospheres are. It is important to keep in mind here that there can be a significant difference in the conditions on the earth group of planets and the giant planets. While, in the first case, investigation of the phase equilibrium in the atmosphere can be accomplished, regardless of processes in the solid crust, in the second, the situation may be completely different, since the solid crust (if it exists) consists of the same components (in the condensed phase) as the atmosphere and the pressure can reach 10^5 atm. In such cases, the phase equilibrium conditions in the deep layers of the atmosphere have to significantly affect the properties of the atmosphere at all altitudes. Therefore, for example, the H_2/He concentration ratio in the outer part of the atmosphere can be determined by the phase equilibrium conditions in its lower layers and not be representative of the entire mass of the atmosphere. R.M. Goody [61] called the atmosphere of Jupiter above the clouds a "passive appendix," the properties of which are determined by the complex interaction of the physical, chemical and dynamic processes in the clouds and underlying layers of the atmosphere.

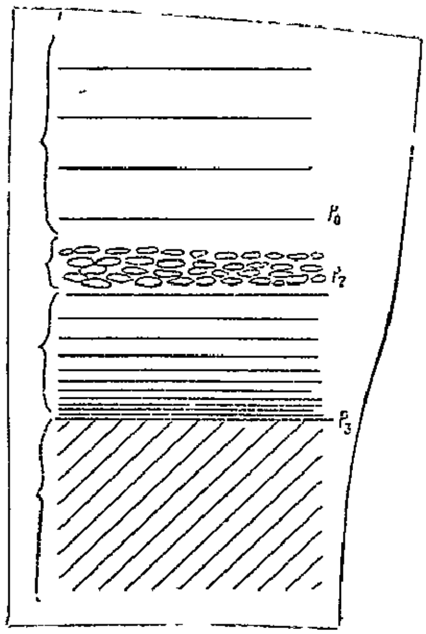

Fig. 3. Schematic vertical structure of isothermal atmosphere, which is a binary H_2-He mixture (a similar structure can exist with a vertical temperature gradient).

Based on extrapolation to high pressures, of measurements of a phase diagram for a H_2-He binary mixture, W.B. Street /122
[127] arrived at the diagram of the vertical structure of this kind of atmosphere represented in Fig. 3. The upper layers of the atmosphere (above the p_0 pressure level) are uniform, and they are characterized by a constant He/H ratio. Clouds of solid, hydrogen enriched matter form near the p_2 level, which "float" in a helium enriched liquid, which is in phase equilibrium with it. A layer of liquid atmosphere is located below the p_2 level, in which the helium content increases with depth. A solid crust of a H-He mixture is below the p_3 level. The p_3-p_0 pressure difference evidently is about 10^5 atm. If the average density in this layer is 0.5 $g \cdot cm^{-3}$, it is approximately 800 km thick. Of course, this model of the vertical structure of the atmosphere is hypothetical. To substantiate the reality of the model, experimental studies of the phase equilibrium of a H-He mixture at high pressure is necessary, first and foremost.

Observation of the brightness and polarization phase curves are a basic source of information on the vertical structure of planetary atmospheres. In the case of such planets as Venus and Jupiter, which have a thick, continuous cloud cover, this kind of observation in the visible and near IR regions of the spectrum enable an opinion to be formed only on the vertical structure of the upper part of the cloud cover. In this case, the theoretical basis of interpretation of observation data is examination of the processes of production of the spectral lines, in the absorbing and anisotropically scattering atmosphere above the clouds and the upper part of the cloud layer (in some studies, the cloud tops are considered to be a reflecting surface; this kind of scheme is called a reflecting layer model -- RLM). An example of the use of the theory of spectral line production in study of the vertical structure of the upper part of the cloud cover of Venus is the work of G.E. Hunt [72-76]. A similar theory was used by G.E. Hunt [77,78], for interpretation of observation data on Jupiter.

G.E. Hunt has the hypothesis that the basic components of the atmosphere of Jupiter are hydrogen, helium and methane as a basis. The presence of ammonia is not considered, in view of the complexity of the corresponding problems, which is determined by the fact that ammonia is probably a component of both the atmosphere and the clouds [90]. M.B. McElroy [97] has described observations of the methane band in the spectrum of Jupiter in detail. Methane has an abundant dipole spectrum, but only the $R-3\nu_3$ branch of the band at 1100 nm was analyzed in detail. J.S. Margolis [93-95] came to the conclusion that the observation data of the $3\nu_3$ band are consistant with the RLM. G.E. Hunt [77,78] noted the incorrectness of this conclusion, which requires reexamination, with /123
consideration of the vertical heterogeneities of the cloud cover. The unsatisfactory nature of the RLM was noted earlier by V.G. Teifel [22].

Molecular hydrogen does not have a dipole moment and, correspondingly, hydrogen does not have a dipole spectrum. However, it has a quadrupole moment and, correspondingly, quadrupole lines. Study of the production of these lines is complicated by the necessity of taking account of the collision line narrowing phenomenon, until normal collision broadening occurs. The lack of accounting for this kind of effect, for example, takes away the justification of the two layer model of the cloud cover, proposed by R.E. Danielson and M.G. Tomasko [45]. Hydrogen increase curves, with collision narrowing taken into account, were first plotted by U. Fink and J.S. Belton [52].

In studying the production of methane lines in the $3\nu_3$ band and the hydrogen quadrupole lines, G.E. Hunt [77,78] proceeded on the basis of the model of the atmosphere of Jupiter represented in Fig. 4 (the cloud layer is noted here by cross hatching). According to the data of F.C. Gilett et al [59], measurements of the emissions of Jupiter at a wavelength of 5000 nm, were the atmosphere is the most transparent, results in a temperature of about 230°K. This should be attributed to the vicinity of the upper

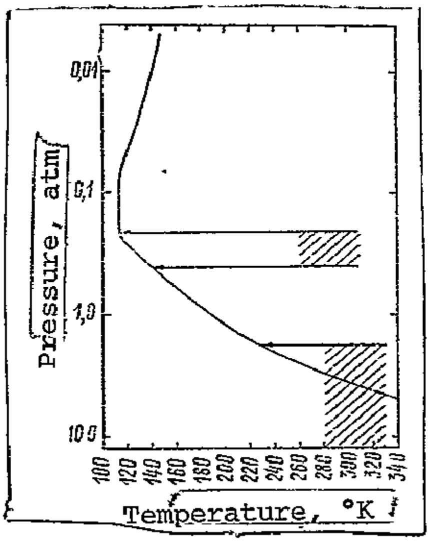

Fig. 4. Vertical temperature profile and cloud cover structure of Jupiter.

boundary of the dense cloud layer. /124 This layer evidently is not always horizontally uniform, since the high temperature (around 310°K) found by J. Westphal [148], from measurements at the same wavelength, can be interpreted as due to breaks in the cloud cover [109]. G.E. Hunt [77,78] used a pressure of 2 atm and a temperature of 240°K, for the upper boundary of the dense cloud cover. It is possible that a second layer of diffuse cloudiness is located above the primary cloud layer, the presence of which should be detected by observations in the visible and IR regions of the spectrum, owing to the partical transparency of the cloud layer under consideration. These clouds probably consist of ammonia crystals (in this connection, F.W. Taylor [136] studied the absorption spectrum of solid ammonia particles in the 2-125 μm wavelength range). G.E. Hunt proposes that the upper boundary of the diffuse cloud layer is at the 0.2 atm and 0.4 atm levels, to which temperatures of 113°K and 140°K correspond (Fig. 4). Since this cloud layer may be highly variable, G.E. Hunt [77,78] carried out calculations of the equivalent line widths, for various models of the cloud cover structure, in the absence of the upper cloud layer, in particular. The basis of the calculation method is reported in the works of G.E. Hunt and I.P. Grant [72] and A. Uesugi and W. Irvine [143]. The cloud scattering indicatrix γ ($\cos\phi$) was assigned by the Hen'ye-Greenstein function

$$\gamma(\cos\theta) = \frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}},$$

where

$$g = \langle\cos\theta\rangle = \frac{1}{2}\int_{-1}^{1}\gamma(\cos\theta)\cos\theta\, d(\cos\theta).$$

It is assumed that the lower layer of clouds consists of particles of radius a=10 μm, the concentration of which is N=20 cm^{-3}, single scattering albedo $\tilde{\omega}_c$=0.95 and <cos ϕ>=0.88 (ϕ is the scattering angle). The parameters of the upper cloud layer are a=1 μm, $\tilde{\omega}_c$=0.995, <cos ϕ>=0.8, and N varies. The change in equivalent width of the R(1) methane line ($3\nu_3$ band of methane at 9050 cm^{-1}), from the center to the edge of the disc of the planet, for various models of the vertical structure of the cloud cover, is represented in Fig. 5. As is evident, the calculation

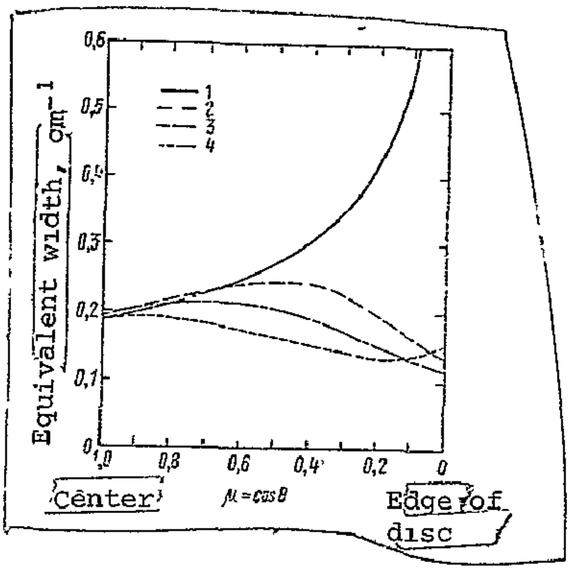

Fig. 5. Change in equivalent width of R (1) line of methane from center to edge of disc of planet: 1. no upper cloud layer; 2. no lower cloud layer (upper layer parameters a=1 μm, N= 5 cm^{-3}, <cos ϕ>=0.8); 3,4. two layer cloud cover, N=10 cm^{-3} and N=20 cm^{-3} for the upper layer, respectively; the following atmospheric composition is used: H_2/He= 6:1; $CH_4/H_2 \sim 7\cdot 10^{-4}$ (the latter estimate was confirmed by the calculations of J.S. Margolis and G.E. Hunt [95]).

results very graphically reveal the effect of the upper cloud layer. If, in the absence of this layer, the increase in equivalent width from the center to the edge of the disc characteristic of the RLM occurs, the appearance of a thin, diffuse layer radically changes the picture, causing a decrease in equivalent width toward the edge of the disc, at small cos ϕ. Particle size and concentration are of great importance here. If N=20 cm^{-3}, the minimum equivalent width occurs at cos $\phi \sim 0.15$ (with the existing resolving power of ground based observations, the situation corresponding to curve 4 should be perceived as the lack of variation in equivalent width from the center to the edge of the disc). /125

Calculations of the level of production of spectral line R (1) with different cloud structures have shown that, in the case of the two layer structure, the line production level at $\mu<0.5$ (near the edge of the disc) rises upward significantly, to the zone of the upper cloud layer. This causes the decrease in equivalent width towards the edge of the disc shown in Fig. 5. The presence of a maximum equivalent width with its change from the center to the edge of the disc can be a criterion of the existence of an upper cloud layer. In this connection, it is significant to note that the spectral line profiles are very much less sensitive to the characteristics of the vertical cloud structure [73-76].

