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Temperature, Pressure, and Density of the Atmosphere of Venus from Measurement Data of the "Venera-4" Automatic Interplanetary Station

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On 18 X 1967 the Soviet automatic station "Venera-4" reached the planet Venus. The main task of the station' s descent vehicle was to study the parameters of the atmosphere of Venus—pressure, temperature, density, and composition.

The basis for ideas about the atmosphere of Venus consisted of a variety of hypotheses founded on data from ground-based observations in the optical and radio ranges and on certain theoretical estimates. These led to great uncertainty in constructing models of the planet' s atmosphere. The proposed values of pressure at the surface lay in the interval from 1 to 100 atm, and temperatures approximately from 300 to 650° K. The scientific apparatus was designed for a model of the atmosphere of Venus with values of pressure and temperature at the surface of about 10 ata and 700° K, respectively.

Two thermometers were installed to measure temperature. Hermetic resistance thermometers, capable of operating in dense gaseous and liquid media in the presence of chemically aggressive substances, were used as the sensors. The sensitive element of the sensors was a platinum wire with ohmic resistance at 20° C of 36.8 and 16 ohms, respectively. The sensors were connected into balanced bridge circuits. The unbalance voltage was amplified by highly stable semiconductor amplifiers. The measurement range of the first sensor was 270–600° K, and of the second 210–730° K. The root-mean-square error of temperature measurements, σ_T, did not exceed $\pm 4^\circ$ for the first sensor and $\pm 7^\circ$ for the second.

To determine density a special densitometer was used, whose sensor was an ionization chamber. The principle of operation of the densitometer is based on the dependence of the magnitude of the recorded current on gas density. The chamber is a hollow cylinder of stainless steel 14 mm in diameter and 25 mm long, with a wall thickness of 0.3 mm. A thin layer of β-active strontium-90 with a total activity of about 1 millicurie was deposited on the inner surface of

Fig. 1. Results of measurements of T, ρ, P

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Fig. 2. Entropy-pressure diagram

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the cylinder. The measurement range of the densitometer is $5 \cdot 10^{-4}$–$1.5 \cdot 10^{-2}$ g/cm^3 for air, CO_2, N_2, O_2, and mixtures of the indicated gases. The root-mean-square error of the densitometer readings, σ_ρ, is $\pm 0.18 \cdot 10^{-3}$ g/cm^3 at the beginning of the measurement range and $\pm 3 \cdot 10^{-3}$ g/cm^3 at the end.

Pressure was measured by an aneroid-type manometer. The measurement range of the instrument was 100-5200 mm Hg. The mean square measurement error was $\sigma_P = \pm 150$ mm Hg.

The transmission of data from measurements of the parameters of the atmosphere of Venus began after the opening of the main parachute, when the transmitter of the descent vehicle switched on. The descent velocity of the vehicle on the parachute varied approximately from 10 to 3 m/sec and therefore could not exert an aerodynamic influence on the measurement results.

Interrogation of the sensors by the telemetry commutator began at 07 h 40 min 52 s Moscow time and was carried out, on average, at a frequency of once every 48 s. The variation of the temperature T, pressure P, and density ρ as functions of time τ is shown in Fig. 1. The temperature was measured throughout the entire experiment up to the moment communication with the descent vehicle ceased, at 09 h 13 min 57 s. Pressure and density were measured until the instruments went off scale, respectively at 08 h 30 min 31 s and 08 h 50 min 00 s. These moments are marked on the graphs $P_{\text{meas}}(\tau)$ and $\rho_{\text{meas}}(\tau)$ in Fig. 1. The limits of deviations of the measured parameters corresponding to the indicated root-mean-square errors σ_T, σ_P, and σ_ρ are also shown there.

Fig. 1. Results of measurements of T, ρ, P

Fig. 2. Entropy-pressure diagram

The values of P and ρ for the subsequent time intervals were obtained by extrapolation, with the known variation of T, and under the assumption that the atmosphere consists of CO_2. On the entropy-pressure diagram (Fig. 2) are shown the curves of the change of the gas state over the measurement intervals, calculated from T, P_{meas} (curve 1) and T, ρ_{meas} (curve 2). The curves are continued to the isotherm $T = 544°\text{K}$, corresponding to the last measured temperature, with a slope determined from the terminal straight-line segments of the curves. The condition for atmospheric stability is the condition $\Delta S \leq 0$ with increasing temperature. The horizontal dashed lines in Fig. 2 correspond to limiting extrapolation along the adiabat $\Delta S = 0$. The pressure values obtained at the intersection of curves 1 and 2 with the isotherm $T = 544°\text{K}$ are, respectively, 19.5 and 20.75 atm. The extrapolated segments of the curves P_{meas} and ρ_{meas} are plotted on the graphs in Fig. 1 as dashed lines.

