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GREENHOUSE EFFECT IN THE ATMOSPHERE OF VENUS

by

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SUMMARY

Investigated here is the action of greenhouse mechanism in lower layers of the atmosphere of Venus, the parameters of which were determined by the Soviet AIS "Venera-4". It is shown that the greenhouse effect could ensure the heating of planet's surface up to temperatures corresponding to that of venusian atmosphere as registered by "Venera-4" at the end of measurements, and the data of ground measurements of Venus' brightness temperature in the radioband.

The undercloud layers of Venus atmosphere are apparently found in convective equilibrium while turbulent heat exchange between the surface and the atmosphere on Venus is considerably greater than on Earth. The indicated conclusions agree completely with the results of direct measurements of the altitude distribution of the venusian atmosphere temperature, conducted by "Venera-4", and with the data of level fluctuation of "Venera-4" radiosignals.

* * *

One of the most widespread hypotheses explaining the intensive radiation of Venus in the radioband, is the greenhouse hypothesis [1], according to which the observed radiation is emitted by planet's surface heated to a high temperature due to thermal effect in its lower atmosphere. At the same time it is assumed that the strong thermal effect in the atmosphere of Venus is conditioned by the presence of a considerable amount of carbon dioxide and water vapor, which have numerous absorption bands in the infrared region of the spectrum.

On 18 October 1967, the Soviet AIS "Venera-4" performed a great complex of measurements directly in the planet's atmosphere. According to the obtained data, the temperature of Venus on the nighttime side of the planet, registered at the end of measurements by "Venera-4", is about 550°K, the atmospheric pressure at the corresponding level constituting approximately 20 atm, with carbon dioxide as the main component of its atmosphere. The H_2O content in Venus' atmosphere also proved to be sufficiently high. The obtained data allow us to conclude that on the whole, the greenhouse hypothesis corresponds to the conditions found on Venus by the Soviet AIS "Venera-4". Therefore, it is of interest to find a possible thermal effect in the planet's atmosphere with the parameters measured by "Venera-4".

In the works [1,2] the value of a possible thermal effect in the atmosphere of Venus was estimated on the basis of experimental or computed data on the transmissibility of homogeneous gas layer containing CO_2 and H_2O. In [3-5] the action of the greenhouse mechanism in the atmosphere of Venus was examined on the basis of the theory on radiation transfer in "gray" approximation. It is known, however, that within the limits of the infrared, the absorption factor of gas mixture CO_2 and H_2O varies by several orders of magnitude; so, the adaptation of the "gray" approximation during the examination of the greenhouse hypothesis is not, generally speaking, substantiated. Nor strictly rigorous are the estimates of thermal effect in the atmosphere made according to data on homogeneous gas layer permeability. In real atmosphere, temperature and pressure decrease with the altitude and, consequently, so does the absorption factor. Besides, such estimates do not take into account the atmosphere's counter radiation to the surface, which with the direct solar heating, plays a great role in the settling of surface temperature conditions.

Examined in [6] is the radial energy transfer in the undercloud atmosphere of Venus found to be in the state of radial equilibrium. It is assumed that atmosphere's absorption factor α in the wavelength interval 8-12 μ, is much smaller than in the entire remainder of the infrared band. Such a dependence on wavelength approximately describes the infrared spectrum of atmosphere absorption by the absorption components which are carbon dioxide and water vapor. Assuming p = 20 atm as the lower boundary of surface pressure on Venus, $p_{пов}$ * from [6], it is possible to find that in this case the

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* Here and further the subscript "пов" will be systematically retained in all formulas and texts, meaning "surface".

heating of planet's surface up to $T_{\text{пов}}$ = 550-770°K is sufficient for the venusian atmosphere to contain ~ 5-15 g/cm^2H_2O and ~ 6 km·atm CO_2. Such an amount of CO_2 corresponds to ~ 5% of the total mass of planet's atmosphere.

But, in reality, according to "Venera-4" measurements [7] and ground radioastronomical investigations of Venus, (see for examp.[8]), substantially greater CO_2 and H_2O contents correspond to the mentioned $T_{\text{пов}}$ values of surface temperature in the planet's atmosphere. This divergence is apparently explained by the fact that on Venus, the important role in settling of superficial temperature is played by the radial transfer as well as the turbulent heat transfer from the surface to the atmosphere. The results of the solution of the system of equations, describing the vertical structure of the atmosphere, lead also to the conclusion on the possibility of convective motions, at least in the lower layers of the Venusian atmosphere. With $T_{\text{пов}}$ = 550-700°K, the temperature gradient of the atmosphere in the state of equilibrium exceeds on the surface level by 2-3 times the value of temperature's adiabatic gradient. Thus, the atmosphere in radial equilibrium, with high value of $T_{\text{пов}}$ is found to be convectively unstable. The nascent convection should lead to the determination of temperature's adiabatic gradient, at least in the atmosphere's near-surface layers [9-10].