Calculations of the equivalent width of the quadrupole lines of molecular hydrogen seriously complicate the complexity of the problem of the profiles of such lines, which is connected with the necessity of taking account of collision narrowing of the lines. As J.S. Margolis and G.E. Hunt have shown [95], correct accounting for the line spectrum is of great importance in calculations of the equivalent halfwidths. Based on the results of work [95], G.E. Hunt [77,78] undertook calculations of the equivalent width of the (3-0) S (1) hydrogen line, centered at 81.5075 nm. Calculation results, similar to those presented in Fig. 5, are presented

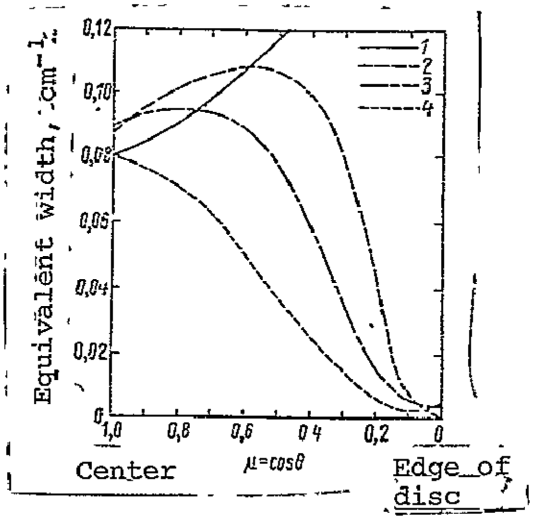

Fig. 6. Change in equivalent width of quadrupole line (3-0) S (1) of hydrogen; designations of curves same as in Fig. 5.

in Fig. 6. As examination of this figure shows, there is a complete qualitative analogy in the variability of the equivalent widths of the methane and hydrogen lines, despite the specific nature of the production of these lines. However, a considerably stronger variability /126
compared with the methane lines, is characteristic of the equivalent width of the hydrogen lines. In particular, the equivalent width curves differ significantly at $N=20$ cm^{-3}.

Thus, the calculation results considered show that the spectroscopic observations of changes in the equivalent widths of the methane and hydrogen lines, from the center to the edge of the disc of the planet (equivalent width phase curves) can be a basis for study of the vertical structure of the cloud cover of Jupiter. Therefore, more reliable quantitative observations of the quadrupole lines of hydrogen and the $3\nu_3$ band of methane, which permit study of their variability over the disc of the planet and over time, could permit determination of the vertical structure of the cloud cover of Jupiter. The scanty qualitative observations presently available still do not permit testing of the adequacy of a given model, by using the theory of the equivalent width phase curves.

However, G.E. Hunt [77] showed that, in the absence of quantitative data on the equivalent width phase curves, observation data for the center of the disc, of lines of various intensities and kinds with a fixed phase angle, can be used for determination of the atmospheric parameters of Jupiter. Such an approach has permitted confirmation of the composition of the atmosphere above the clouds, based on observation data, determined by the mixing ratios $H_2/He=6:1$ and $CH_4/H_2\sim(7\pm1)\cdot10^{-4}$. Analysis of the observation data also indicates that there are two layers of visible cloud cover of Jupiter, which corresponds to the model described above and presented in Fig. 4. The free path length of photons in the upper cloud layer increases from 1 ± 0.1 km at 637.0 nm to 1.9 ± 0.2 at 1000 nm. The following optical parameters of this diffuse layer are in agreement with observation data: continual optical thickness of layer $\tau_c=15\pm1.5$ and single scattering albedo $\tilde{\omega}_c=0.999\pm0.001$ at 636.7 nm; $\tau_c=9\pm1.5$ and $\tilde{\omega}_c=0.999$ (+0.001, -0.0015) at 815.0 nm and 1100 nm. Estimates of the "isotropic" parameters for the entire region of the spectrum under consideration give $\tau_c^*=1.5$-3 and $\omega_c^*=0.996\pm0.003$.

In studies of the terrestrial group of planets, observations of the polarization and interpretation of the polarization phase curves have played an important part. In the case of Jupiter, similar observations are hindered by the small range of phase angles (11.7°) accessible to ground based telescopes. The few polarization observations as a function of wavelength [55] have resulted in an estimate of the molecular optical depth of penetration of light into the atmosphere of $\tau \sim 0.6$ above the north pole and $\tau \sim 0.4$ above the south pole, while $\tau \sim 0.05$ in the equatorial zone. Thus, the atmosphere above the poles of Jupiter turns out to be very much more transparent than above the equator (especially in the bright belts with their thick cloud cover).

After analyzing the polarization phase curve measurements, made at the Main Astronomical Observatory, Academy of Sciences, Ukrainian SSR, A.V. Morozhenko and Ye.G. Yanovitskiy [101] concluded that the information content of such measurement data can be significantly increased by means of observations at different wavelengths. The interpretation of data for 7 spectral intervals in the 373-800 nm range, made in work [101], resulted in values of the index of refraction of the cloud particles $n=1.36 \pm 0.01$ and an average radius of about 200 nm. This index of refraction is in agreement with the hypothesis that the clouds of Jupiter consist of ammonia particles. /127

Of course, the difficulty in obtaining brightness and polarization phase curves of Jupiter from ground measurements is attracting special attention to the possibility of making such measurements from unmanned interplanetary spacecraft, operating as an artificial satellite of Jupiter.

II. General Circulation of Atmosphere

A basic indicator of the general circulation of the atmosphere on Jupiter is the cloud cover pattern. A detailed description of information on the atmospheric currents, obtained from analysis o of photographs of Jupiter, can be found in the books of B.M. Peek [112], V.V. Sharonov [26], V.I. Moroz [14] and V.G. Teifel [22].

1. Cloud Bands

According to available data [83], very intense zonal circulation, with a period of rotation of from 9h49m to 9h59m predominates on Jupiter, in which the shortest period of rotation is characteristic of the equatorial zone. However, in the midlatitudes, strong contrasts in period of rotation at distances of no more than 10° of latitude can be observed.

C.R. Chapman [39] correlated all available data on zonal circulation speed vs. latitude, having discovered its asymmetry relative to the equator. Considerable variability of circulation from year to year and the appearance of anomolously high rates of rotation in the subtropical latitudes from time to time are found. Anticyclonic shear of the bright zones and cyclonic shear of the dark belts are characteristic, but this sort of correlation is not sufficiently distinct. As P.M. Stone showed [126], it also is important that the observed rate of rotation in the extra-tropical latitudes is phasic and not actual.

In the work of G.S. Golitsyn and S.S. Zilitinkevich [5] and the monograph of G.S. Golitsyn [4], based on considerations from similiarity theory, estimates of some circulation parameters in the cloud layer zone were obtained. According to [4], the kinetic energy of motion of parts of the cloud layer is $E \approx 10^{28}$ Merg, where M is the mass of a unit column of that part of the atmosphere, covered by the motions. Estimates of M result in a value on the order of 10^3 $g \cdot cm^{-2}$, i.e., $E \approx 10^{31}$ erg. Considerations from similarity theory lead to the conclusion that the circulation lifetime on Jupiter should be very long. /128

A.P. Ingersoll and J.N. Cuzzi [83] made an effort to explain the atmospheric circulation on Jupiter, based on the concept of geostrophic balance, with a thermal contrast between the dark belts and light zones. In this case, the basic assumption was that the differential rotation is connected with horizontal temperature contrasts, which lessen with depth. (it is considered that the lower layers of the atmosphere rotate as a solid body, with a period of 9h 55m 30s). It was shown in work [83] that this approach is in agreement with available observation data and, also, that the barotropic stability criterion is adequate for Jupiter. If the "driver" of atmospheric circulation on Jupiter is an internal heat source and not differential absorption of solar radiation by the zones and belts, the banded structure of Jupiter means that there is convection, associated with rise of warm masses in the zonal regions and sinking of cold masses in the belts. Thus, the light zones apparently are clouds and the dark, cloudless sections of the atmosphere. A. Barcilon and P.J. Gierasch [33] attempted to substantiate a hypothesis, according to which the banded structure of Jupiter is due to change in concentration of condensed matter with latitude.

P.J. Gierasch [57] proposed a simplified theory of the cloud bands observed on Jupiter, based on examination of instability in the atmosphere (instability is considered a relative state of calm), which can arise as a result of radiation factors in vertical mixing of the horizontally uniform cloud cover. Measurements of the distribution of thermal radiation over the disc of Jupiter, which indicate that the dark belts correspond to maximum radiation, were the experimental basis of the theory (the fact of variability of radiation can be interpreted as the development of significant differences in the energy balance, due to the effect of small components of the atmosphere).

It was shown in work [57] that the mechanism of radiation instability, caused by change in concentration of condensed components of the atmosphere, is responsible for instability phenomena, which have the same wave length and axial symmetry as Jupiter. There also is nonaxisymmetric instability, associated with shorter zonal wavelengths, which are "suppressed" by friction (the amplitude of these waves is at a maximum in the high latitudes). The wave mode structure is in agreement with the conclusion, previously obtained from observation data, that the cloud zones are warmer than the dark belts [148]. /129

The instability mechanism considered does not explain the equatorial jet stream on Jupiter. It is possible that the jet stream is due to the existence of secondary instability, which is responsible for the transport of momentum toward the equator and determines the existence of this stream. If this conclusion is valid, the theory of general circulation of the atmosphere of Jupiter has to be very complicated. Another cause of the complexity of the general circulation phenomena is the fact that, if this theory of instability is adequate, it should make allowance for the mutual dependence of the composition (concentrations of condensible components), energetics and dynamics of the atmosphere. Possible ways of improving the approximate theory is to account for the vertical structure of the atmosphere, radiation heating, friction and other factors. Measurements of the thermal radiation spectra of the planet, with sufficient spatial resolution to distinguish the belts and zones, as well as measurements of the reflected solar radiation spectra (to determine the radiation absorbed by Jupiter) are of great importance. However, it is possible that accounting for the absorbed solar radiation is of secondary importance, if an internal heat source is dominant.

2. General Circulation of Atmosphere

The general circulation patterns of the atmospheres of different planets are essentially specific. Since the general circulation characteristics of the atmospheres of the earth and the sun have been studied most completely at this time, V.P. Starr [122] undertook a study of the general circulation of the atmosphere of Jupiter, with the use of results for the earth and the sun. The dimensions of Jupiter are approximately an order of magnitude greater than those of the earth, but an order of magnitude less than those of the sun. Jupiter rotates twice as fast as the earth, while the rotation rate of the sun is about 3% that of the earth. It can be considered that the atmosphere of Jupiter is very much deeper than that of the earth but, nevertheless, compared with the sizes of the planets, it is a thin shell. Since the axis of rotation of Jupiter is almost normal to the orbital plane, seasonal effects are small, compared with those on the earth (the great distance from the sun and the high albedo of Jupiter also contribute to this). It should be assumed that Jupiter has a solid underlying surface, apparently devoid of orographic irregularities. The most significant irregularity of the relief is that which probably is connected with the existence of the Great Red Spot. V.P. Starr assumes, therefore, that the rotation of the latter coincides with the rotation of the solid crust of the planet. /130

To a certain extent, the source of energy for the atmospheric circulation on Jupiter is absorption of solar radiation, which causes differential heating at the equator and the poles. The rapid rotation of the planet and other factors determine the zonal nature of the circulation. On the other hand, some facts indicate the existence of an intense internal heat source, which is responsible for vertical differential heating. More than that, this heat source evidently is dominant. Although there is no similar heat source on the earth, the nonuniformity of absorption of solar radiation with altitude produces a situation which can be considered similar, in a certain sense. The circulation is determined by the aggregate of the effects of horizontal and vertical differential heating (this situation has not been sufficiently taken into account so far). Such a situation occurs on the sun, where the powerful internal heat source determines the dominant nature of vertical differential heating, but the effect of convection may cause the development of meridional temperature gradients near the surface.

