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"VENERA-11" AND "VENERA-12": PRELIMINARY ESTIMATES FOR THE WIND SPEED AND TURBULENCE IN THE ATMOSPHERE OF VENUS

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16. Abstract

The methods and results of measurements for wind speed and atmospheric turbulence in the clouds of Venus are described, and compared with earlier results.

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"VENERA-11" AND "VENERA-12": PRELIMINARY ESTIMATES FOR THE WIND SPEED AND TURBULENCE IN THE ATMOSPHERE OF VENUS

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Doppler data from the Venera-4 - Venera-10 stations have revealed extraordinary properties of the troposphere of Venus [1-3]. It has been established that, at heights of 20-60 km, there exists a very intense zonal movement, whose wind speed is from 20-40 to 100 m/sec and more. At altitudes of 10-20 and 40-45 km, there may occur an abrupt rise in the wind speed, while in the 20-40 km range the increase of the wind occurs significantly more slowly or is not observed at all. In the lower portion of the atmosphere, below 10 km, where more than half its mass is concentrated, the winds are insignificant and their speed near the surface does not exceed 1-1.5 m/sec. The movement of the atmosphere has a pronounced spatial-time variability and the wind speeds obtained in separate experiments differ by tens of meters per second. /1*

Despite the considerable wind speeds and their gradients, the dynamic turbulence of the atmosphere, appearing in pulsations of the wind speed, is relatively slight: The maximum variations in the speed, registered by the Venera-4-10, were 1-2 m/sec above 40 km and did not exceed tenths of a meter per second at lower altitudes for a broad spectrum of spatial scales, beginning from units of meters.

Observations on the drift, made by the descending Venera vehicles, directly proved that the displacement of UV-objects in the cloud layer, observed from Earth, is connected with an actual movement of the atmosphere. It is interesting to note that in fact the displacement of small cloud formations, invisible from the /2

*Numbers in the margins indicate pagination in the original text.

Earth is connected with an actual movement, while the observed displacement of global cloud systems, having been interpreted as a "four-day circulation", is possibly linked with the propagation of atmospheric waves [4].

Recently new observations were carried out that confirm the data of Doppler measurements aboard the Venera stations. Among these are the measurements for the shift of the UV-cloud drift by the photographs of Mariner-10 [5], the measurements of the Doppler shift of CO_2 bands [6], and the direct measurements for wind speed at the surface of Venus by the cup anemometers of the Venera-9 and Venera-10 stations [7]. New data as to the structure of the cloud layer and the dynamic activity have been obtained in the course of a television experiment aboard the Venera-9 station [8,9].

However the accumulated data are insufficient for either drawing up a rather complete phenomenological picture of the movement or for explaining the mechanism of its development and maintenance. Considerable supplementary information as to the dynamics of the Venusian atmosphere has been obtained as a result of experiments carried out aboard the Venera-11 and Venera-12 stations, the preliminary result of which are presented in this paper, and also in the course of a simultaneous sounding of the atmosphere by four Pioner-Venera probes.

Features in carring out the measurements. The experiments to investigate the dynamics of the Venusian atmosphere aboard the Venera-11 and Venera-12 stations were carried out by a procedure similar to that used aboard the Venera-9 and Venera-10 AMS[1]. The descent capsule descended on the side of the planet invisible to the Earth. The magnitude that was observed was the difference between the projections of the flight vehicle speed and the descent vehicle speed on a sighting line (the relative speed), measured with a rebroadcast signal by the fixed Doppler method. /3

[1] [Automaticheskaya mezhplanetnaya stantsiya, Robot space station]

Using the measurements of the relative speed, a projection was found for the horizontal speed of the capsule and the wind speed in the wake of the flight vehicle's trajectory. To measure the speed, the spectrum of a signal, received from the descent capsule aboard the flight vehicle, was rebroadcast to Earth in the 60 Khz band.

The diagram for carrying out the experiment is shown in Figure 1. The trajectories of the descent and the flight vehicles were optimized to insure the most favorable communication conditions. The parameters of the trajectories were similar for both descent and both flight vehicles. Separation of the descent vehicle was executed 48 hours before entering the atmosphere. The planes of the trajectories for the descent and the flight vehicle coincided, while the descent region was chosen close to the pericenter of the flight vehicle's orbit. The time required to pass through the pericenter was close to the time required for the descent vehicle to land on the surface of the planet. The pericenters of the orbit of the flight vehicles were situated at an altitude of 34,000 km.