Investigated below are the structure and radial heat transfer in the undercloud atmosphere of Venus, whose parameters were determined by "Venera-4" Estimated also are the values of planet's surface temperature that may assure the action of greenhouse mechanism in Venus atmosphere with the experimentally found contents in CO_2 and H_2O. The $T_{\text{пов}}$ values are determined by taking into account the dependence of the atmosphere's absorption factor on frequency.

RADIAL HEAT TRANSFER IN THE PLANET'S CONVECTIVE LOWER ATMOSPHERE

The structure of the atmosphere of a star or planet, in which alongside with radial transfer, convective energy transfer also takes place, is determined by the heat flow balance equation [9]. In this equation the sum of radial and convective heat flows at a certain level z, is equated with the experimentally measured heat flow outgoing into the outer space from the upper boundary of the atmosphere. For our case the balance equation has the form [9]

$$\frac{C_p H^3 \sqrt{g_{♀}}}{4} \frac{\rho(z)}{\sqrt{T(z)}} \left[-\frac{dT}{dz} - \beta\right]^{3/2} + \int_0^{\infty} F_1^{\nu}(z)\, d\nu - \int_0^{\infty} F_2^{\nu}(z)\, d\nu = \sigma T_e^4. \tag{1}$$

In this expression the first addend from the left determines the heat flow conditioned by convection. For $|dT/dz| \leqslant |\beta|$ it is zero. The second addend in (1) gives the radial heat flow directed upward, the third represents the radial heat flow directed downward, C_p is the heat capacity of gas mixture with constant pressure, H is the height of uniform atmosphere, $g_{♀} = 850$ cm/sec^2 is the gravitation acceleration on Venus, ρ is the atmosphere density, β is the adiabatic gradient of temperature T, ν is the emission frequency, σ is the Stephen-Boltzman constant and T_e = 235-240°K is the effective Venus emission in the infrared.

The monochromatic fluxes of radial energy F_1^{ν} and F_2^{ν} are [11]:

$$F_1^{\nu}(z) = 2\pi B^{\nu}(0) E_3\left(\int_0^z \alpha^{\nu}\rho\, d\xi\right) + 2\pi \int_0^z \alpha^{\nu}\rho B^{\nu}(\xi) E_2\left(\int_{\xi}^z \alpha^{\nu}\rho\, d\eta\right) d\xi. \tag{2}$$

$$F_2^{\nu}(z) = 2\pi B^{\nu}(d) E_3\left(\int_z^d \alpha^{\nu}\rho\, d\xi\right) + 2\pi \int_z^d \alpha^{\nu}\rho B^{\nu}(\xi) E_2\left(\int_z^{\xi} \alpha^{\nu}\rho\, d\eta\right) d\xi. \tag{3}$$

where α^{ν} is the mass absorption factor of the atmosphere in the frequency ν, d is the altitude of clouds' lower boundary

$$E_n(x) = \int_1^{\infty} t^n \exp(-tx)\, dt, \quad B^{\nu}(x) = \frac{2hc\nu^3}{\exp(hc\nu/kx) - 1}$$

and h is the Planck's constant.

The adiabatic temperature gradient is

$$\beta = \frac{\gamma - 1}{\gamma} \frac{g_{♀}}{R_B}, \tag{4}$$

where γ is the ratio of gas mixture heat capacities at constant pressure and constant volume, and R_B is the Universal gas constant. In accordance with the data of "Venera-4" (see [7]) we shall assume the venusian atmosphere to consist of 95% CO_2 and 5% N_2. In this case we have [12]: $C_p = 0.24$ cal/g·deg, $\gamma = 1.25$ and $R_B = 1.931 \cdot 10^6$ ergs/g·deg. The accounting of H_2O and O_2 content in venusian atmosphere changes the indicated values by less than 1%. Substituting in (4) the numerical values of the quantitties, we find: $\beta \approx 8.8 \cdot 10^{-5}$ °K/ /cm = 8.8°K/km.

The average vertical gradient of temperature for the lower atmosphere of Venus may be found on the basis of "Venera-4" data on measurements of temperature [13]. It appears to be equal ~ 8.9°K/km, i.e. it practically coincides with β.

We shall estimate a possible departure of the temperature gradient from the adiabatic one in the presence of convection. Neglecting in (1) the terms which describe the radial transfer, and assuming $p = 20$ atm, $T = 550$°K, $H = 10^6$ cm and $T_e = 240$°K, we obtain, that $|-dT/dz - \beta| \approx 2 \cdot 10^{-3}$°K/km, or less than 0.1% of the quantity β. If we take into account the radial transfer, the difference $|-dT/dz - \beta|$ decreases still further.