An important feature of the atmosphere of Jupiter is the abrupt jump in zonal wind speed, from a value on the order of 100 $m \cdot sec^{-1}$ in the $\pm 9°$ latitude band, almost to zero outside the equatorial belt, with the exception of narrow zones of a strong west wind around 20-25° latitude. However, they are not as stable as the equatorial jet stream. After deciding on the basic factors which determine the general circulation of the atmosphere of Jupiter, with the use of observation data and theoretical conclusions, V.P. Starr [123] built up a system of meridional circulation.

With the limitations imposed by the laws of conservation of mass, momentum and angular momentum taken into account, he reached the following conclusions: 1. the equatorial acceleration of rotation of the atmosphere cannot be explained by allowing only for axisymmetric motions, if negative viscosity is not assumed; 2. deviations from symmetry in the rotating atmosphere (nonzonal vortex type convection), with the equatorial acceleration, should cause a selective transfer of angular momentum to those particles which move toward the jet stream maximum and "take it away" from particles moving in the opposite direction; 3. the tangential stresses which determine the transfer of angular momentum develop spontaneously, in production of the convective movements mentioned (due to vertical differential heating), which depend on longitude, /131 with appropriate convective cell sizes and other conditions.

Since there are data which indicate that the dark spots on

Jupiter have a statistically maximum frequency of recurrence of wind shear along the zones near the equator (±9° latitude), it can be proposed that these spots are a system of vertical convection cells, which form in a layer of the atmosphere up to 10000 km thick, and which are responsible for the development of great amounts of angular momentum in the equatorial latitude belt. Analysis of some other considerations on general circulation factors and a comparison of general circulation features of the atmospheres of Jupiter, the earth and the sun, lead to the conclusion that a definite analogy with the earth is, in particular, that owing to the effect of large scale turbulence, zones of accumulation of angular momentum (formation of jet streams) develop in the atmosphere of the earth (like that of Jupiter) at ±35° latitude. Their origin can be interpreted in terms of negative turbulent viscosity. There evidently is a similar phenomenon in the atmosphere of the sun. Besides, here, as on Jupiter, there should be some characteristic scales of vertical convection.

The basic problem in understanding the general circulation regularities of the atmosphere on Jupiter and the tropical circulation on the earth is the question of the possibility of existence of ordered circulation, with statistical instability in the atmosphere. In connection with this, G.P. Williams and J.B. Robinson [151] analyzed the problem of circulation in an unstable atmosphere, the results of solution of which were compared with Jupiter observation data. One of the simplest classifications of atmospheric circulation systems is the possibility of examining the baroclinic and convective circulation systems. In the first case the circulation is determined by a horizontal (meridional) potential temperature gradient and horizontal heat transport from a warm region to a cold region. For the second case, the existence of a vertical potential or equivalent potential temperature gradient and upward transfer of heat are characteristic, as the "moving force." If "hybrid" models are taken into account (an example of this kind is the earth), this defines the possibility of a fairly broad class of circulation models.

However, the possibility of the existence of a convective circulation model on the scale of an entire planet has not yet been definitely established (the atmospheric circulations on the earth, Mars and Venus are baroclinic; only the tropical atmosphere of the earth can, to a certain extent, be an example of convective circulation). The substantiation of such a possibility constitutes the main content of work [151]. There apparently /132
is a simple system of planetary convective circulation only on Jupiter and Saturn. In this case, the presence of a dominant internal heat source contributes to this. Evidence of this are the general outlines of circulation on Jupiter and Saturn: 1. axisymmetric band system of planetary cloud cover; 2. strong equatorial jet streams; 3. similar physical parameters (rotation rate, high albedo of about 0.6, small orbital eccentricity). On the other

hand, the specific nature of the conditions of development of circulation are: 1. different orbital inclination to the plane of the ecliptic (3° on Jupiter and 27° on Saturn); 2. Saturn obtains one fourth the solar radiation of Jupiter, but its jet stream is four times stronger.

Since the difference in conditions on Jupiter and Saturn are reduced to divergence in the influx of solar radiation, it follows from this that the dynamics of the atmospheres of these giant planets are not determined by insolation conditions, but by an internal heat source. To substantiate the hypothesis that the atmospheric circulation on Jupiter is due to large scale convective instability, caused by an internal heat source, the regularities of convection in an unstable, rotating atmosphere were studied in work [151], by means of numerical integration of the equations of motion represented in the Bussinex approximation. The quantitative characteristics of convection, considered as the movement of a fluid in a spherical layer of thickness d, were estimated for both laboratory simulation conditions (Benard cells), and with allowance made for the characteristic parameters of Jupiter.

It is assumed that the inner boundary of the spherical layer rotates at constant angular velocity $\Omega=1.76\cdot10^{-4}\,\mathrm{sec}^{-1}$. The inner and outer boundaries are at different constant temperatures, T_1 and T_2, respectively (thus, convection is due to the radial temperature difference $\Delta T=T_1-T_2$). The greater part of the calculations have been done for a hemispherical layer, with boundaries at the equator, through which there is no heat flux. The most realistic conditions on Jupiter correspond to an atmospheric thickness $d<500$ km. Since the results for the 200-500 km thickness range are fairly similar, the greater part of the calculations of circulation were carried out in work [151] for thickness d=50 km, which is considered as representative.

The calculations lead to the conclusion that there is a tropical westerly jet stream on Jupiter, generated by axisymmetric flow, on condition that the atmosphere is comparatively "shallow." With strong diffusion of the tropical jet stream, the west-east transport zone covers the entire equatorial latitude belt. This kind of diffusion can only be the result of large scale nonaxi- /133
symmetric disturbances. The axisymmetric nature of the convective "banks" (i.e., their longitudinal stability) is determined by the latitude variability of the factor $\Omega\cos\theta$ (Ω is the angular velocity of rotation of the planet, θ is the latitude, counted from the poles). Precisely this variability ("differential rotation") suppresses the ordered large scale convection in the latitude zone of over 45°, while convection appears very distinctly at the equator.

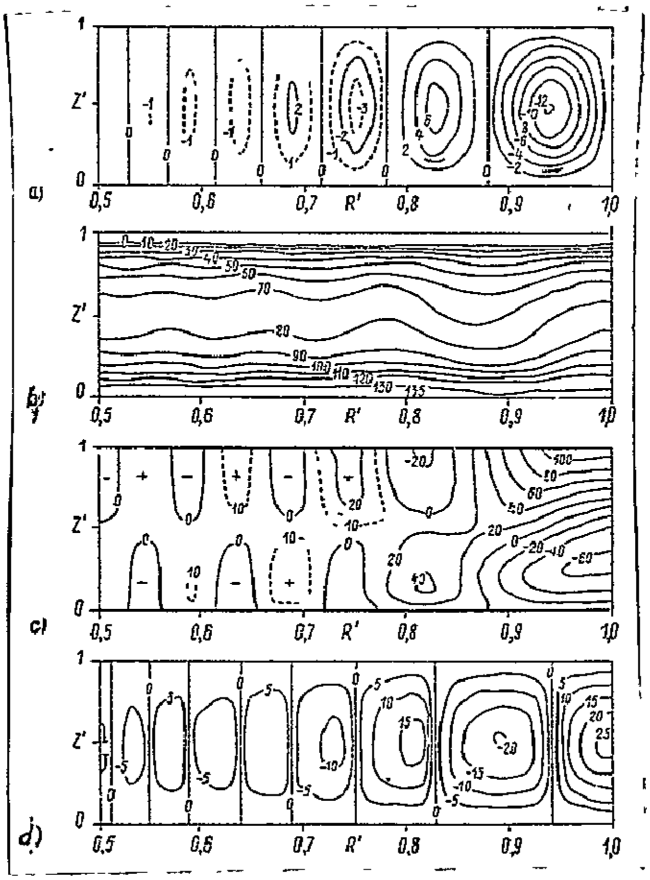

Fig. 7. Current (a), temperature (b), zonal velocity component (c) and vertical velocity (d) field lines for most realistic model of atmosphere of Jupiter.

The results of calculations for the northern hemisphere, of the current (a), temperature (b), zonal velocity component u (c) and vertical velocity w (d) field lines, are presented in Fig. 7, for the case which is considered to be the most realistic and which is characterized by the following basic input parameters $\Delta T=135°K$, $d=50$ km, coefficient of turbulent diffusion for momentum $\nu_V=10^{-3}$ $km^2 \cdot sec^{-1}$, for quantity of heat $\nu_H=m\nu_V$, with $m=10^6$. The values of the Rayleigh; Rossby and Nusselt numbers are $3.5 \cdot 10^9$, $5.4 \cdot 10^{-3}$ and 1.07, respectively. The coordinates in Fig. 7 have the following meanings: $z'=z/d$ is the dimensionless altitude; $R'=\theta/\frac{\pi}{2}$ (θ is the complement of the latitude) is the dimensionless complement of the latitude ($R'=0$ at the pole and $R'=1$ at the equator). /134

The banded circulation structure and the field of the zonal wind speed component (Fig. 7) reproduce the observed features of atmospheric circulation on Jupiter rather well, by bringing out the existence of 5 zones of ascending (w>0) and four belts of descending (w<0) movements, with their characteristic latitudinal zonal transport gradients. The intensity and width of the bands decrease with distance from the equator. There is no ordered, large scale movement in the polar regions, since they are "suppressed" by rotation, but random small scale circulation probably develops here.

Outside the equatorial belts, the velocity components u (horizontal) and w (vertical) are coupled, in such a manner that the equatorial side of the zone (w>0) moves in the direction opposite to the rotation of the planet (u<0), and the polar half moves in the opposite direction (u>0). The reverse is true (but in a less distinctly expressed form) for the belts (w<0). These conclusions correspond to observation data, which indicate the presence of differential rotation within the belts of Jupiter (it should be recalled that, according to P.M. Stone [126], the observed rotation rate of the belts in the extratropical latitudes is phased, and not actual).

The high altitude equatorial jet stream, the speed of which reaches 100 $m \cdot sec^{-1}$ (u>0), is accompanied by a counterflow below it, which has a speed of 60 $m \cdot sec^{-1}$ (Fig. 7c). Between these jet streams and the region of absence of ordered large scale circulation, beginning at 45° latitude, alternating belts of positive and negative zonal flows are located, which are correlated with the band structure of Jupiter. The flows with a positive sign are stronger. Near the lower and upper boundaries of the atmosphere, thermal "boundary" layers form (Fig. 7b), and temperature waves are observed within the atmosphere. The graduated meridional profile of the average vertical velocity defines the existence of distinctly outlined latitude zones of transport of uniform intensity. Calculations, carried out for the purpose of estimating the resistance of the axisymmetric flow to longitudinal disturbances, showed that the most likely geometric shapes of the disturbances are ovals and jets.

The existence of convective cells on Jupiter, with regions of rising and descending movements of equal areas (Fig. 7d) is an indirect indicator of the unimportance of the effect of instability conditions of the second kind in this case. This is an important factor in tropical convection on the earth, connected with the inflow of heat due to the condensation of water vapor, which determines the asymmetry of tropical convection. Regions of rising flows occupy approximately one fifth the area of regions of descending flows [40]. In summarizing the results of numerical modeling of the atmosphere of Jupiter which they carried out, G.P. Williams and J.B. Robinson [151] correctly noted that the weakest point of their work is the provisional model of /135 parameterization of large scale turbulent movement. Further development of the theory of general circulation on Jupiter also requires allowance for the effect of boundary layers, radiation and some other factors.

