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DYNAMICS OF AUTOMATIC STATIONS' DESCENT IN PLANETARY ATMOSPHERES AS MEANS OF MEASUREMENT DATA CONTROL

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SUMMARY

A method is proposed of verifying the mutual agreement of measurement data of pressure p, density ρ and temperature T, conducted on automatic stations, descending in planetary atmospheres with the aid of parachutes.

At the basis of the method lies the utilization of hydrostatics and dynamics equations of stations' descent, and in certain cases, also of equations of state. For illustration we utilized the data of the Soviet AIS "VENERA-4". This method shows a good coordination of all the measured quantities. The empirically determined harmony constants may be utilized for the extrapolation of data, for example, on pressure and density, and on those portions of descent trajectories, where measurements of only one parameter, i.e. the temperature, were carried out, as was the case on VENERA-4.

The final value of pressure thus extrapolated, is found to be 17.6 ± 0.5 kg/cm^2 . It is shown that the utilization of coordinates (log p, log T), taken at the respective moments of time, provides the possibility of judging about the character of atmosphere's temperature stratification.

* * *

Analysis of the descent of an automatic interplanetary station (AIS) on parachute provides an additional means of controlling the inner coordination of data on planet's atmosphere, provided simultaneous measurements are carried out of at least two any thermodynamic parameters of the atmosphere out of three,

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connected by gas' equation of state. The method described below will be applied with the view of analysis and checking the concordance of data obtained during the descent of AIS "VENERA-4" (see [1 - 3]).

It is assumed that the atmosphere of the planet is in hydrostatic equilibrium and that its gas content is constant with height. Both these assumptions are well fulfilled in the Earth's atmosphere, where the gas composition is constant through altitudes of the order of 100 km. We shall consider as valid the equation of state of an ideal gas (although, as will be seen below, in a series of cases the precise form of the equation of state is immaterial)

$$p = \mu^{-1} R \rho T, \qquad (1)$$

where p is the pressure, μ is the molecular weight, ρ is the density, T is the absolute temparature, R is the Universal gas constant. At great pressures, as is the case in the lower part of Venus' atmosphere, gas digression from ideal are already beginning to be noticeable [2]. We shall not pause at that, though the corresponding theory may be developed also for an equation of state, more complex than (1).

Let us consider at the outset the case, when both the density and pressure are known as a function of time. In conditions of hydrostatic equilibrium, the variation of pressure with time is

$$dp \,/\, dt = \rho g w, \qquad (2)$$

where g is the gravitation acceleration, w is the vertical velocity of the descending apparatus relative to planet's surface (axis z being directed downward). For a steady fall the weight of the descending system is equilib ated by air drag

$$mg = C_x \rho w^2 /\, 2, \qquad (3)$$

where m is the mass of the system, C_x is the aerodynamic drag coefficient, S is the midship area (*). Eliminating w from (2) and (3), we obtain

$$dp \,/\, dt = A\sqrt{\rho}, \qquad (4)$$

where

$$A = (2mg^3 /\, C_x S)^{1/2} . \qquad (5)$$

(*) It might be taken into account that in (3) w is the descent velocity relative to gas, as was done in [2]; however, here we disregard this difference inasmuch as vertical velocities in Venus' atmosphere are apparently small [4].

Integrating this equality over time, we have

$$p(t) - p_0 = A \int_0^t \sqrt{\rho(t)}\,dt. \tag{6}$$

This equality is valid only at one assumption of hydrostatic equilibrium independently of the form of the equation of state. Generally speaking, the quantity A is not rigorously constant, inasmuch as g rises slowly as the descent takes its course. In the case of AIS "VENERA-4", at its passage at altitudes of the order of 30 km [1 - 3] the value of g increases by about 1%, i.e., the value of A must increase by about 1.5%. For the time being, we shall neglect this variation.

Fig.1

If the experimental values of p(t) and ρ(t) are known, the validity of formula (5) fulfilment on empirical material can be verified on experimental material. Inasmuch as on the utilized Venera-4 manometer the root-mean-square error was constant and equal to ± 0.2 kg/cm², for checking the concordance of measurement data of p and ρ, it would be more advantageous to utilize fromula (6) by integrating over time backward

$$p_1 - p(t) = A \int_{t_1}^t \sqrt{\rho(t)}\,dt, \tag{6'}$$

where the moment of time t_1 corresponds to the last measurement of pressure, when $p_1 = 7.3$ kg/cm². The values of $p_1 - p(t)$ are plotted in Fig.1 in ordinates beginning from t_1 and after each $\Delta t = 5$ min and backward in time through the moment of time corresponding to the beginning of measurements; the values of