As mentioned above, "Venera-4" measurements have shown that the temperature of planet's atmosphere varies with altitude according to linear law with gradient practically coinciding with the adiabitic one. This apparently, points to the presence of convective motions in the lower atmosphere of Venus. Therefore, the dependences of T, <u>p</u> and ρ on <u>z</u> under the clouds are determined with great precision by the expressions [10]:

$$T(z) = T_{\text{пов}} - \beta z, \tag{5}$$

$$p(z) = p_{\text{пов}} \left(\frac{T_{\text{пов}} - \beta z}{T_{\text{пов}}} \right)^{\frac{\gamma}{\gamma - 1}}, \tag{6}$$

$$\rho(z) = \frac{p_{\text{пов}}}{R_B T_{\text{пов}}} \left(\frac{T_{\text{пов}} - \beta z}{T_{\text{пов}}} \right)^{\frac{1}{\gamma - 1}}. \tag{7}$$

We shall examine the transfer of radial energy in the convective lower atmosphere of Venus. The comparison of radial heat flow F(z) with the flow outgoing into the outer space from the upper boundary of the atmosphere allows us to determine at what values of atmosphere parameters the latter could actually be in a state of convective equilibrium. To that effect it is imperative that the inequality $F(z)\sigma T_e^4 \leqslant 1$ be fulfilled for any $z \leqslant d$.

The absorption factor of Venus atmosphere in the infrared band is conditioned by the superposition of multiple rotation-vibration CO_2 and H_2O bands and is a complex function of frequency. Besides the "transparency window" 8-12 μ examined in [6], the atmosphere has also other "windows" which are located in the near infrared. They can play noticeable role in the radiation cooling of the surface at sufficiently great values of $T_{\text{пов}}$. We shall also note that the absorption factor in 8-12 μ band is not always constant, as was assumed in [6].

We shall divide the infrared band into sufficiently narrow spectral bands, so that within the framework of every one of them, the absorption factor will vary little. From (2) and (3), after series of transformations, it is possible to obtain that the heat flow F_i at the level <u>z</u> is

$$
\begin{aligned}
F_i(z) &= \int\limits_{\nu_{i1}}^{\nu_{i2}} F^\nu d\nu = \int\limits_{\nu_{i1}}^{\nu_{i2}} (F_1^\nu - F_2^\nu)\, d\nu = \\
&= -2\pi \int\limits_{\nu_{i1}}^{\nu_{i2}} \int\limits_{0}^{z} \frac{dB^\nu}{d\xi} E_3\Big(\int\limits_{\xi}^{z} a^i \rho\, d\eta \Big)\, d\xi\, d\nu - 2\pi \int\limits_{\nu_{i1}}^{\nu_{i2}} \int\limits_{z}^{d} \frac{dB^\nu}{d\xi} E_3\Big(\int\limits_{z}^{\xi} a^i \rho\, d\eta \Big)\, d\xi\, d\nu = \\
&= 2\pi \int\limits_{\nu_{i1}}^{\nu_{i2}} \int\limits_{T(z)}^{T_{\text{пов}}} \frac{dB^\nu}{d\xi} E_3\Big(\frac{1}{\beta} \int\limits_{T}^{\xi} \alpha^i \rho\, d\eta \Big)\, d\xi\, d\nu + \\
&+ 2\pi \int\limits_{\nu_{i1}}^{\nu_{i2}} \int\limits_{T_0}^{T(z)} \frac{dB^\nu}{d\xi} E_3\Big(\frac{1}{\beta} \int\limits_{\xi}^{T} \alpha^i \rho\, d\eta \Big)\, d\xi\, d\nu.
\end{aligned}
\qquad (8)
$$

Denoted here respectively by ν_{i1}, ν_{i2} and α^i are the lower and upper boundaries by frequency and the mean mass absorption factor of the atmosphere for the i-th spectral interval, and T_0 is the temperature of the clouds. Summing up (8) with respect to all i, we find that total flow of radial energy F(z).

The mean mass absorption factor α^i of the atmosphere in the i-th interval may be written in the form [6]

$$\alpha^i = f_{H_2O}\,\alpha^i_{H_2O} + f_{CO_2}\,\alpha^i_{CO_2}. \qquad (9)$$

where $\alpha^i_{H_2O}$ and $\alpha^i_{CO_2}$ are the mean mass absorption factor of vapor and carbon dioxide in the i-th interval and f_{H_2O} and f_{CO_2} are the relative H_2O and CO_2 contents in atmosphere by density. We shall assume that $\nu_{i2} - \nu_{i1} = 50\ cm^{-1}$. In this case the values of $\alpha^i_{H_2O}$ may be determined on the basis of work [14] data, and those of $\alpha^i_{CO_2}$ on the basis of works [2,15] data.

Brought out in [14] are the experimentally measured mean H_2O absorption factors in the infrared band for spectrum portions of 25 cm^{-1} width at p = = 1 atm and T = 300-3000°K. For each examined interval we shall find the value of α_{H_2O} as the mean average of absorption factors in two portions corresponding to it with 25 cm^{-1} width.

The mean values computed at p = 1 atm and T = 300°K, of carbon dioxide transmission function in the infrared band for portions of the spectrum 50 and 100 cm^{-1} wide, are brought in [2,15]. The knowledge of the transmission function allows us to determine the corresponding value of $\alpha^i_{CO_2}$.