The descent vehicles were landed in regions close to each other, in the meridional region somewhat south of the equator. The zenith angle of the Sun was $\sim 20^\circ$ for Venera-11 and $\sim 25^\circ$ for Venera-12, which corresponds to the second hour of Solar time.

(1) of the vehicle's horizontal speed on the sighting line /4
and, consequently, the contribution of the wind speed to the relative velocity changed during the descent from $30-35^\circ$ to $4-5^\circ$ at the moment of landing. Since the planes of the trajectories for the descent and the flight vehicle coincided, the measurements of the relative velocity were used to determine the component of the wind speed lying in the plane of the flight vehicle's trajectory: The azimuths of these components were -132° and -128°.

As before, the speed measurements aboard the Venera-11 and

(1) Translator's note: incomplete in the original.

Venera-12 were carried out by the fixed Doppler method. During the interplanetary flight, no calibrations were carried out for the frequency of the spaceborne master oscillators, so that the initial value of the frequency was known only with a considerable error and was not used to process the data; the actually-measured magnitude was the change in the relative velocity. The error in determining this parameter mainly depends on the unpredictable temperature drift for the frequency of the master oscillator. For Venera-11 and Venera-12, this factor was not limiting. There was practically no temperature drift for the frequency during the descent, and for approximately 1 1/2 hours after landing the drift did not exceed 4-5 m/sec. The actual error of the measurements, due to the portion of this drift that was not accounted for, does not exceed 1-1.5 m/sec.

The reception of the signals and the speed measurements of the descent vehicles were begun 10 sec after turning on the transmitter on board and continued for 2.5 hours for Venera-11 and more than 3 hours for Venera-12, of which ~2 hours followed the touchdown on the surface. In this manner, Venera-12 and Venera-11 created a unique record for the time of active operation from the surface of Venus. For 15 minutes prior to the landing of Venera-12 there were frequency variations in the signal that were not connected with the wind action; the measurements in this section were not included in the further processing. /5

The magnitude of the relative speed of the vehicles varied from -2.7 km/sec at the beginning to +3.6 km/sec at the end of the measurements with an average acceleration of 0.65 m/sec^2. This velocity change in the section covered was caused by the orbital movement of the flight vehicle; the contribution of the descent velocity of the descent vehicle was less than 2%, while the wind velocity was less than 1% (Fig. 2). Considering the errors with which the trajectory of the flight vehicle, the descent site of the landing vehicle, and the atmospheric parameters are known, the isolation of the wind speed contribution is a complicated problem. In order to estimate the wind speed from the measured magnitude of the relative velocity, certain values that had been calculated by an integration of the movement equation for the landing and the flight vehicles, beginning at a time several hours before entry into the atmosphere, were subtracted. The calculations were carried out with a model for the motion that was similar to the one developed in [10]; the initial conditions were in the form of data obtained by processing the trajectory measurements from the Earth as to the flight vehicle and data as to the drift momentum. When calculating the movement in the atmosphere, aerodynamic characteristics of the landing vehicle and parachute system, obtained during terrestrial tests with an allowance for the work cyclogram, were employed. The mean value of the aerodynamic lift force was taken to be zero. /6

The model of the atmosphere was given in the form of a dependence of density on altitude $\rho = \rho(R-a)$, where a = 6050 km is the radius of the planetary surface, R is the distance from the landing vehicle to the gravitational center of Venus. The density was given in accordance with the basic model of the atmosphere [11], by the direct measurements of Venera-9 and Venera-10, and also by the direct measurements of Venera-11 and Venera-12 as time functions.

In calculating the Doppler shift, corrections for the temperature drift of the master oscillators' frequency, the refraction in the troposphere of Venus, and the Doppler shift in the line from the flight vehicle to Earth were also taken into account.

The difference between the measured and the calculated magnitudes of the relative velocity form the Doppler remainders. In addition to the influence of the wind, errors connected with inaccuracies in the trajectory parameters of the flight and the descent vehicles, the density of the atmosphere, and aerodynamic coefficient, as well as the unaccounted-for temperature drift of the frequency, enter into these remainders.