One of the most interesting and still puzzling manifestations of the general circulation of the atmosphere of Jupiter is the Great Red Spot (a survey of the data on this phenomenon and previously proposed hypotheses of its origin can be found in the monographs of V.I. Moroz [14] and V.G. Teifel [22]). Like other features of the visible structure of the surface of Jupiter, the Great Red Spot (GRS) is a large scale cloud system. Similar cloud systems on earth are either intermittent systems with lifetimes of about 1-2 weeks, which characterize the features of the weather, or quasi-permanent, dependent on the distribution of the continents and oceans.

Since the GRS has existed at least 100 years, it is natural to assume by analogy that it defines a characteristic of the solid underlying surface. However, there are some difficulties with such an explanation: 1. Jupiter possibly does not have a solid surface but, if it exists, it is at a distance of thousands of kilometers under the clouds observed on the earth; 2. the rotation rate of the GRS is variable and less than the stable rate of the magnetic field, which should coincide with the rotation rate of the solid crust of the planet. These circumstances force consideration of a model of circulation of the atmosphere of Jupiter, without accounting for interaction with the underlying surface.

A.P. Ingersoll [82] examined a hydrodynamic model of similar steady state "free flows," which well reproduce many properties of the GRS, as well as of the zones and belts of Jupiter and does not assume any special mechanism resulting in formation of the GRS. In this connection, it was noted in work [82] that, from the point of view of dynamics, the GRS is similar to the zones which, together with the darker belts, are the main features of /136 the axisymmetric banded structure of Jupiter. Analysis of observation data leads to the conclusion that the GRS and the zones are regions of well developed cloud cover, anticyclone vortexes and rising movements, while low and thin cloud cover, cyclonic circulation and descending movements are characteristic of the belts.

By the use of the barotropic vortex equation, A.P. Ingersoll [82] showed that an elliptical system of stream lines can develop as a vortex in the free atmosphere, unconnected with any effect (for example, orographic) of the underlying surface. The lifetime of the GRS should be attributed to the weakness of dissipative processes on Jupiter. A physical factor which maintains the circulation described in the free atmosphere may be differential radiation cooling of the upper and lower stories of clouds. However, the question of the stability of circulation remains confused (under earth conditions, baroclinic flows due to horizontal temperature gradients are unstable). It is possible that, on Jupiter, baroclinic instability is either suppressed or it is expressed in the form of axisymmetric disturbances.

In concluding the discussion of the regularities of circulation of the atmosphere of Jupiter, we recall interesting considerations of the possibility of life on Jupiter, expressed by P.M. Molton [99]. Studies of the moon, Mars and Venus from Soviet and American unmanned interplanetary spacecraft have refuted the extreme optimism as to the possibility of life on these celestial bodies, and they have only left the prospects of further search rather doubtful. In this connection, the possibilities of the discovery of life on Jupiter were discussed in work [99]. According to the hypothetical model of the vertical structure of this planet, alternating layers of crystalline, liquid drop and gaseous ammonia, layers of liquid water drops and water vapor, liquid (or solid) hydrogen, metallic hydrogen and, finally, a metal and silicate core, may be located under the cloud layer observable from the earth. Laboratory experiments have shown that certain organic compounds are produced by coronal discharge in mixtures of methane and ammonia at room temperature and a pressure below 1 atm, which can be transformed into amino acids during hydrolysis. A typical product is a red resin, which has a color like the color of the Great Red Spot of Jupiter. This fact makes possible hypotheses about life on Jupiter. The positive results of analysis of the probability of survival of some species of bacteria under conditions of the atmosphere of Jupiter (at a temperature of 20°C and pressures on the order of 100 atm in the liquid water drop cloud) are evidence in favor of this possibility.

III. Thermal Emission Field

The active growth of studies of the planetary atmospheres, especially by means of interplanetary spacecraft, is arousing great interest in the regularities of formation of the emission fields in the atmospheres, which significantly affect their thermal conditions and dynamics [9-11, 87]. Data on the outgoing thermal emission field are of great importance for estimation of the radiation balance and solution of problems of remote sounding of the atmospheres. Information on the spectral structure and spatial distribution of the thermal emission of planets is necessary for the development and operation of opticalmechanical and electron optic systems, as well as calculation of the radiant heat influxes. /137

Obtaining reliable data on the spectral intensities of the thermal emission at various altitudes and directions in the atmospheres of planets by calculation are especially important, in connection with the fact that measurements are costly and technically difficult to accomplish, in this case. Besides, experimental studies always are limited by the spectral and spatial resolution, working spectral ranges and are occasional in time, place, altitude and observation angle. It is important that calculation methods permit estimation of the effect of each factor, both separately and as a set and, thus, permit the extent of the effect of variability of the state of the atmosphere and underlying surface of a planet to be determined, on the spectral and spatial distribution of the emission field.

While the regularities of production of the thermal emission fields of the earth, Mars and Venus have been studied in sufficient detail, there is no information in the literature, on the spectral and spatial distribution of the outgoing and incoming emissions in the atmosphere of Jupiter. We next consider the results of detailed calculations of the spectral intensities of the incoming and outgoing thermal emmisions at various altitudes and sighting directions, in the atmosphere of Jupiter above the clouds, and some models of the structure of the atmosphere. The basic characteristics of production of the thermal emission fields and the effect of various factors which characterize the state of the atmosphere and the underlying surface on the spectral and spatial structure of the emission field will also be discussed.

As has been noted (Chapter I), the atmosphere of Jupiter consists primarily of hydrogen and helium, but it contains small amounts of ammonia and methane, which apparently determine the optical properties of the atmosphere in the IR region of the spectrum. We now discuss the quantitative characteristics of absorption of IR radiation by the atmosphere of Jupiter.

1. Infrared Absorption Spectrum

In recent years, particular attention has been given to study /138
of the IR absorption spectra of hydrogen, methane and ammonia [29, 46, 52, 60, 93, 94, 113, 134, 136, 139, 140]. Precisely these components in particular cause the greenhouse effect of the atmosphere of Jupiter above the clouds. Methane has a single strong absorption band (at 1306 cm^{-1}), which makes a significant contribution to attenuation of the IR radiation of the atmosphere of Jupiter, and it is of considerable interest, both from the point of view of calculation of the radiation field and solution of the problems of remote sounding of the part of the atmosphere of this planet above the clouds, from spectral measurements of the outgoing thermal emissions. Solution of both of these problems involves the necessity of having available data on the average transmission functions for comparatively broad spectral intervals, which contain many lines, with extended visual pathways in a heterogeneous atmosphere. Direct calculations of the transmission functions in such circumstances is too laborious. The use of a model

representation of the transmission function and approximate allowance for the effect of inhomogeneities of the medium are considerably more expedient.

In order to select an adequate model of the transmission function, F.W. Taylor [134] made a comparison of the results of precise ("line by line") and approximate (for a number of models) calculations, for 20 cm^{-1} wide spectral intervals (this approximately corresponds to the transmission bandwidth of the interference filters), centered on wave numbers 1297, 1250 and 1215 cm^{-1}. Calculations for the mass of the atmosphere above the clouds, in the pressure range from 3 to $4 \cdot 10^{-5}$ atm, showed that the statistical model of Goody best approximates the results of precise calculations (in this case, the line profile is considered Lorentzian). Allowance for the effect of inhomogeneities of the atmosphere can be made by use of the Curtis-Godson approximation.

A. Leupolt [88] made laboratory measurements of the absorption spectrum of ammonia at high pressures (up to 100 atm), for the 32-52 μm wavelength range. A comparison of the measurement data with the results of precise calculations disclosed good agreement.

The subsequently considered results of calculation of the intensities of the incoming $I_\lambda^{\downarrow}$ and outgoing $I_\lambda^{\uparrow}$ radiation were based on the use of the parameters of the spectral transmission functions of methane and ammonia, obtained in works [15-17], for conditions of their broadening by hydrogen and helium.

Calculation of the spectral transmission function for a ray path geometry corresponding to a spherical atmosphere was carried out, with the use of the single parameter equivalent mass method, according to which transmission function τ_λ can be presented in the form /139

$$\tau_\lambda = \exp\left[-\beta_\lambda\left(\int_L \rho(L)\, p(L)^{n_\lambda/m_\lambda}\right)^{m_\lambda}\right],$$

where L is the ray path, ρ(L) and p(L) are the concentration and pressure of the component under consideration, β_λ, m_λ and n_λ are empirical parameters of the transmission function, determined from absorption spectrum measurements. The values of parameters β_λ, m_λ and n_λ of the transmission function of ammonia, with NH_3 broadening by the hydrogen-helium atmosphere, for a number of spectral intervals of the rotational and vibrational-rotational absorption spectra, can be found in works [15,16]. Verification of the accuracy of these data, by means of comparison of the calculated and measured absorption spectra, showed that, with a content $\omega(NH_3) \leq 10000$ atm·cm, $\omega(CH_4) \leq 1000$ atm·cm and temperature T=296°K, the errors in calculation of $\tau_\lambda(CH_4)$ and $\tau_\lambda(NH_3)$ are not over 5-10%. In calculation of the spectral transmission for the atmospheric conditions of Jupiter, the error increases somewhat, due to the effect of the temperature dependence of transmission function τ_λ, which were disregarded in the calculations being considered. The considerable effect of the absorption, induced by collisions of H_2-H_2 and H_2-He molecules, on the transparency of the atmosphere was taken into account, by use of spectral absorption coefficients taken from works [25,85].

2. Calculation Results

For calculation of the spectral, angular and altitude distribution of the thermal emission intensity in the atmosphere of Jupiter above the clouds, a program, based on the calculation scheme presented in [17], was compiled and implemented in a BESM-4 computer. Data on the vertical temperature, pressure and atmospheric gas concentration profiles were loaded in digital form. The atmosphere was divided into 53 isobaric layers, with unequal altitude spacing. In calculations of the spectral intensities of the incoming $I_\lambda^{\downarrow}$ and outgoing $I_\lambda^{\uparrow}$ radiations at different observation altitudes z and zenith sighting angles θ took into account the sphericity of the planet and refraction of the radiation in the atmosphere, as well as the selectivity of the counterradiation of the atmosphere, reflected from the underlying surface.

To make analysis of the results obtained by computer easier, tables were compiled and printed, which characterize the spectral, angular and altitude distributions of thermal emission intensities. The spectral resolution of the calculated intensities was 0.025 μm /140
at $\lambda \leq 3$ μm, 0.05 μm at $3 \leq \lambda \leq 6$ μm, 0.1 μm at $6 < \lambda \leq 20$ μm, 0.5 μm at $20 < \lambda \leq 50$ μm and 2.5 μm at $\lambda > 50$ μm.

Calculations of $I_\lambda^{\uparrow}$ and $I_\lambda^{\downarrow}$ were carried out for five vertical temperature profiles, with different concentration $\rho(CH_4)$ and $\rho(NH_3)$ for zenith sighting angles θ=0°, 30°, 60°, 70°, 75°, 80°, 85°, and 90°, and different observation altitudes z≤150 μm.

Hereafter, we limit ourselves mainly to analysis of regularities of the radiation field in the atmosphere of Jupiter, with the vertical temperature profiles T(z) with the greatest contrast, presented in Table 11 (P(z) is the vertical pressure profile, z is the altitude above the cloud top level).