$$\int_{t_1}^t dt/\sqrt{T(t)}.$$

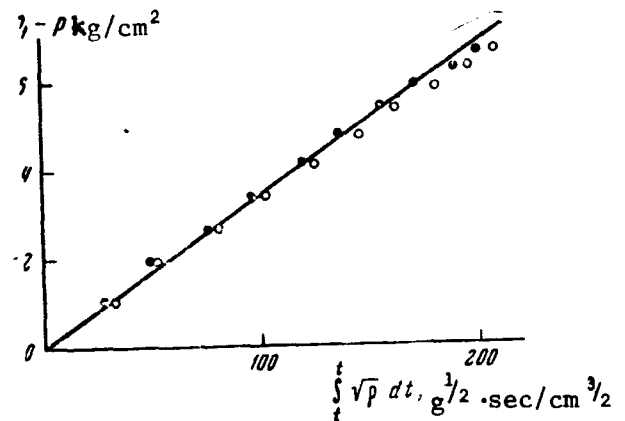for the corresponding moments of time are plotted in the same Fig.1 in abscissa.

The clear circles in Fig.1 correspond to primary data on density measurements, when there is a "hump" on that curve; note that a detailed discussion of data on density measurements can be found in the works [3 - 5]. The dots correspond to a smoothed out density curve [5], when the "hump" is simply cut off "by sight", if one may say so. It may be seen that all points fit perfectly a single straight line, whose tangent of inclination angle to the abscissa axis is equal to A. The quantity A, determined over this segment of descent trajectory by the method of least squares is found to be 3.38 ± 0.02 atm·cm $^{3/2}$ / /g $^{1/2}$ · min, or $(3.31 \pm 0.02) \cdot 10^4$ g $^{1/2}$ cm $^{1/2}$ /sec^3(the root-mean-square deviations are indicated here). The clear circles are fitting fairly well the straight line, but with a smaller inclination angle, which corresponds to a certain overrating of densimeter readings in the region of the "hump".
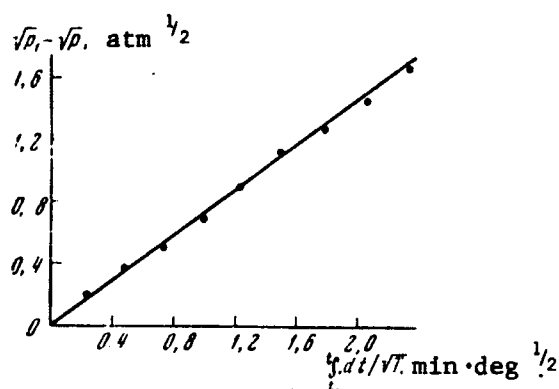
Let us turn now to the pair of variables, pressure p(t) and temperature T(t). If we substitute in (4) the density from Eq.(1), it may be possible to write the following equality

$$dp / 2p^{1/2} = Bdt / T^{1/2}, \qquad (7)$$

where

$$B = (mg^3\mu / 2C_xSR)^{1/2}. \qquad (8)$$

The integration of equality (7) yields

$$\sqrt{p_1} - \sqrt{p(t)} = B \int_{t_1}^{t} dt/\sqrt{T(t)}, \qquad (9)$$

where the counting of pressure and the integration are again conducted backward in time starting from the last point. Plotted in ordinates of Fig.2 are the values of $\sqrt{p_1} - \sqrt{p(t)}$, taken every $\Delta t = 5$ min, and in abscissa the values of

$$\int_{t_1}^{t} dt/\sqrt{T(t)}$$

for the corresponding moments of time. All the points again fit well a straight line of which the tangent of the inclination angle to the abscissa axis is B.

Fig.2

The quantity B, determined by the method of the least squares, is fo nd to be equal to 0.733 ± 0.003 deg$^{1/2}$·atm$^{1/2}$/min, or 12.0 ± 0.05 deg$^{1/2}$·g$^{1/2}$·cm$^{-1/2}$sec^{-2}

Let us finally consider the last pair of the three parameters linked by the equation of state, i. e. the temperature and density. Eliminating from (4) the pressure with the aid of (1), we obtain

$$d(\rho T)/dt = 2C\sqrt{\rho},$$ (10)

where

$$C = \frac{\mu}{R}\left(\frac{mg^3}{2C_x S}\right)^{1/4}$$ (11)

The constant C is theoretically linked with the remaining constants of agreement A and B by the following equalities:

$$C = \left(\frac{\mu}{R}\right)^{1/4}, B = \frac{\mu}{2R}A.$$ (12)