On the basis of an analysis of the descent data, the results of terrestrial tests, and also the measurements of Venera-9 and Venera-10, the latter factors can lead to an error in wind speed not exceeding several m/sec at great altitudes and do not significantly influence the interpretation of the result. However errors in the trajectory data, especially in the descent region of the vehicle, can lead to a shift in the estimates to substantially larger values.

A control of the accuracy of trajectory parameters was carried out by measurements after landing on the surface, where the Doppler remainders of the vehicle at rest should not interfere. /7 For Venera-12, the Doppler remainder was practically constant for almost an hour after landing (CF. Fig. 3), which indicates the good accuracy of the trajectory data and of the prediction for the temperature drift of the frequency. For Venera-11, the change in the Doppler remainder after landing was several m/sec in the course of an hour, although during descent in the atmosphere the behavior of the Doppler remainders for Venera-11 and Venera-12 was qualitatively the same. In virtue of this, the interpretation of the wind speed data for Venera-11 has not been completed and will be done in subsequent papers.

If, for Venera-4 to Venera-8, where the measurements were carried out in the line of direct communication between the descent vehicle and the Earth, the Doppler shift could be directly converted into the wind speed, in the case of rebroadcasting the course of the Doppler remainder is associated with both the change in the angle between the horizontal speed of the vehicle and the sighting line, due to the movement of the flight vehicle, and also with the additional displacement of the sighting line and the Doppler speed of the flight vehicle upon deflection of the descent vehicle by the wind.

The magnitude of the Doppler remainder with an appropriate geometrical factor was used as a 0-point approximation to the wind speed. More precise magnitudes were found by successive approximations. At each step the movement equations of the descent vehicle were integrated with the corrections to the wind speed obtained in the preceding step; the initial position was /8 correspondingly displaced to compensate for the influence of the deflection. The approximations were continued until the change in the Doppler remainder during the descent was reduced to 1-1.5 m/sec. It was considered that the wind has an exclusively latitudinal direction. The altitude correlation was realized along the trajectory of the descent vehicle. In conformity with the results of the direct measurements, the pressure at the surface was taken equal to 89 kg/cm^2.

The resulting profile of the wind speed is shown in Fig. 4; the error in the speed estimate at this phase of the analysis was 5-7 m/sec at high altitudes. Attention is directed to the fact that the measured component at all altitudes preserves the sign corresponding to movement in the direction of the natural Venusian rotation. The absence of directional variations is also seen immediately in the Doppler remainders for both Venera-12 and Venera-11. Figure 4 shows that, in a large altitude range, the movement occurs with velocities of 40-50 m/sec. The principal increment in the wind speed occurs at altitudes from 10 to 20 km, where the gradient of the wind speed is approximately 0.4 m/sec km; above 20 km, the rise in the wind speed slows down considerably and the mean gradient of the speed from 20 to 60 km is less than 0.25 m/sec. Although measurements were not carried out at altitudes of 0-10 km, due to the noted variations in the signal frequency, the course of the wind speed at larger altitudes indicates an abrupt lessening to magnitudes on the order of units of m/sec at approximately 10 km. This indicates that in the lower layers of /9 the atmosphere the wind speed was not great. The small value of the wind speed near the surface is well confirmed by the data of Venera-11 at the section near the landing (Fig. 6). Prior to the landing, speed variations associated with the turbulence of the atmosphere and oscillations of the vehicle were noted. The mean inclination is determined by the above-mentioned change in the Doppler remainder. The velocity jump upon landing, with an accuracy of 10 cm/sec, corresponds to the calculated value, which appears in the absence of a drop between the Doppler remainders before and after the landing. The variations after the landing are specified by instabilities in the frequency of the master oscillators and noise in the receiving device. The magnitude of these variations -- approximately 4 cm/sec for Venera-11 and approximately 2 cm/sec for Venera-12 -- determines the actual fluctuation error of the measurements. If it is considered that the enith angle of the flight vehicle at the moment of landing was approximately 5^{o} , then the 10 cm/sec discrepancy between the measured and the calculated speed of the vehicle corresponds to an estimate of 1-1.2 m/sec for the maximum value of the wind speed at the planetary surface. The conformity between the calculated and measured velocities also testifies to the absence of irreversible jumps in the frequency changes of the oscillators upon landing.