To calculate the thermal emission intensities for stratifications 1 and 2 of the atmosphere, indicated in Table 2, the bulk concentrations of the gaseous components were assumed to be 0.86578, 0.13214, 0.00062 and 0.00015 for H_2, He, CH_4 and NH_3, respectively. /142
The average radius of the planet at the level of the underlying surface R=69350 km. Figs. 8-11 illustrate some results of calculation of intensities $I_\lambda^{\uparrow}$ and $I_\lambda^{\downarrow}$, in the 4-30 μm wavelength region, for various altitudes and sighting directions in the atmosphere.

TABLE 11. VERTICAL PRESSURE P(z) AND T ($T_{1,2}(z)$) PROFILES

z, km	P (z), atm	T_1 (z) °K	T_2 (z) °K	z, km	P (z), atm	T_1 (z) °K	T_2 (z) °K
0	3,0	266	225	54	0,64	116,3	154
2	2,86	262,5	220	56	0,60	115,8	148
4	2,75	259	215,6	58	0,55	115,2	143
6	2,65	254,8	211,8	60	0,52	115	138
8	2,55	250	206,1	62	0,48	115	130
10	2,4	243	202,3	64	0,44	115,2	125
12	2,3	239	198,7	66	0,38	116	119
14	2,2	236	192,6	68	0,34	117	114
16	2,1	233	187,8	70	0,28	118,2	110
18	1,95	227	182,0	72	0,24	119,5	110
20	1,85	223,4	178,8	74	0,18	120,8	110
22	1,75	218	174,4	76	0,14	123,2	110
24	1,65	215	167,5	78	0,11	125,5	110
26	1,51	210,6	161,3	80	0,096	127,8	110
28	1,39	206	157,7	82	0,090	129,9	110
30	1,4	202	152,5	84	0,084	131,7	110
32	1,25	198	146,0	86	0,083	133,4	110
34	1,15	195,6	141,3	90	0,078	135,1	112
36	1,06	189,2	138,2	95	0,061	136,3	117
38	1,0	187,0	134,7	100	0,050	137,7	120
40	0,96	182	131,2	105	0,038	138,4	125
42	0,92	177	128,8	110	0,032	139,0	128
44	0,88	171	125,9	115	0,021	139,5	133
46	0,82	167	123,5	120	0,010	142,0	138
48	0,78	165	120,0	125	0,009	146,0	143
50	0,73	163	118,8	130	0,007	148,0	146
52	0,70	161	117,2	140	0,005	152,0	146
				150	0,003	158,0	146

[Translator's note: commas in tabulated figures are equivalent to decimal points.]

Characteristic features of production of the radiation fields in the atmosphere of Jupiter are explained by the spectral structure of the transmission function of the atmosphere: strong IR radiation absorption in vibrational-rotational bands of ammonia and methane and pressure induced H_2 bands. There is no doubt that ammonia plays a decisive part in the thermal conditions of Jupiter, just like water vapor in the atmosphere of the earth. The numerous ammonia bands cover a broad region of the spectrum, from 0.8 to 200 μm, and the transparency windows in this ammonia spectrum are overlapped by CH_4 and H_2 absorption bands. In the wavelength region from 2 to 200 μm, even in the vertical direction, the mass of the atmosphere of Jupiter above the clouds is practically opaque, with the exception of a narrow part of the spectrum near λ=4.5 μm. In connection with this, determination of the cloud top temperatures can be carried out, only from measurements of the thermal emissions in the 4.4-4.7 μm wavelength interval [148]. /143

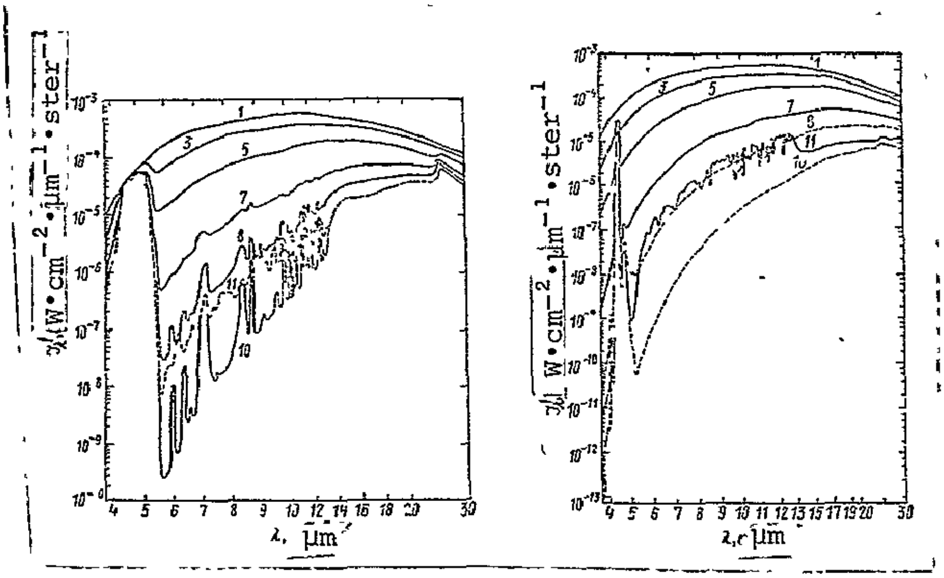

Fig. 8. Spectral distributions of outgoing radiation intensities for stratification 1 of atmosphere of Jupiter in 4-30 μm wavelength region, for sounding altitude z(km): 1. 0; 3. 10.4; 5. 26; 7. 47; 8. 60; 10. 88; 11. 143; a. θ=0°, b. θ(z=0)=90°.

The spectral structure of the incoming $I_\lambda^\downarrow$ and outgoing $I_\lambda^\uparrow$ radiation at altitudes below 50 km appears weakly (Figs. 8,9). With increase in altitude, the maximum intensity of the outgoing radiation $I_\lambda^\uparrow$ is shifted to a longer wavelength region of the spectrum. In the 5-25 m range, the values of $I_\lambda^\downarrow$ and $I_\lambda^\uparrow$ at low altitudes do not depend on zenith angle, and they are practically identical to the black body radiation, at the temperature of the atmospheric layer adjacent to the observation level z. For z<50 km, the angular dependence of the radiation intensity appears only in the 4.3-5.3 μm interval. In this case, the value of $I_\lambda^\uparrow(z,\theta)$ decrease with increase in zenith angle θ, but those of $I_\lambda^\downarrow(z,\theta)$ increase. The minimum $I_\lambda^\downarrow$ and the maximum $I_\lambda^\uparrow$, due to slight absorption of radiation in the atmosphere, are located in the 4.3-5.3 μm interval. The depth of the $I_\lambda^\uparrow$ minimum decreases with increase in sighting angle. In connection with the fact that, at z<50 km, the temperature decreases with altitude, the values of $I_\lambda^\downarrow$ and $I_\lambda^\uparrow$ decrease with increase in altitude.

At altitudes Z>50 km (Figs. 8,10), the spectral structure of the outgoing radiation $I_\lambda^\uparrow$ intensity begins to appear in the entire wavelength region λ<50 μm. In this case, in the altitude range with a negative temperature gradient, the maxima correspond to the transparency windows of the atmosphere and the minimum $I_\lambda^\uparrow$

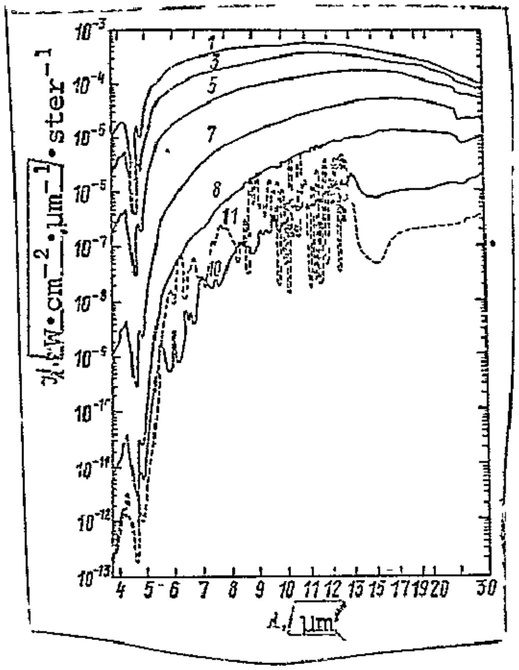

Fig. 9. Spectral distributions of intensity of incoming $I_\lambda^\downarrow$ thermal radiation for stratification 1 of atmosphere of Jupiter in 4-30 μm region, for zenith angle θ(z)= 75° and altitude z, km: 1. 0; 3. 10.4; 5. 26; 7. 47; 8. 60; 10. 88; 11. 11.5.

with the sections of the spectrum with the strongest absorption. The spectral structure of $I_\lambda^\downarrow$ (z,θ) smooths out with increase in zenith sighting angle. The spectral structure of $I_\lambda^\downarrow$ (Fig. 11) is most distinctly expressed at high altitudes, and it corresponds to the variation of the absorption function. The intensity maxima of $I_\lambda^\downarrow$ correspond to sections of the spectrum with the strongest absorption of radiation.

In connection with the greater vertical temperature differences in the atmosphere of Jupiter, the spectral intensities $I_\lambda^{\uparrow\downarrow}$ are subject to strong variations with change in altitude z and zenith angle. They are most distinctly expressed in the intensities of the absorption bands of the shortwave part of the spectrum, where the Planck function depends most strongly on temperature. Thus, for example, in the case of stratification 1, $I_\lambda^\uparrow$ varies within the limits presented in Table 12, with change in altitude z and angle θ. /144

TABLE 12. VARIATIONS OF INTENSITY OF OUTGOING RADIATION DUE TO CHANGE IN TEMPERATURE WITH ALTITUDE AT VARIOUS SIGHTING ANGLES

λ, μm	3,8	4,0	4,6
$I_\lambda^\uparrow$, W·cm^{-2}·μm^{-1}·ster^{-1}	1 10^{-13}—1·10^{-5}	2,5·10^{-12}—1,5·10^{-5}	1,3 10^{-5}—4,5·10^{5}
λ, μm	5,0	5,3	7
$I_\lambda^\uparrow$, W·cm^{-2}·μm^{-1}·ster^{-1}	1 10^{-9}—7 10^{-5}	4·10^{-11}—1,2·10^{-4}	6,5·10^{-9}—2,4·10^{-4}
λ, μm	9,0	11,0	30
$I_\lambda^\uparrow$, W·cm^{-2}·μm^{-1}·ster^{-1}	1,2·10^{-7}—5 10^{-4}	5 5 10^{-7}—5·10^{-4}	6,5 10^{-6}—1 10^{-4}

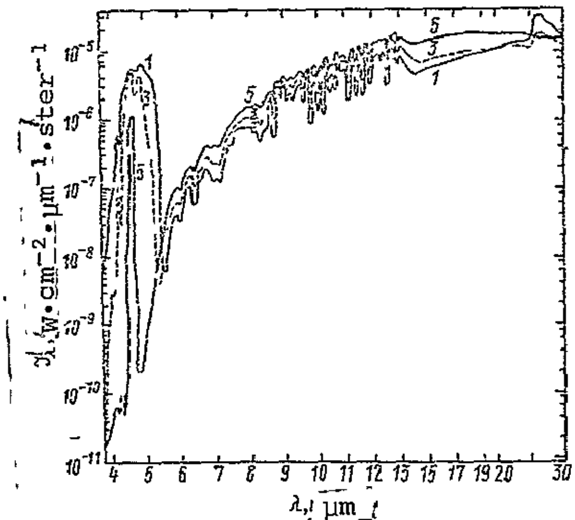

Fig. 10. Spectral intensity $I_\lambda^\uparrow$ of outgoing radiation for zenith sighting angles θ(z= 0): 1. 0°; 3. 75°; 5. 90°.