We shall conduct the computation of radial energy fluxes in the portions of the spectrum corresponding to atmosphere's "transparency windows", whose absorption components are carbon dioxide and water vapor. The "window" regions may be determined from the conditions:

$$\alpha^i_{H_2O} \leqslant 10\ cm^2/deg.\ \text{and}\ \alpha^i_{CO_2} \leqslant 1\ cm^2/deg. \qquad (10)$$

at p = 1 atm and T = 300°K. Estimates show that in the regions of spectrum for which the absorption factors of H_2O and CO_2 are greater than the indicated values, the radiation transfer is practically absent. Conditions (10) are satisfied by five regions of spectrum, which are included in the limits: 825-1325, 2025-2175, 2525-3425, 3975-5125 and 5525-7025 cm^{-1}. Further in frequency interval 7025-7500 cm^{-1} the absorption band H_2O is located.

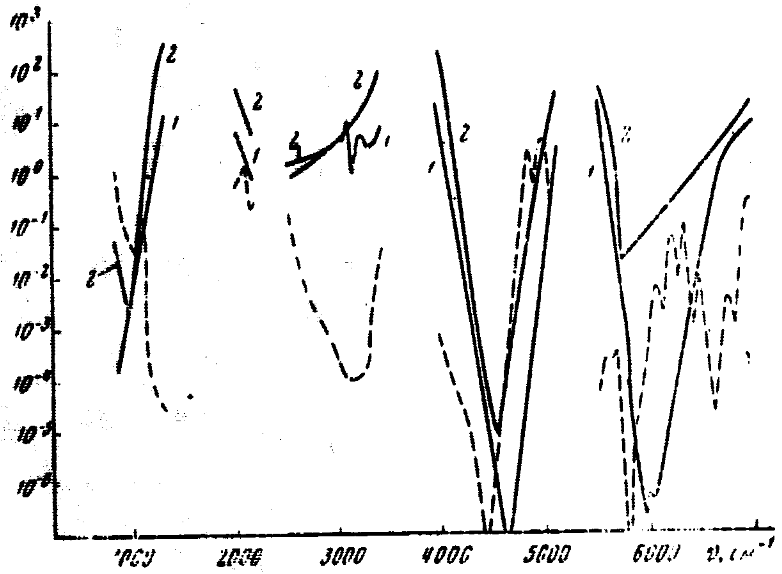

Fig.1.

Absorption factors of water vapor and carbon dioxide in "transparency windows"
1) α_{H_2O} (T = 300°K), 2) α_{H_2O} (T = 600°K), dashed lines is α_{CO_2}

In the region $\nu > 7500$ cm^{-1} ($\lambda < 1.33$ μ) the radiation transfer may be omitted, for only an insignificant fraction of energy ($\sim 10^{-2}$) corresponds to it which is emitted by the surface at temperatures that can be expected on Venus.

The results of numerous experimental investigations (see for examp. [14,16 17]) show that with the rise of temperature, the H_2O absorption factors also increase practically in the entire infrared band. The most remarkable rise of α_{H_2O} takes place in the "transparency windows". From the data brought in [14] it follows that the variation of α_{H_2O} with temperature is very well described by a linear function in the interval T = 300-900°K. Therefore, during the computations we shall accept the following dependence of the values $\alpha^i_{H_2O}$ on temperature

$$\alpha^i_{H_2O} = \alpha^i_{H_2O}(300)\,(a_i + b_i \cdot T), \qquad (11)$$

where

$$a_i = 2 - \alpha^i_{H_2O}(600)/\alpha^i_{H_2O}(300),$$
$$b_i = \frac{1}{300}\left[\alpha^i_{H_2O}(600)/\alpha^i_{H_2O}(300) - 1\right],$$

and $\alpha_{H_2O}(300)$ and $\alpha_{H_2O}(600)$ are the absorption factors of water vapor in the i-th interval with T = 300 and 600°K. It is known that the absorption factor of carbon dioxide in the infrared band also rises with the increase of T (see for examp.[18-20]). However, due to the absence of corresponding numerical data, we shall consider below, that the values of $\alpha^i_{CO_2}$ do not vary with temperature. As regards the dependence on pressure, we shall assume as is generally done that the values of the H_2O and CO_2 absorption factors in "transparency windows" are directly proportional to p.

The general character of the dependence of α_{H_2O} and α_{CO_2} in the "windows" on frequency is presented in Fig.1. (at p = 1 atm).

Taking into account the abovementioned we find from (8) that the total heat flow conditioned by radial transfer in convective atmosphere is