On the whole, the distribution of wind speed obtained from the data of Venera-12 is in good conformity with the data of the preceding Veneras, indicating the existence of a constant and powerful zonal movement of the troposphere. It is characteristic/10 that the wind profile of Venera-12 is closer to the data of Venera-9 and Venera-10 than to that of Venera-7 and Venera-8: The wind speed in the region of the cloud layer is considerably less than 100 m/sec and there is no zone of wind speed shift at 40-45 km. The experiments of Venera-9 to Venera-12 were carried out close to midday by local Solar time and thus the observed reduction in the wind speed is apparently a consequence of the daily cycle that is characteristic for the upper troposphere; it may also be a phenomenon of a large-scale disturbance in the subsolar zone and identified with the disturbances observed in the UV-photographs [4]. Below 40 km, the daily cycle is considerably less pronounced.

Turbulence. The movement of the descent vehicle is also influenced by the dynamic turbulence of the atmosphere, manifested in pulsations of the wind speed and corresponding variations in the velocity of the descent vehicle (contrary to the temperature turbulence, which determines the fluctuation in the refractive coefficient and the parameters of the radio signal). The response of the vehicle to the action of the turbulence cannot be taken into account, since the variations in the vehicle speed coincide with those of the wind speed, the characteristic time of which exceeds the "entrainment" time of the vehicle [13]. For Venera-11 and Venera-12, the entrainment time, depending on the altitude, was from five to one m/sec, which corresponds to spatial scales from 300 to 10-20 m.

Natural vibrations are also superimposed on the pulsations /11 of the vehicle speed due to turbulence; however, as a rule these vibrations have a quasi-harmonic nature and can be removed.

In the descent of Venera-11 and Venera-12, perceptible variations were observed throughout the entire descent, being more intense in the upper troposphere. In the descent of Venera-11 above 40-45 km, the mean amplitude of the velocity pulsations was approximately 1 m/sec with a maximum value of 2.35 m/sec for the strongest variations; the time scale for the greatest pulsation was 30-40 sec, which corresponds to a spatial scale of 600-800 m. For Venera-12, the maximum value of the pulsations was 3 m/sec. Below 40 km, the amplitude of the velocity pulsations, which can be identified with the influence of the turbulence, was up to 0.4 m/sec, while the characteristic time was from 10-12 to 16-20 sec.

The rate of dissipation of kinetic energy $\mathcal{E}=(\sigma \nu)^3/L$ [14], where σV is the root-mean-square value of the velocity pulsations and L is a characteristic spatial scale, can be estimated by these data. Taking into consideration the rate of descent in the corresponding sections of the measurement, for the value of $\mathcal{E}$ we obtain 50-180 cm^2/sec^3 above 40 km and 3-9 cm^2/sec^3 for the lower troposphere. The latter magnitude is in good agreement with that calculated in [15] by the measurement of Venera-9 and Venera-10 at the surface.

On the whole, the turbulence was found to be substantially higher than it was in the similar condition for Venera-9 and Venera-10 and for Venera-5 to Venera-8, which probed the morning and the pre-morning atmosphere.

In conclusion we shall compare the profiles of wind speed in the Venusian atmosphere, obtained aboard the Venera station, with the data of the Pioner-Venera probes.

Figure 4 shows the profiles of wind speed obtained by the /12
daylight (4) and evening (5) Pioner-Venera probes [16]. They are shown in the same diagram with the Venera data (Fig. 6). Despite the discrepancies, the general similarity between the profiles of wind speed obtained after an interval of several years in a broad range of latitude and Solar longitudes is remarkable. The wind profiles of the Pioners display a good agreement with the Venera data, reproducing their basic features. The hypothesis as to the zonality of the movement, assumed in interpreting the Venera results, has been confirmed. The existing data also confirm the empirical wind models for the Venusian atmosphere, proposed in [17].

It is clear that all the way down to the deep layers the atmosphere of Venus is involved in a powerful, although irregular, zonal movement. This has also revealed a new type of circulation in the deep atmosphere, the maintenance mechanism of which urgently demands theoretical explanation.