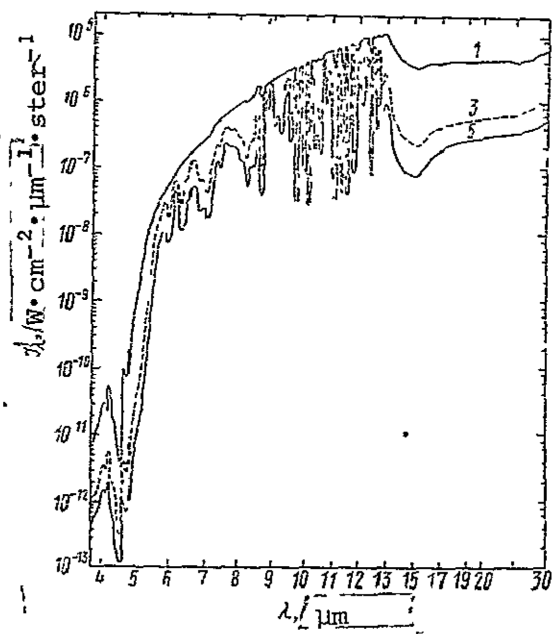

Fig. 11. Spectral intensity $I_\lambda^\downarrow$ of incoming thermal radiation for stratification 2 of atmosphere: zenith sighting angles θ(z): 1. 90°; 3. 75°; 5. 0°; z=115 km.

In the altitude range with a negative temperature gradient (troposphere), the intensity of the outgoing radiation decreases with increase in z but, in the tropopause region, where the vertical temperature profile undergoes inversion, both an increase and a decrease in the radiation intensity $|I_\lambda|$ (see curves 10, 11, Fig. 8), as a function of z and θ, are observed.

Analysis of the results of calculation, made for various vertical temperature profiles and ammonia and methane concentrations, has shown that, under the conditions of Jupiter, just as occurs on the earth, Venus and Mars, the vertical temperature profiles have a decisive effect on formation of the outgoing radiation field. Variations of the spectral albedo A_λ of the clouds appear only in a narrow 4.4-4.8 μm interval. In other sections of the spectrum, the radiation of the underlying surface is completely shielded by the strongly absorbing atmosphere; therefore, the effect of A_λ does not show up in the values of $|I_\lambda|$ at $\lambda > 5$ μm.

From the point of view of the results considered above, the 4.4-4.8 μm and 15-25 μm wavelength intervals, where the absorption of radiation is determined by hydrogen, as well as the 7.5 μm methane band, are the most promising for solution of the problem of thermal sounding of the troposphere of Jupiter. For altitudes z>70 km, sections of the spectrum can be used, which have the /145
strongest absorption of radiation of the vibrational-rotation bands of ammonia in the $7 \leq \lambda \leq 15$ μm range and in the region of the purely rotational spectrum with $\lambda > 30$ μm.

A detailed examination of the prospects of thermal sounding of the atmosphere of Jupiter above the clouds led F.W. Taylor [135] to the conclusion that the greatest vertical span can be ensured, by the use of measurements of the outgoing radiation in five or six sections of the ν_4 band of the methane spectrum at 7.5 μm. Data for the region of strong absorption by ammonia turns out to have little information content. The use of measurements in the 7.5 μm methane band permits sounding to a maximum depth, at the level of about 1 atm. The location of the upper boundary of the layer being sounded depends on the spectral resolution in the center of the band. If the resolution is 20 cm^{-1}, the upper boundary is located at about the 5 mb level, and it rises to the 1 mb level with a resolution of 1 mb [sic]. The use of the pressure induced absorption spectrum of hydrogen permits recovery of the temperatures of three or four layers in the 1 atm-100 mb range.

As was noted above, S.S. Weidenschilling and J.S. Lewis [147] proposed a model of the atmosphere of Jupiter, in which, besides ammonia and methane, the presence of a small amount of water vapor, with a relative bulk concentration $\rho(H_2O) < 10^{-3}$, is assumed. A comparison of the calculated spectra of the incoming and outgoing radiation intensities, for dry and moist conditions of the atmosphere of Jupiter, showed that the effect of water vapor on intensities $I_\lambda^{\downarrow}$ and $I_\lambda^{\uparrow}$ are manifested only in the region of the 4.4-4.5 μm and 2.5-2.9 μm ammonia transparency windows. An increase in atmospheric moisture results in an increase in intensity of the incoming radiation $I_\lambda^{\downarrow}$ and a decrease in intensity of the outgoing radiation $I_\lambda^{\uparrow}$. In other regions of the spectrum, the water vapor bands are overlapped by strong bands of other gaseous components. Therefore, the effect of water vapor on the transport of thermal radiation only appears very slightly.

Conclusion

The increasing interest in recent years in studies of Jupiter and the successful accomplishment of the scientific programs of Pioneer 10 and 11 contributed to a considerable expansion and deepening of our ideas of the nearest Jovian planet to the earth. Models of the atmosphere above the clouds and of the macro- and microstructure of the cloud cover of Jupiter have been developed, which apparently can be considered fairly realistic. There is /146 great interest in the results of theoretical studies of the general circulation of the atmosphere on this rapidly rotating Jovian planet with an internal heat source. Study of the regularities of the unusual global convection will undoubtedly contribute to a better understanding of the characteristics of tropical circulation on the earth. Studies of the radiation field of Jupiter are of great importance. They will permit more reliable estimation of the radiation balance of the planet, as well as of the prospects of remote sounding of the atmosphere.

Despite substantial progress in study of Jupiter, much remains puzzling on this planet. In particular, this concerns the inner portion of the atmosphere and the core of Jupiter (a detailed discussion of the basic problems of the study of Jupiter can be found in the monograph of V.G. Teifel [22]). Experience in study of Venus and Mars has shown that the most effective means of studies is spacecraft, functioning as artificial satellites of the planet, from which remote reading of the atmospheric and surface parameters and, in particular, direct measurements from descent vehicles are accomplished.

There is no doubt that only spacecraft will give final answers to questions as to the composition and structure of the atmosphere of Jupiter (including its entire thickness and the cloud cover), and will permit discovery of the physical factors which determine the general circulation of the atmosphere.

H.G. Winkler et al [152] have discussed the interrelated questions of the scientific program and technical accomplishment of entry into the atmosphere of Jupiter by unmanned interplanetary spacecraft, for direct measurements of the parameters of the atmosphere, right down to the lower boundary of the cloud cover (where the pressure reaches 17 atm and the temperature, 425°K) and remote sounding of the underlying layers of the atmosphere. The basic requirements, subject to mutual agreement, are the following: 1. spacecraft launches in 1978 and 1980 and, on the Grand Tour, in 1979; 2. the use of Pioneer type spacecraft; 3. the use of direct and relay communications lines; 4. entry into the atmosphere on the night or day side. One of the most important technical problems is the development of heat insulation, since the speed of entry into the atmosphere is about 48 $km \cdot sec^{-1}$.

The basic goals of the scientific program should be studies of: 1. the chemical and isotope composition of the atmosphere; 2. cloud temperature, composition and structure; 3. the possibilities of existence of complex organic compounds; 4. the nature of the compounds which color the clouds. The authors of [152] characterized the set of equipment which can be used to solve the problems listed (temperature and pressure sensors, mass spectrometers, radiometers for various wavelength ranges, etc.). From the point of view of selection of a spacecraft point of entry, moderate latitudes and longitudes, ±70° relative to the sun, are /147 preferable (the latter is necessary to ensure successful functioning of the solar batteries). Of course, the equipment has to be capable of functioning under the environmental conditions on Jupiter. Data are presented in work [152] concerning calculation of the spacecraft trajectory, communications lines and possible combinations of the basic parameters which determine the conditions of launch and accomplishment of the entire mission.

Of course, the Jupiter spacecraft project described by the authors of [152] is only one possible alternate version. There is no doubt, however, that just the use of spacecraft will ensure new, most significant progress in studies of Jupiter.

References

1. Avramchuk, V.V., "Results of observation of absorption bands of methane (619.0 nm) and ammonia (644.1 and 647.8 nm) on the disc of Jupiter," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, Moscow, 1972, p. 439-443.

2. Aksenov, A.N., Z.N. Grigor'yeva, V.G. Teifel' and G.A. Kharitonova, "Study of characteristics of molecular absorption in the spectrum of Jupiter," Ibid., p. 433-438.

3. Bronshten, V.A. (ed), Issledovaniya planety Yupiter [Studies of the Planet Jupiter], Nauka Press, Moscow, 1967, 90 pp.

4. Golitsyn, G.S., Vvedeniye v dinamiku planetnykh atmosfer [Introduction to the Dynamics of Planetary Atmospheres], Gidrometeoizdat Press, Leningrad, 1973, 104 pp.

5. Golitsyn, G.S. and S.S. Zilitinkevich, "Estimates of global characteristics of the circulation of planetary atmospheres with various hypotheses on the nature of dissipation," Izv. AN SSSR. Fizika atmosfery i okeana 8/8, 785-798 (1972).

6. Yefanov, V.A., A.G. Kislyakov, I.G. Moiseyev and A.I. Naumov, "Radio emissions of Venus and Jupiter at 2.25 and 8 mm," Astronom. zhurn. 46/1, 147 (1969).

7. Kuiper, G.P., "Survey of the atmospheres of planets," in the collection Atmosfery Zemli i planet [Atmospheres of the Earth and Planets], G.P. Kuiper (ed), Foreign Literature Publishing House, Moscow, 1951, p. 341-386.

8. Kondrat'yev, K.Ya., Sputnikovaya klimatologiya [Satellite Climatology], Gidrometeoizdat Press, Leningrad, 1971, 64 pp.

9. Kondrat'yev, K.Ya., Sravnitel'naya meteorologiya planet [Comparative Meteorology of the Planets], Gidrometeoizdat Press, Leningrad, 1975.

10. Kondrat'yev, K.Ya. and A.M. Bunakova, Meteorologiya Marsa [Meteorology of Mars], Gidrometeoizdat Press, Leningrad, 1973, 62 pp.

11. Kondrat'yev, K.Ya. and V.N. Konashenok, "Theoretical foundations of the meteorology of planetary atmospheres," collection of articles Problemy fiziki atmosfery [Problems of the Physics of the Atmosphere], Leningrad State Univ. Press, 1970, No. 8, p. 142-161.

12. Kondrat'yev, K.Ya. and N.I. Moskalenko, "Basic characteristics of production of the thermal emission fields in the atmosphere of Jupiter," Doklady AN SSSR 221/3, (1974).

13. Kuz'min, A.D., A.P. Naumov and T.V. Smirnova, "Estimate of the ammonia content of the atmosphere of Jupiter above the clouds from radioastronomy observations," Astron. vestnik 6/1, 13-18 (1972).

14. Moroz, V.I., Fizika planet [Physics of the Planets], Nauka Press, Moscow, 1967, 496 pp.

15. Moskalenko, N.I., "Spectral transmission functions in some infrared H_2O as well as CO and CH_4 bands," Izv. AN SSSR. Fiz. atmosf. i okeana 4/7, 777-780 (1968).