$$F(z) = \sum_{i=1}^{M} F_i(z) = 2\sigma \sum_{i=1}^{M} \int_{T(z)}^{T_{\text{пов}}} \xi^3 \left\{ 4\,\frac{15}{\pi^4} \int_{\frac{hc\nu_{i1}}{k\xi}}^{\frac{hc\nu_{i2}}{k\xi}} \frac{x^3\,dx}{e^x - 1} + \right.$$
$$+ \frac{15}{\pi^4}\left[\frac{\left(\frac{hc\nu_{i1}}{k\xi}\right)^4}{\exp\left(\frac{hc\nu_{i1}}{k\xi}\right) - 1} - \frac{\left(\frac{hc\nu_{i2}}{k\xi}\right)^4}{\exp\left(\frac{hc\nu_{i2}}{k\xi}\right) - 1}\right]\Bigg\} E_3\left\{\frac{1}{\beta}\left[\left(f_{CO_2}\alpha^i_{CO_2} + \right.\right.\right.$$
$$+ f_{H_2O}a_i\alpha^i_{H_2O}(300)\right)\frac{p_{\text{пов}}}{1\ \text{атм}}\,\rho_{\text{пов}}\,\frac{\gamma - 1}{2\gamma}\,T_{\text{пов}}\left[\left(\frac{\xi}{T_{\text{пов}}}\right)^{\frac{2\gamma}{\gamma-1}} - \left(\frac{T}{T_{\text{пов}}}\right)^{\frac{2\gamma}{\gamma-1}}\right] +$$
$$+ f_{H_2O}b_i\alpha^i_{H_2O}(300)\,\frac{p_{\text{пов}}}{1\ \text{атм}}\,\rho_{\text{пов}}\,\frac{\gamma - 1}{3\gamma - 1}\,T^2_{\text{пов}}\left[\left(\frac{\xi}{T_{\text{пов}}}\right)^{\frac{3\gamma-1}{\gamma-1}} - \left(\frac{T}{T_{\text{пов}}}\right)^{\frac{3\gamma-1}{\gamma-1}}\right]\Bigg]\Bigg\}\,d\xi +$$
$$+ 2\sigma \sum_{i=1}^{M} \int_{T_0}^{T(z)} \xi^3 \left\{ 4\,\frac{15}{\pi^4} \int_{\frac{hc\nu_{i1}}{k\xi}}^{\frac{hc\nu_{i2}}{k\xi}} \frac{x^3\,dx}{e^x - 1} + \frac{15}{\pi^4}\left[\frac{\left(\frac{hc\nu_{i1}}{k\xi}\right)^4}{\exp\left(\frac{hc\nu_{i1}}{k\xi}\right) - 1} - \frac{\left(\frac{hc\nu_{i2}}{k\xi}\right)^4}{\exp\left(\frac{hc\nu_{i2}}{k\xi}\right) - 1}\right]\right\} \times$$
$$\times E_3\left\{\frac{1}{\beta}\left[\left(f_{CO_2}\alpha^i_{CO_2} + f_{H_2O}a_i\alpha^i_{H_2O}(300)\right)\frac{p_{\text{пов}}}{1\ \text{атм}}\,\rho_{\text{пов}}\,\frac{\gamma - 1}{2\gamma}\,T_{\text{пов}} \times\right.\right.$$
$$\times \left[\left(\frac{T}{T_{\text{пов}}}\right)^{\frac{2\gamma}{\gamma-1}} - \left(\frac{\xi}{T_{\text{пов}}}\right)^{\frac{2\gamma}{\gamma-1}}\right] + f_{H_2O}b_i\alpha^i_{H_2O}(300)\,\frac{p_{\text{пов}}}{1\ \text{атм}}\,\rho_{\text{пов}}\,\frac{\gamma - 1}{3\gamma - 1}\,T^2_{\text{пов}} \times$$
$$\left.\left.\times \left[\left(\frac{T}{T_{\text{пов}}}\right)^{\frac{3\gamma-1}{\gamma-1}} - \left(\frac{\xi}{T_{\text{пов}}}\right)^{\frac{3\gamma-1}{\gamma-1}}\right]\right]\right\} d\xi, \qquad (12)$$

where the summing-up is spread over 84 spectral intervals of 50 cm^{-1} width, constituting the "transparency windows" of the atmosphere (see (10)).

The results of the heat flow computation carried out with the aid of (12) for a series of values of atmosphere parameters are brought in Fig.2.

The ratio of the quantity F at level z to energy flow outgoing into the outer space from the upper boundary of Venus cloud cover, i.e. $Q(z) = F(z)/\sigma T_e^4$ is plotted along the ordinate axis of Fig.1, and the atmosphere temperature corresponding to it is in the abscissa. The computations were performed for the following values of Venus atmosphere parameters: $p_{\text{пов}} = 20$ atm, $T_{\text{пов}} = 550-750$°K, $T_0 = 300$°K, $f_{CO_2} = 0.95$ and $f_{H_2O} = 0.1-0.3\%$. The indicated values $p_{\text{пов}}$, $T_{\text{пов}}$, f_{CO_2} and f_{H_2O} correspond to data of "Venera-4" measurements, and to the values of Venus brightness temperature $T_{\text{я}0}$.