It follows from consideration of Figs. 1 and 2 that the course of the curves obtained with the manometer and the densimeter differs up to the moment τ = 08 h 30 min and T = 440°K. Table 1 gives the values of the molecular weight μ, cal-

calculated from the measured P, ρ, and T and from the Clapeyron equation. Near 08 h 30 min the values of μ approach 44, which corresponds to a CO_2 atmosphere and agrees with direct measurements of the composition. The value $\mu = 44$ is also retained in the extrapolation intervals. In the preceding interval, the overestimate of μ is associated with the character of the measured course of the density curve, as well as with the greater relative error of the instruments at the beginning of the measurements.

Table 1

Moscow time	kg/mole	Moscow time	kg/mole	Moscow time	kg/mole
7 h 40 m	56.6	8 h 15 m	57.5	8 h 45 m	45.0
45	52.0	20	50.7	50	44.7
50	50.3	25	46.7	55	45.5
55	50.6	30	44.9	9 h 00 m	44.7
8 h 00 m	49.5	35	45.2	05	45.2
05	51.7	40	44.7	10	44.7
10	56.7				

The increase in density recorded in the interval approximately from 08 h 03 min to 08 h 24 min may be explained by the influence on the densitometer readings of components of the atmosphere of Venus that do not affect the readings of the temperature and pressure sensors. As one possible assumption, moisture may be supposed to have entered the measuring chamber of the densitometer.

From consideration of Fig. 2 it follows that the densitometer readings approach the manometer readings directly beyond the curve of the water-vapor phase transition (curve 3). The possible influence of water, as well as of some other components, is currently being studied for the corresponding pressures and temperatures.

To obtain the distribution of the atmospheric parameters with altitude, it was necessary to determine the change in altitude above the surface during the descent of the spacecraft by parachute; this was calculated in two ways.

In the first case, the equation of motion for a quasi-uniform descent was used:

Fig. 3 and Fig. 4

Figure 3: Fig. 3 and Fig. 4

$$H(\tau) = \sqrt{\frac{2mg}{C_x S}} \int_{\tau_1}^{\tau_2} \rho^{-1/2}(\tau)\, d\tau, \tag{1}$$

where C_x is the aerodynamic drag coefficient; S is the characteristic area; m is the mass of the descending spacecraft.

In the second case, the relation of hydrostatic equilibrium was used

$$H(\tau) = \frac{1}{g} \int_{P_1}^{P_2} \frac{dP}{\rho} \tag{2}$$

($g = 880$ cm/sec^2). The calculations were made using the parameters of the gas corresponding to state curves 1 and 2 of the entropy diagram (Fig. 2).

The curves obtained by independent methods for the change of altitude with time (Fig. 3), corresponding to the path length traversed by the descending spacecraft in the atmosphere of Venus, agree satisfactorily with one another on average. The total altitude agrees, to within 10%, with the radio-altimeter reading (26 ± 1.3 km).

Equations (1) and (2) could have been used for an independent extrapolation of the initial pressure values according to the formula

$$P^{1/2} = P_1^{1/2} + g^{3/2} \sqrt{\frac{m}{2C_x SR}} \int_{\tau_1}^{\tau_2} T(\tau)^{-1/2}\, d\tau, \tag{3}$$

where R is the gas constant.

However, the resulting character of the change of atmospheric parameters is unstable ($\Delta S > 0$). Condition (3), for constant values of the coefficients, is not fulfilled even in the section where the measurements were made. This

may be explained by the fact that local vertical currents exist in the atmosphere. Thus, for example, calculation by formula (3) agrees with curve 1 in Fig. 2 for a velocity of the descending gas flow near the surface of about 0.4 m/sec.

The maximum discrepancy in determining the altitude by different methods, including by the radio altimeter, is evidently determined by errors in measuring C_x, the atmospheric parameters, and also by the presence of vertical currents and the influence of the terrain relief in the possible wind drift of the apparatus.

Fig. 3. Altitude intervals. 1—by P_{meas}, barometric formula; 2—by P_{meas}, parachute; 3—ρ_{meas}, parachute

Fig. 4. Atmospheric model

Figure 4 presents a vertical cross section of the atmosphere of Venus. To tie the atmospheric parameters to altitude, the curve of Fig. 3 with nominal altitude $H = 27.3$ km was chosen.

The nature of the processes of change in the state of the gas in the atmosphere of Venus up to altitudes of 10–15 km is close to adiabatic. The mean temperature gradient was about 8.5–8.7 deg/km, which differs little from the adiabatic gradient for CO_2 at the corresponding values of temperature and pressure. This indicates that in the lower layers of the atmosphere there exist conditions of convective equilibrium with intense mixing, and that the lower boundary of the cloud layer lies above 27 km (approximately at an altitude of 29–33 km).

Thus, at the surface of Venus near the morning terminator on the night side, the pressure is 20 ± 3 atm, the density $19 \cdot 10^{-3}$ g/cm$^3 \pm 15\%$, and the temperature $544 \pm 10^{\circ}$K.

The height of the homogeneous atmosphere at the surface of Venus proves to be about 12 km, and the total mass of gas approximately 10^{20} tons.

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