16. Moskalenko, N.I., O.V. Zotov and S.O. Mirumyants, "Absorption of infrared radiation by ammonia in the 0.8-25 µm spectral region," Izv. AN SSSR. Fiz. atmosf. i okeana 8/4, 477-479 (1972).

17. Moskalenko, N.I. and A.O. Zakirova, "Calculation of spectral, angular and altitude distribution of thermal emission field of the atmosphere and surface of the earth," Izv. AN SSSR. Fiz. atmosf. i okeana 8/8, 829-842 (1972). /148

18. Pariyskiy, Yu.N., "The atmosphere of Jupiter from radio observations," Astronom. zhurn. 48/1, 163-165 (1971).

19. Rubashev, B.M., Problemy solnechnoy aktivnosti [Problems of Solar Activity], Nauka Press, Moscow-Leningrad, 1964, 362 pp.

20. Soboleva, N.S. and Yu.N. Pariyskiy, "Results of observations of Jupiter in the centimeter range," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, Moscow, 1972, p. 449-451.

21. Teifel', V.G., "Molecular absorption of light in the atmosphere of Jupiter and surface structure of the cloud layer of the planet," in the collection Issledovaniya planety Yupiter [Studies of the Planet Jupiter], Nauka Press, Moscow, 1967, p. 3-20.

22. Teifel', V.G., Atmosphera planety Yupiter [Atmosphere of the Planet Jupiter], Nauka Press, Moscow, 1969, p. 182.

23. Teifel', V.G., (ed), Fizicheskiye kharakteristiki planet-gigantov [Physical Characteristics of the Jovian Planets], Nauka Press, KazSSR, Alma-Ata, 1971.

24. Teifel', V.G., "Present state and problems of study of the Jovian planets," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, Moscow, 1972, p. 426-430.

25. Filimonov, V.N., "Induced absorption of infrared radiation by molecules," Usp. fiz. nauk 69/4, 565-590 (1959).

26. Sharonov, V.V., Priroda planet [The Nature of the Planets], Fizmatgiz Press, Moscow, 1958, 552 pp.

27. Shisho, Sh., Planeta Yupiter [The Planet Jupiter], Mir Press, Moscow, 1970.

28. Adcock, B.S., "Determination of longitude of features in the atmosphere of Jupiter," J. Atmos. Sci. 24/2, 23-25 (1971).

29. Anderson, R.C., S.G. Pipes, A.L. Broadfoot and L. Wallace, "Spectra of Venus and Jupiter from 1800 to 3200 A," J. Atmos. Sci. 26/5, Part I, 874-888 (1969).

30. Arnold, H.J.P., "Mission to Jupiter," The British J. Photogr., 30 November and 7 December 1973.

31. Aumann H., C.M. Gillespie and F.J. Low, "The internal powers and effective temperatures of Jupiter and Saturn," Astrophys. J. 157, L 69 (1969).

32. Axel, L., "Inhomogeneous models of the atmosphere of Jupiter," Astrophys. J. 173, 451-468 (1972).

33. Barcilon, A. and P. Gierasch, "A moist Hadley cell model for Jupiter cloud bands," J. Atmos. Sci. 27/4, 550-560 (1970).

34. Barrow, C.H., "Decametre-wave radiation from Jupiter and solar activity," Planet and Space Sci. 20/12, 2051-2056 (1972).

35. Beer, R., C.B. Farmer, R.H. Norton, J.V. Martonchik and T.G. Barnes, "Jupiter: observation of deuterated methane in the atmosphere," Science 175/4028, 1760-1761 (1972).

36. Bergstrahl, J.T., "Methane in the Jovian atmosphere. II. Absorption line formation," Icarus 19/3, 390 (1973).

37. Carlson, R.W., J.C. Bhattacharya, B.A. Smith, T.V. Johnson, B. Hidayat, S.A. Smith, G.E. Taylor, B. O'Leary and R.T. Brinkmann, "An atmosphere of Ganymede from its occultation of SAO 186800 on 7 June 1972," Science 182/4107, 53-55 (1973).

38. Cess, R.D. and S. Khetan, "Radiative transfer within the atmospheres of the major planets," J. Quant. Spectr. Radiat. Transfer 13/10, 995-1010 (1973).

39. Chapman, C.R., "Jupiter's zonal winds: variation with latitude," J. Atmos. Sci. 26/5, Part I, 986-990 (1969).

40. Charney, J.G., "Tropical cyclogenesis and the formation of the intertropical convergence zone," Mathematical Problems in Geophysical Sciences, W.H. Reid, Ed., Amer. Mathem. Soc. Providence, R.I., 1970, p. 355-368.

41. Coffeen, D.L., "Pioneer 10 observations of Jupiter: an appeal for ground-based coverage," Icarus 20, 52-53 (1973).

42. Cook, W.S., "Engineering models for Jupiter's troposphere and /149
NH_3-H_2O cloud systems," AIAA Paper 129, 1973, 7 pp., ill.

43. Cruikshank, D.P. and A.B. Binder, "Minor constituents in the atmosphere of Jupiter," Astrophys. and Space Sci. 3/3 (1969).

44. Cuzzi, J.N. and D. Van Blerkom, "Microwave brightness of Saturn's rings," Icarus 22/2, 149-158 (1974).

45. Danielson, R.E., M.G. Tomasko, "A two-layer model of the Jovian clouds," J. Atmos. Sci. 26/5, Part I, 889-897 (1969).

46. Encrenaz, T., D. Gautier, L. Vapillon and J.P. Verdet, "The far infrared spectrum of Jupiter," Astron. Astrophys. 11, 431-449 (1971).

47. Eshelman, R., "The radio occultation method for study of planetary atmospheres," Planet. and Space Sci. 21/9, 1521-1531 (1973).

48. Evans, D.C., A. Boggess and R. Scolnik, "The reflectivity of Venus and Jupiter in the middle ultraviolet," Astron. J. 70/5, (1965).

49. Evans, D.S. and W.B. Hubbard, "Discrepancies in measurements of the Jupiter atmospheric scale height," Nature Phys. Sci. 240/103, 162 (1972).

50. Farmer, C.B., "An estimate of line width and pressure from the high resolution spectrum of Jupiter at 11000 A," J. Atmos. Sci. 26/5, Part I, 860-861 (1969).

51. Ferrin, I.R., "Saturn's rings. I. Optical thickness of rings A.B.D. and structure of ring B," Icarus 22/2, 159-174 (1974).

52. Fink, U. and J.S. Belton, "Collision-narrowed cruves of growth for H_2 applied to new photoelectric observations of Jupiter," J. Atmos. Sci. 26/5, Part I, 952-962 (1969).

53. French, R.G. and P.S. Gierasch, "Waves in the Jovian upper atmosphere," J. Atmos. Sci. 31/6, (1974).

54. Fun-Min Wu, Ch.L. Beckel, M. Shafi and Ch.L. Hyder, "Possible H_2+ ultraviolet spectrum of Jupiter," Icarus 22/2, 220-224 (1974).

55. Gehrels, T., "Photopolarimetry of planets and stars," Vistas in Astronomy 15, 113-129 (1973).

56. Gehrels, T., "The flyby of Jupiter," Sky and Telesc. 47/2, 76-78 (1974).

57. Gierasch, P.S., "Jupiter's cloud bands," Icarus 19/4, 482-494 (1973).

58. Gierasch, P.J. and R.M. Goody, "Radiative time constants in the atmosphere of Jupiter," J. Atmos. Sci. 26/5, Part I, 979-980, (1969).

59. Gilett, F.C., F.J. Low and W.A. Stein, "The 2.8-14 micron spectrum of Jupiter," Astrophys. J. 157, 925-934 (1969).

60. Gille, J.C. and T.H. Lee, "The spectrum and transmission of ammonia under Jovian conditions," J. Atmos. Sci. 26, 932-940 (1969).

61. Goody, R.M., "The atmospheres of major planets," J. Atmos. Sci 26/5, Part I, 997-1001 (1969).

62. Goody, R.M. and J.C.C. Walker, Atmospheres, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1972, 150 pp.

63. Greenspan, J.A. and T. Owen, "Jupiter's atmosphere, its structure and composition," Science, 156/3781, (1967).

64. Gross, S.H., "The atmosphere of Titan and Galilean satellites," J. Atmos. Sci. 31/5 1413-1420 (1974).

65. Gross, S.H. and S.I. Rasool, "The upper atmosphere of Jupiter," Icarus 3/4, 311-322 (1964).

66. Haffner, J.W., "The magnetospheres of Jupiter and Saturn," AIAA Paper 30, 1971, 8 pp., ill.

67. Hall, Ch.F, "Pioneer 10," Science 183/4122, 301-302 (1974).

68. Hall, J.S. and L.A. Roley, "Polarization measurements of Jupiter and Saturn," J. Atmos. Sci. 26/5, Part I, 920-923 (1969).

69. Hide, R., "Dynamics of the atmospheres of the major planets with an appendix on the viscous boundary layer at the rigid bounding surface of and electrically-conducting rotating fluid in the presence of a magnetic field," J. Atmos. Sci. 26/5, Part I, 841-853 (1969). /150

70. Hobbs, R.W. and S.L. Knapp, "Planetary temperature at 9.55 mm wavelength," Icarus 14/2, 204-209 (1971).

71. Hogan, J., S.I. Rasool and T. Encrenaz, "The thermal structure of the Jovian atmosphere," J. Atmos. Sci. 26/5, Part I, 898-905 (1969).

72. Hunt, G.E. and I.P. Grant, "Discrete space theory of radiative transfer and its application to problems in planetary atmosphere," J. Atmos. Sci. 26/5, Part I, 963-972 (1969).

73. Hunt, G.E., "Formation of spectral lines in a planetary atmosphere. I. Theory for cloudy atmospheres: application to Venus," J. Quant. Spectrosc. and Radiat. Transfer 12/3, 387-404 (1972).

74. Hunt, G.E., "Formation of spectral lines in a planetary atmosphere. II. Spectroscopic evidence for the structure of the visible Venus clouds," J. Quant. Spectrosc. and Radiat. Transfer 12/3, 405-419 (1972).

75. Hunt, G.E., "Formation of spectral lines in a planetary atmosphere. III. The use of analytic scattering diagrams in computations of synthetic spectra for cloudy atmospheres," J. Quant. Spectrosc. and Radiat. Transfer 12/8, 1023-1028 (1972).

76. Hunt, G.E., "There is evidence for two scattering layers in the Venus atmosphere," J. Quant. Spectrosc. and Radiat. Transfer 13/5, 465-466 (1973).

77. Hunt, G.E., "Interpretation of hydrogen quadrupole and methane observations of Jupiter and the radiative properties of the visible clouds," Mon. Nat. Roy. Astron. Soc. 161, 347-363 (1973).

78. Hunt, G.E., "Formation of spectral lines in planetary atmosphere. IV. Theoretical evidence for structure of the Jovian clouds from spectroscopic observations of methane and hydrogen quadrupole lines," Icarus 18, 637-648 (1975).