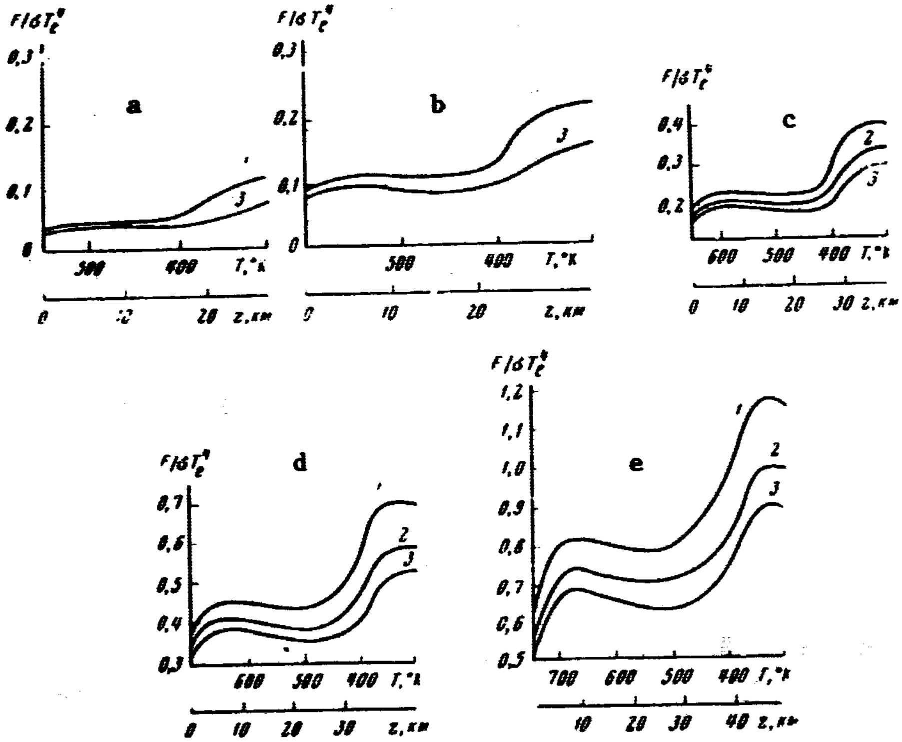

Fig.2.

Heat flow in the lower atmosphere of Venus, conditioned by radial transfer

a) $T_{\text{пов}}$ = 550°K, b) $T_{\text{пов}}$ = 600°K, c) $T_{\text{пов}}$ = 650°K, d) $T_{\text{пов}}$ = 700°K,

e) $T_{\text{пов}}$ = 750°K.

1) $f_{H_2O} = 0.1\%$, 2) $f_{H_2O} = 0.2\%$, 3) $f_{H_2O} = 0.3\%$.

The dependences Q(z) shown in Fig.2a are obtained in the assumption that $T_{\text{пов}} = 550°K$, i.e. it is equal to the temperature of venusian atmosphere, determined by "Venera-4" at the end of measurements. In this case the role of radial heat transfer in planet's lower atmosphere is immaterial. The heat flow conditioned by radial transfer does not exceed over all the levels 0.1 of the flow outgoing from the upper boundary of the cloud cover ($Q(z) \lesssim 0.1$), so that in the undercloud atmosphere the energy transfer is basically convective.

The increase of surface temperature leads to a quick rise of total heat flow. Presented in Fig.2b,c,d,e are the dependence Q(z) computed with $T_{\text{пов}} = 600$, 650 and 700°K. At the same time for the remaining atmosphere parameters, we assumed the abovementioned values. Comparison of curves in Fig.2a and Fig.2b,c,d, shows that the increase of surface temperature from 550 to 700°K leads to a rise of heat flow by approximately 7-8 times at all the levels. However, in all the cases inequality $Q(z) < 1$ is fulfilled so that with such parameters in the atmosphere, there should settle the adiabatic temperature gradient.

With $T_{\text{пов}} = 750°K$, the convective equilibrium in the atmosphere may settle only for $f_{H_2O} > 0.1\%$ (see Fig.2d).

The temperature of the cloud layer, equal to 300°K, was chosen during computation because the absorption factors of CO_2 and H_2O are computed in [2,14,16] for this value of T. The estimates of A.M. Obukhov [21] made on the basis of "Venera-4" measurements, show, that the temperature of lower cloud boundary constitutes about 270-280°K. However, the indicated difference is immaterial, inasmuch as the clouds provide an insignificant contribution to the magnitude of thermal effect [6].

The curves Q(z), found for the above indicated values of atmosphere parameters, may be divided into two regions with different character of the dependence of the value of radial energy flow on height. In the first one of them, corresponding to the near-surface layers of the atmosphere with temperature from $T_{\text{пов}}$ up to 400-500°K, a negligible flow variation with altitude takes place. To the contrary, in the second region corresponding to upper layers of the undercloud atmosphere with temperature from 400-450°K to T_0, a rapid flow increase takes place. In order to explain the indicated character of the dependence F(z), we shall examine heat fluxes transfered in separate portions of the infrared band. Brought out in Fig.3 is the dependence on altitude of the quantities $Q_{123} = F_{123}/\sigma T_e^4$ and $Q_{45} = F_{45}/\sigma T_e^4$, computed for a series of values of atmosphere parameters. One of them corresponds to the aggregate heat flux which is transfered in the atmospheric "transparency windows" 825-1325, 2025-2175 and 2525-3425 cm^{-1}, with moderate values of the H_2O and CO_2 absorption factors (see Fig.1.). The other corresponds to the sum of heat fluxes transfered in the "windows" 3975-5125 and 5525-7025 cm^{-1}. In the centers of these "transparency windows" α_{H_2O} and α_{CO_2} descend to rather low values by comparison with the first three "windows"