If we consider the temperature as a well known function of time, the differential equation (10) has the following solution:

$$\sqrt{\rho} = T^{-1/4}\left\{\sqrt{\rho_0 T_0} + C\int_0^t dt/\sqrt{T(t)}\right\},$$ (13)

when the index (subscript) 0 denotes the quantities related to the initial moment of time. From this formula we may obtain the following one:

$$\sqrt{\rho_1 T_1} - \sqrt{\rho}T = C\int_{t_1}^t dt/\sqrt{T(t)}.$$ (14)

where index 1 denotes the moment of time, when density measurements terminated, while the integration is conducted backward in time. From the form of formula (14) it is clear that it may be obtained from (9) directly by utilizing the equation of state. Nonetheless, for an independent determination of ρ and T formula (14) may be utilized for the verification of the "constancy" of the coordination constant C. The verification of formula (14) on the empirical material provided by "VENERA-4" was performed in [5]. Here the value of the constant C was found to be equal to $(8.65 \pm 0.07) \cdot 10^{-3}$ g$^{1/2}$ deg/cm$^{3/2}$·sec.

The temperature T may, to the contrary, be expressed by ρ, which yields an independent verification of agreement of the just described method.

Considering ρ as known, from Eq.(10), we may obtain

$$\rho_1 T_1 - \rho T = 2C \int_{t_1}^{t} \sqrt{\rho(t)}\, dt, \tag{15}$$

which will constitute a second variant of the method of coordination checking between T and ρ. A series of data once again agree well, and the empirical value of constant C, determined by the method of least squares, is found be equal here to $(8.85 \pm 0.17) \cdot 10^{-3} g^{1/2} \cdot deg/cm^{1/2} \cdot sec$. This second value of constant C, determined independently, agrees well within the limits of errors with the above presented its first empirical value. We may assume, as an average that $C = (8.75 \pm 0.12) \cdot 10^{-3} g^{1/2} \cdot deg/cm^{1/2} \cdot sec$.

From formulas (12) it is possible to obtain the following three formulas for the determination of atmosphere's molecular weight by the coordination constants A, B, C:

$$\mu = 2RC/A, \quad \mu = RC^2/B^2, \quad \mu = 4RB^2/A^2 \tag{16}$$

Making use of the above-found empirical values of constants A and B and of the mean value of constant C, we find that the molecular weight is respectively equal to 44.0 ± 0.9; 44.2 ± 1.5; and 43.7 ± 0.9. All the three values are in good agreement among themselves and with the fact that the atmosphere of Venus consists mostly of carbon dioxide.

Thus, the method developed here on the example of data supplied by AIS "VENERA-4" has shown a good intrinsic concordance of all the three measured parameters of the atmosphere. Besides,indications on the correctness of measurements, this corroborates also the fundamental hypotheses laid at the basis of theory, namely, that the atmosphere of Venus is in a state of hydrostatic equilibrium, and that the descent of the AIS with parachute was quasi-uniform, i.e. the fall was steady.

It should be noted that what is compared in the procedure of coordination are not the results of measurements with their possible errors, but those points which correspond to curves, traced according to primary measurement data, which does ensure a relatively small scattering in the values of coordination constants.

At the same time, the fact that the determination of constants takes place over the entire measurement sector lowers sharply the weight of possible isolated ejections and provides the basis to regard the found values of these constants with a certain confidence.

Inasmuch as "VENERA-4" measured only temperature to the very end, it is natural to make use of the empirical values of constants B and C for the determination of the course of pressure and density over those portions of the trajectory where measurements of these parameters were not performed. Such an extrapolation of density was conducted in [5]; here, we shall limit ourselves to extrapolation of pressure. Making use of $B = 0.733$ deg .atm /min according to formula (10), but already transformed forward in time, we find that the final value of pressure is $p_f = 17.2$ kg/cm^2. An identical procedure used in [2] yielded the same value. But if we take into account the certain increase in gravitational acceleration with descent and the possible errors in the determination of temperature, pressure and the very value of B, we find $p_f = 17.6 \pm 0.5$ kg/cm^2.

The value $p_f = 20 \pm 3$ kg/cm^2 was brought out in the preliminary work [1]; it was obtained with the help of a $(p - S)$-diagram (entropy-pressure) for pure carbon dioxide, and also by way of pressure extrapolation (and also of density) according to the inclination of the conditional polytrop. A more detailed analysis, conducted in [2], provided the authors with the possibility of deriving for the most probable value of final pressure 18.5 kg/cm with possible fluctuations ± 1.3 and even ± 2.3 kg/cm^2. Our own value is included within these limits, but has fewer admissions, which is assured by the minimum number of utilized hypotheses.

The values of pressure $p_f < 18.5$ kg/cm^2 on the $(p - S)$-diagram correspond to unsteady stratification (superadiabatic temperature gradient) in the lower part of the atmosphere consisting of pure carbon dioxide; this apparently is precisely the circumstance that incited the authors of [2] to consider the value of 18.5 kg/cm^2 as the most probable. We shall show that from the standpoint of atmosphere stability, smaller values of p_f are also conceivable, provided. we deny ourselves the idea that the atmosphere of Venus consists only of carbon dioxide (CO_2).