79. Hunt, G., "Pioneer 10: the preliminary results," New Sci. 61, 881, 125-127 (1974).

80. Hunten, D.M., "The upper atmosphere of Jupiter," J. Atmos. Sci. 26/5, Part I, 826-834 (1969).

81. Hunten, D.M., "The escape of H_2 from Titan," J. Atmos. Sci. 30/4, 726-732 (1973).

82. Ingersoll, A.P., "Jupiter's Great Red Spot: a free atmosphere vortex?," Science 182/4119, 1346-1348 (1973).

83. Ingersoll, A.P. and J.N. Cuzzi, "Dynamics of Jupiter's cloud bands," J. Atmos. Sci. 26/5, Part I, 981-985 (1969).

84. Jenkins, E.B., "Far-ultraviolet spectroscopy of Jupiter," Icarus 10/3, 379-385 (1969).

85. Ketelaar, J.A., "Infrared spectra of compressed gases," Spectrochm. Acta 14/2, 237-248 (1957).

86. Khare, B.N. and C. Sagan, "Red clouds in reducing atmospheres," Icarus 20/3, 311-321 (1973).

87. Kondartyev, K.Ya., "Radiation Processes in the Atmosphere," WMO Monograph No. 309, Geneva, 1972, 214 pp.

88. Leupolt, A., "Absorption by ammonia in the 40 μm wavelength range," Infrared Physics 14/2, 99-126 (1974).

89. Levin, G.M., "The Jovian turbopause probe -- a first step in probing the atmosphere of Jupiter," AIAA Paper 833, 1971, 7 pp., ill.

90. Lewis, S.S., "The clouds of Jupiter and the NH_3-H_2O and NH_3-H_2S systems," Icarus 10/3, 365-378 (1969).

91. Lewis, J.S. and P.G. Prinn, "Jupiter's clouds: structure and composition," Science 169, 472-473 (1970).

92. Liller, W., J.L. Elliot, J. Veverka, L.H. Wasserman and C. Sagan, "Theoccultation of Beta Scorpii by Jupiter. III. Simultaneous high time -- resolution records at three wavelengths," Icarus 22/1, 82-104 (1974).

93. Margolis, J.S., "Studies of methane absorption in the Jovian atmosphere. III. The reflecting layer model," Astrophys. J. 167, 559-568 (1971). /151

94. Margolis, S.S. and K. Fox, "Extension of calculations of rotational temperature and abundance of methane in the Jovian atmosphere," J. Atmos. Sci. 26/5, Part I, 862-864 (1969).

95. Margolis, J.S. and G.E. Hunt, "On the level of H_2 quadrupole absorption in the Jovian atmosphere," Icarus 18/4, 593-598 (1973).

96. Maxworthy, T., "A review of Jovian atmospheric dynamics," Planet. and Space Science 21/4, 623-642 (1973).

97. McElroy, M.B., "Atmospheric composition of the Jovian planets," J. Atmos. Sci. 26/5, Part I, 798-912 (1969).

98. McGovern, W.E. and S.D. Burk, "Upper atmospheric thermal structure of Jupiter with convective heat transfer," J. Atmos. Sci. 29/1, 179-189 (1972).

99. Molton, P.M., "Exobiology, Jupiter and life," Spaceflight 14/6, 220-223 (1972).

100. Moroz, V.I. and D.P. Cruikshank, "Distribution of ammonia on Jupiter," J. Atmos. Sci. 26/5, 865-869 (1969).

101. Morozhenko, A.V. and E.G. Yanovitskii, "The optical properties of Jovian Planets. I. Atmosphere of Jupiter according to polarimetric observations," Icarus 18/4, 583-592 (1973).

102. Newburn, R.L., Jr., W.S. McDonald, R.L. Gâsteiger and A.R. Eisenman, "Why go to the outer planets," Astronaut. and Aeronaut. 8/9, 39-44 (1970).

103. Newburn, R.L., Jr. and S. Gulkis, Space Science Rev. 3, 179 (1973).

104. Öpik, E., "Jupiter: chemical composition, structure and origin of giant planet," Icarus 1/3, 200-257 (1962).

105. Owen, T., "The atmosphere of Jupiter," Science 167/3926, 1675-1681 (1970).

106. Owen, T., "The outer solar system: perspectives for exobiology," Orig. Life 5/1-2, 41-55 (1974).

107. Owen, T. and H.P. Mason, "New studies of Jupiter's atmosphere," J. Atmos. Sci. 26/5, (1969).

108. Owen, T. and H.P. Mason, "The spectra of Jupiter and Saturn in the photographic infrared," Icarus 10/3, 355 (1969).

109. Owen, T. and J.A. Westphal, "The clouds of Jupiter: observational characteristics," Icarus 16/2, 392-396 (1972).

110. Oya, H., "Origin of Jovian decameter wave emissions -- conversion from the electron plasma wave to the ordinary mode electromagnetic wave," Planet. and Space Science 22/5, 687-708 (1974).

111. Pearce, J.B., A.L. Lane, K.K. Kelly and C.A. Barth, "Mariner 6 and Mariner 7 ultraviolet spectrometer: in flight measurements of simulated Jupiter atmosphere," Science 172/3986, 941-943 (1971).

112. Peek, B.M., The Planet Jupiter, Faber and Faber, London, 1958, 283 pp.

113. Phillips, P.G. and D.A. Briotta, Jr., "Hadamard transform spectrometry for the atmospheres of Earth and Jupiter," Appl. Opt. 13/10, 2233-2236 (1974).

114. Pilcher, C.B., R.G. Prinn and T.B. McCord, "Spectroscopy of Jupiter: 3200 to 11 200 A," J. Atmos. Sci. 30/2, 702-707 (1973).

115. Podolak, M. and A.G.W. Cameron, "Models of the giant planets," Icarus 22/2, 123-148 (1974).

116. Price M.J., J.S. Hall, P.B. Boyce and R. Albrecht, "The physical properties of the Jovian atmosphere inferred from eclipse of the Galilean satellites. II. 1971 apparition," Icarus 17/1, 49-56 (1972).

117. Prinn, R.G., "Jupiter's clouds structures and composition," Science 169/3944, 472-473 (1970).

118. Reeves, H. and Y. Bottinga, "The D/H ratio in Jupiter's atmosphere," Nature 238/5363, 326-327 (1972).

119. Sagan, C. and G. Mullen, "The Jupiter greenhouse," Icarus /152
16/2, 397-400 (1972).

120. Shimizu, M., "The upper atmosphere of Jupiter," Icarus 14, 273-281 (1971).

121. Stansberry, K.G. and R.S. White, "Jupiter's radiation belts," J. Geophys. Res. 79/16, 2331-2342 (1974).

122. Starr, V.P., "Some dynamic aspects of the Jovian and other atmospheres," Tellus 23/6, 489-499 (1971).

123. Starr, V.P., "A preliminary dynamic view of the circulation of Jupiter's atmosphere," Pure and Appl. Geophys. 110/9, 2108-2129 (1973).

124. Stone, P.H., "An application of baroclinic stability theory to the dynamics of the Jovian atmosphere," J. Atmos. Sci. 24/4, 642-652 (1967).

125. Stone, P.H., S. Hess, R. Hadlock and P. Ray, "Preliminary results of experiments with symmetric baroclinic instabilities," J. Atmos. Sci. 26/5, Part I, 991-996 (1969).

126. Stone, P.M., "on Jupiter's rate of rotation," J. Atmos. Sci. 31/5, 1471-1472 (1974).

127. Street, W.B., "Phase equilibria in planetary atmospheres," J. Atmos. Sci. 26/5, Part I, 924-931 (1969).

128. Street, W.B., H.I. Ringermacher and G. Veronis, "On the structure and motions of Jupiter's red spot," Icarus, 14/3, 319-342 (1971).

129. Strobel, D.F., "The photochemistry of methane in the Jovian atmosphere," J. Atmos. Sci. 26/5, Part I, 906-911 (1969).

130. Strobel, D.F., "The Jovian upper atmosphere," Phys. and Chem. Upper Atmos., Dordrecht-Boston, 1973, p. 745-753.

131. Strobel, D.F., "The photochemistry of hydrocarbons in the Jovian atmosphere," J. Atmos. Sci. 30, 489-498 (1973).

132. Strobel, D.F., "The photochemistry of NH_3 in the Jovian atmosphere," J. Atmos. Sci. 30/6, 1205-1208 (1973).

133. Strobel, D.F. and G.R. Smith, "On the temperature of the Jovian thermosphere," J. Atmos. Sci. 30/4, 718-725 (1973).

134. Taylor, F.W., "Methods and approximations for the computation of transmission profiles in the ν_4 band of methane in the atmosphere of Jupiter," J. Quant. Spectrosc. and Radiat. Transfer 12/7, 1151-1156 (1972).

135. Taylor, F.W., "Temperature sounding experiments for the Jovian planets," J. Atmos. Sci. 29/5, 950-958 (1972).

136. Taylor, F.W., "Preliminary data on the optical properties of solid ammonia and scattering parameters for ammonia cloud particles," J. Atmos. Sci 30/4, 677-683 (1973).

137. Teifel, V.G., "Optical properties and structure of the Jovian atmosphere. I. Photometric contrasts, molecular absorption and possible structure of the dark equatorial belt during 1962-1963," Solar System Res. 2, 194-201 (1968).

138. Teifel, V.G., "Optical properties and structure of Jupiter's atmosphere. II. Effects of multiple scattering in the cloud layer on the profiles of planetary absorption lines," Solar System Res. 3, 69-76 (1969).

139. Teifel, V.G., "Molecular absorption and the possible structure of cloud layers of Jupiter and Saturn," J. Atmos. Sci. 26, 854-859 (1969).

140. Tomasko, M.G., "Ammonia absorption relevant to the albedo of Jupiter. II. Interpretation," The Astrophys. J. 187/3, Part I, 641-650 (1974).

141. Trafton, L.M., "Model atmospheres of the major planets," Astrophys. J. 147/2, 765-781 (1967).

142. Trafton, L.M. and G. Münch, "The structure of the atmospheres of major planets," J. Atmos. Sci. 26/5, Part I, 813-825 (1969).

143. Uesugi, A. and W.M. Irvine, "Computation of synthetic spectra for a semi-infinite atmosphere," J. Atmos. Sci. 26/5, Part I, 973-978 (1969). /153

144. Wallace, L. and D.M. Hunten, "The Lyman -- alpha albedo of Jupiter," Astrophys. J. 182, 1013-1031 (1973).

145. Wasserman, L.H., "The occultation of Beta Scorpii by Jupiter. IV. Diurnal temperature variations and the methane mixing ratio in the Jovian upper atmosphere," Icarus 22/1, 105-111 (1974).

146. Watts, R.N., Jr., "Pioneer observes Jupiter," Sky and Telescop. 47/2, 79-83 (1974).

147. Weidenschilling, S.S. and J.S. Lewis, "Atmospheric and cloud structure of the Jovian planets," Icarus 20/4, 465-476 (1973).

148. Westphal J., "Observations of localized 5 micron radiation from Jupiter," Astrophys. J. 157, L 63-64 (1969).

149. Wildey, R.L., B.C. Murray and J.A. Westphal, "Thermal infrared emission of the Jovian disc," J. Geophys. Res. 70/15, 3711-3719 (1965).

150. Wildey, R.L., "On the interpretation of thermal emission maps of Juipter," J. Geophys. Res. 70/15, 3796-3797 (1965).

151. Williams, G.P. and Robinson, J.B., "Dynamics of a convectively unstable atmosphere: Jupiter?" J. Atmos. Sci. 30/4, 684-717 (1973).

152. Winkler, H.B., D.P. Fields and R.G. Gamache, "A study of Jupiter. Atmospheric entry probe mission to the base of the cloud layers," AIAA Paper 834, 1971, 11 pp., ill.

153. "A new look at Jupiter," Special Report 74-238, NASA, Washington, D.C., September 10, 1974, 20 pp.

154. "Pioneer 10: Jupiter findings," Interavia Air Lett. 7985, 7-8 (1974).

155. "Scientific investigations selected for Jupiter/Saturn," Interavia Air Lett. 7689, 4-5 (1973).