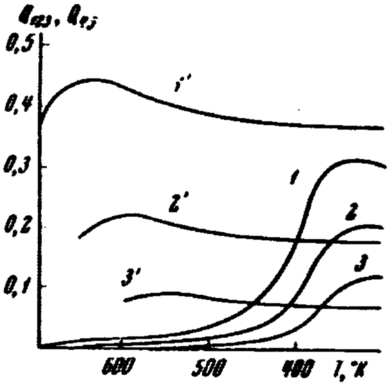

Fig.3.
Heat fluxes conditioned by radial transfer, in separate portion of the infrared band (f_{H_2O} = 0.1%)

1) Q_{123}, 1´) Q_{45}($T_{\text{пов}}$ =700°K);
2) Q_{123}, 2´) Q_{45}($T_{\text{пов}}$ =650°K);
3) Q_{123}, 3´) Q_{45}($T_{\text{пов}}$ =600°K).

From the curves in Fig.3 it follows that at various values of atmospheric parameters, the flux F_{45} remains practically constant in magnitude at all levels. This is explained by the fact, that the absorption factor of H_2O and CO_2 in "transparency windows" 3975-5125 and 5525-7025 cm^{-1} is small, therefore the surface radiation in these "windows" passes freely through the atmosphere. With $T_{\text{пов}}$ = 700°K, the quantity F_{45} constitutes a considerable portion of the flux radiated by Venus into the outer space ($Q_{45} \approx 0.3$-0.4). From here it follows that the "transparency windows" with center near λλ 2.2 and 1.7 μ could influence the settling of planet's surface temperature conditions.

The flux F_{123} undergoes, to the contrary, a considerable variation with altitude. Near the surface we have $Q_{123} \ll Q_{45}$. Then due to temperature and

and pressure drop with altitude, decrease of the atmosphere absorption factor takes place, and the flux F_{123} increases and becomes comparable by magnitude with F_{45}. Computations show that at the same time the basic fraction of the flux $F_{123}(\gtrsim 90\%)$ is constituted by the radiation transferable in the spectrum region 825-1325 cm^{-1}. Beginning from a certain level, the clouds' counterglow becomes effective, and the quantity F_{123} somewhat decreases. Thus, the above noted character of the dependence of the total flux F on z, is basically determined by the variation with altitude of the heat fluxed which are transfered in the "transparency windows" with moderate absorption factors of H_2O and CO_2.

ESTIMATES OF THE MEAN SURFACE TEMPERATURE

One may estimate the magnitude of $T_{пов}$ by examining the incoming and outgoing heat balance, from the surface per unit of time. We shall investigate the mean heat balance of Venus' surface for one solar day. The incoming fraction of the balance is constituted by the direct solar radiation $F_{\odot}$. Considering that the absorbed solar energy is evenly expended on the heating of planet's surface, it is possible to write

$$F_{\odot} = 0{,}25 \cdot E_{♀}(1 - A_{♀}). \qquad (13)$$

Here $E_{♀}$ = 3.8 cal/cm^2·min, is the solar constant for Venus and $A_{♀}$ = 0.76 [22] is the albedo.

The expended fraction of the balance is constituted by the proper surface radiation $F(T_{пов})$ and the turbulent heat transfer from the surface to atmosphere. The quantity $F(T_{пов})$ is determined by the expression (12), provided we postulate z = 0. The dependences $Q(T_{пов}) = F(T_{пов})/\sigma T_e^4$, computed for a series of water vapor content values in the lower atmosphere in the interval $T_{пов}$ = 550-750°K are plotted in Fig.4. The curves for $Q(T_{пов})$ are well approximated by the function

$$Q(T_{пов}) = \left(\frac{T_{пов} - b}{a}\right)^{\varkappa}. \qquad (14)$$

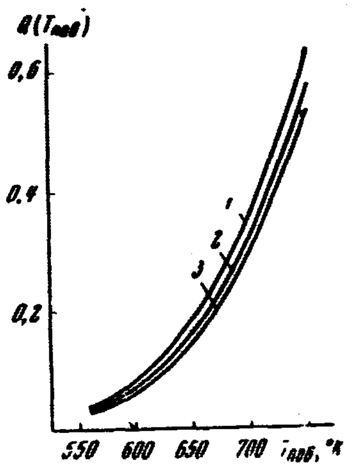

Fig.4.
Radial heat flux on the surface level

1) f_{H_2O} = 0.1%,
2) f_{H_2O} = 0.2%,
3) f_{H_2O} = 0.3%.

The value of a, b and χ for a series of values f_{H_2O} are given in Table 1.

The magnitude of surface turbulent heat yield to atmosphere may be characterized by the ratio $m = F_{turb}/F_0$ where F_{turb} is the turbulent heat flow. We shall note that according to [23], the mean annual heat losses by the terrestrial surface, conditioned by the turbulent transfer, constitute ~ 5%, i.e. for the Earth $F_{turb}/F_{⊕} = 0.05$.