Let us pause at the outset on the question as to how one may judge on atmosphere stratification (magnitude of temperature gradient) without tying the data in height. Knowing the temporal course of pressure and temperature (or any other pairs of parameters), one may construct the dependence of $\log p$ on $\log T$, taken at the same moments of time. This is done in Fig.3 for the entire descent trajectory, whereupon at the end the values of $\underline{p}$ were extrapolated, as already shown above. The linear dependence of $\log p$ on $\log T$ implies the polytropic character of variation of the state of the atmosphere in the time interval of decsent

$$p/p_i = (T/T_i)^{n/(n-1)} \tag{17}$$

where $\underline{n}$ is the polytrop exponent. In this case the dependence of temperature on height has a linear character, which follows from the barometric formula [6].
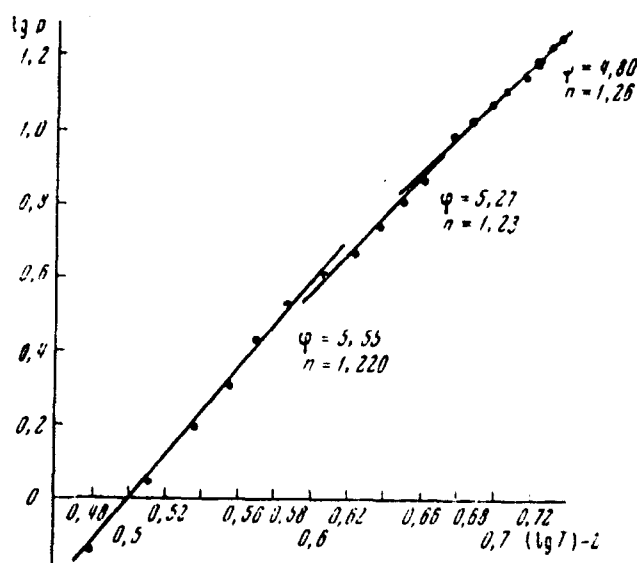

Fig.3

Shown near each group of points are the values of the tangent ϕ of the inclination angle of the corresponding straight line, and the values of $n = \phi/(\phi - 1)$. Over the last portion of the straight line, extrapolated for pressure, the polytrop exponent $\underline{n}$ is found to be equal to 1.26 ± 0.02, taking into account all possible errors in the determination of $\underline{p}$ and T.

Had the exact chemical composition of Venus' atmosphere been known, we might judge on the character of atmosphere stratification by merely comparing the found

value of $\underline{n}$ with adiabate exponent $\kappa = c_p / c_v$ for the mixture of gases composing the atmosphere of the planet. For $n < \kappa$ the atmosphere is stable and the vertical temperature gradient is less than the adiabatic; for $n > \kappa$ the temperature gradient is greater than the adiabatic, i. e. convection must take place. As a result of convective mixing the entropy will tend to equalize in height, which must in the final resort lead to the settling of the adiabatic temperature gradient, equal to g/c_p.

Turning for the sake of comparison to Earth, we remember that the temperature gradient is greater than the adiabatic with the ensuing result that strong convections are encountered only in summer in midday hours over land, or in winter above warm oceans at intrusion of cold air masses: but, as a rule, the Earth's atmosphere is generally stable and has a sub-adiabatic temperature gradient.

The value of the adiabat exponent κ_0 for pure CO_2 under the existing conditions of the lower part of Venus' atmosphere, namely of pressure and temperature, (over the portion of extrapolation) varies from 1.25 to 1.23 at the end of measurements. The value $n = 1.26 \pm 0.02$, found by us, is somewhat higher, i.e. the atmosphere seems to be somewhat unstable. Incidently, the situation apparently is not that bad, inasmuch as small admixtures of other monoatomic and diatomic gases (for example, argon, oxygen or nitrogen) may diminish or liquidate this discrepancy. The exponent κ_0 for a mixture of $\underline{k}$ gases is determined by the formula

$$x_0 = 1 + \left(\sum_{i=1}^{k} \frac{\beta_i}{x_i - 1} \right)^{-1},$$
(18)

where $\sum_{i=1}^{k} \beta_i = 1$. i. e. β_i is the volume fraction of the i-th component. If we assume that the atmosphere of Venus consists, for example, of 90% CO_2 and 10% of Ar, we shall have $\kappa_0 = 1.25$. For the determination of the true value of κ_0 in the planet's atmosphere one must know more accurately its true gas composition. So far, under the existing situation, we must recognize that the temperature gradient in the lower part of Venus' atmosphere is close or equal to the adiabatic. In higher layer it is definitely lower than the adiabatic gradient.

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