TABLE I

f_{H_2O},%	α, °K	b, °K	χ	$T_{пов}$, °K			
				m = 0.05	m = 0.5	m = 0.7	m = 0.95
0.1	471	320	4.72	768	711	671	560
0.2	482	320	4.71	778	720	679	565
0.3	485	325	4.63	786	726	684	569

Thus, we shall write the heat balance equation of Venus' surface in the form

$$0{,}25\cdot E_{♀}(1-A_{♀})(1-m) = \sigma T_e^4\left(\frac{T_{пов}-b}{a}\right)^{\varkappa}. \qquad (15$$

The values of $T_{пов}$, found with the aid of (15), are compiled in Table 1.

They show that heat effect may assure the heating of Venus surface to temperatures, corresponding to the values of $T_{я♀}$, observed in the radioband and the value of Venus atmosphere found by "Venera-4" at the end of measurements. From Table I, it also follows that since the values of $T_{я♀}$ in the radioband correspond to the mean surface temperature, the turbulent surface heat transfer on Venus is substantially greater than on the Earth.

However, the values of $T_{пов}$ which are brought out in Table I, are found in the assumption that all the energy incident on the planet, with the exception of the reflected one from the upper boundary of the cloud cover, is expended on the heating of the surface. In reality a fraction of solar energy is absorbed during the passage through the atmosphere. Compiled in Table I are the absorption factors of water vapor $\alpha^{form}_{H_2O}$, and the optical depths of atmosphere $\tau^{form}_{H_2O}$, conditioned by absorption of H_2O in separate portions $\Delta\lambda$ of the visible region of the spectrum. Brought up in Table 2 also are the values of $E_{♀}(\Delta\lambda)/E_{♀}$, indicating, which fraction of solar energy falls on the portion $\Delta\lambda$ of the spectrum.

TABLE 2

$\Delta\lambda$, μ	$\alpha^{form[10]}_{H_2O}$ cm^2/g	$E_{♀}(\Delta\lambda)/E_{♀}$,	$\tau^{form}_{H_2O}$	
			f_{H_2O} = 0.1%	f_{H_2O} = 0.3%
0-0.55	$2\cdot10^{-4}$	0.34	0.04	0.13
0.55-0.65	$1.63\cdot10^{-3}$	0.13	0.33	1.0
0.65-0.75	$5.53\cdot10^{-3}$	0.10	1.1	3.3
0.75-0.85	$2.04\cdot10^{-2}$	0.08	4.1	12.3
0.85-0.95	$6.9\cdot10^{-2}$	0.06	13.8	42
0.95-1.0	$4.16\cdot10^{-1}$	0.03	83	250

In the visible region of spectrum, carbon dioxide displays a series of absorption bands with centers at 0.96; 0.92; 0.86 and 0.83 μ. However, these bands are weak.

On the basis of work [15] data, it is possible to estimate that the absorption factor in the band with center on λ 0.83 μ, does not exceed 10^{-7} cm^2/g. Thus, the absorption in CO_2 can be neglected at least in long waves λ 0.83 μ.

The data brought in Table 2, allows us to find that for various H_2O

contents in the atmosphere, the energy incoming to planet's surface, varies from $\sim 0.35(1-A_{♀})E_{♀}$ to $\sim 0.45(1-A_{♀})E_{♀}$. Taking into account the absorption of visible radiation in the atmosphere, it is possible to find from (15) that the results of measurements of Venus atmosphere in the radioband correspond to the value of turbulent heat transfer coefficient $m = 0.05-0.4$.

The above results of calculation of radial transfer in venusian atmosphere allow us to derive the following conclusions.

1. For structural parameter values measured by "Venera-4", the lower atmosphere of the planet must be in the state of convective equilibrium. This conclusion totally agrees with the results of direct measurements of temperature distribution with altitude in the lower atmosphere carried out by "Venera-4". The under-cloud adiabatic temperature gradient will settle with surface temperature increase to at least 750°K.

2. During the investigation of Venus' surface temperature system, the radiation transfer cannot be neglected in the spectral regions 3975-5125 and 5525-7025 cm^{-1}. With $T_{\text{пов}} \gg 700°K$, the energy lost by the surface in the mentioned "transparency windows", constitutes a noticeable fraction of heat radiated by the planet in the infrared band. At the same time the radiation transfer in the "window with center near λ 3.3 μkm is insignificant.

3. The action of greenhouse mechanism in venusian atmosphere is sufficient to ensure the heating of planet's surface to temperatures corresponding to the value of $T_{\text{пов}}$, measured by "Venera-4" and the measurement data of Venus' brightness temperature in radiowaves.

4. The turbulent heat exchange between the surface and the atmosphere on Venus is apparently, considerably greater than on Earth. The latter is corroborated by the results of "Venera-4" investigations of level fluctuations of the radiosignals having passed through the atmosphere of Venus [24].

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