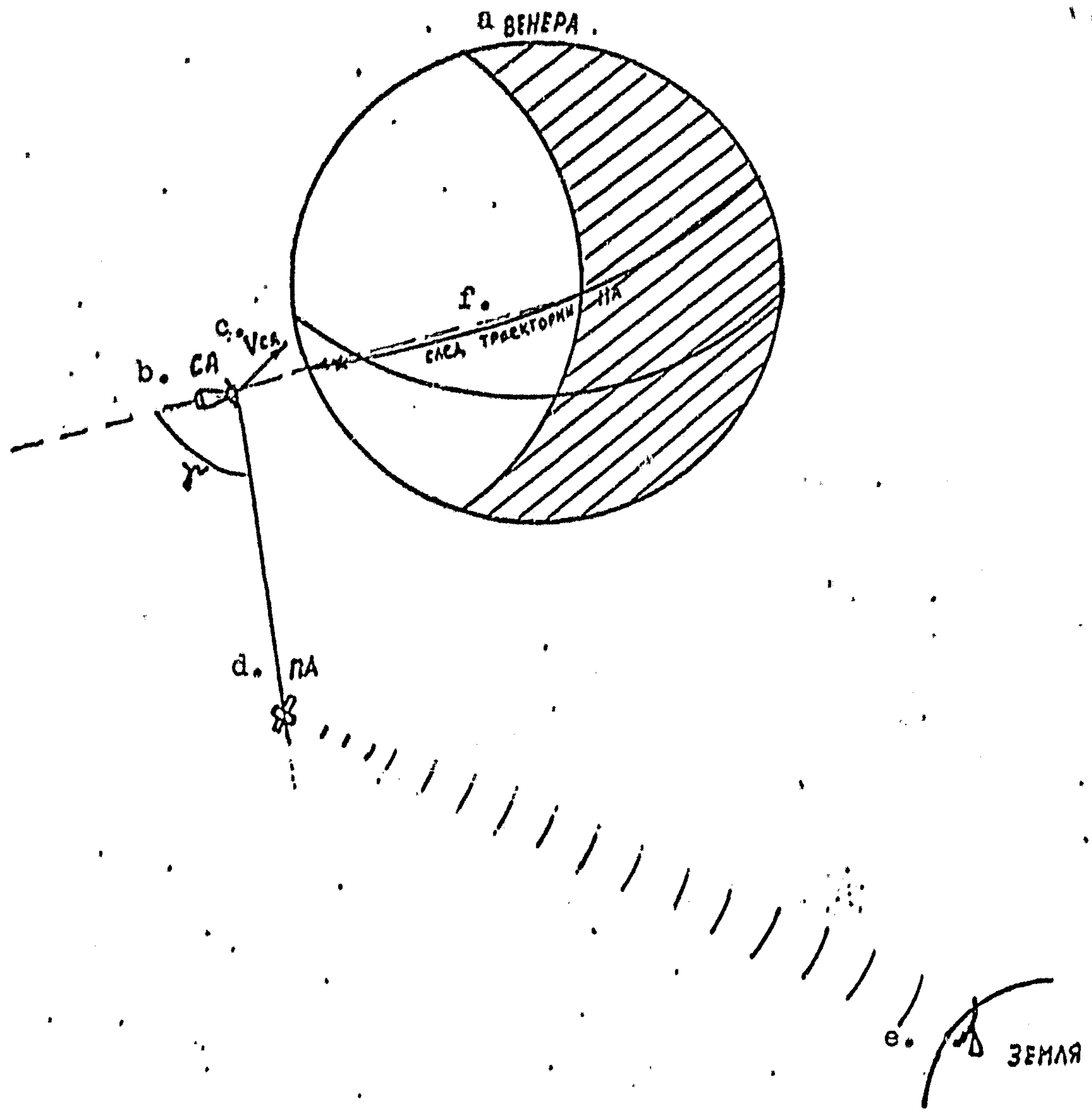

Fig. 1. Diagram for relative velocity measurements.
Key: a, Venus; b, descent capsule; c, $V_{d.c.}$; d, flight vehicle; e, Earth; f, track of flight vehicle trajectory

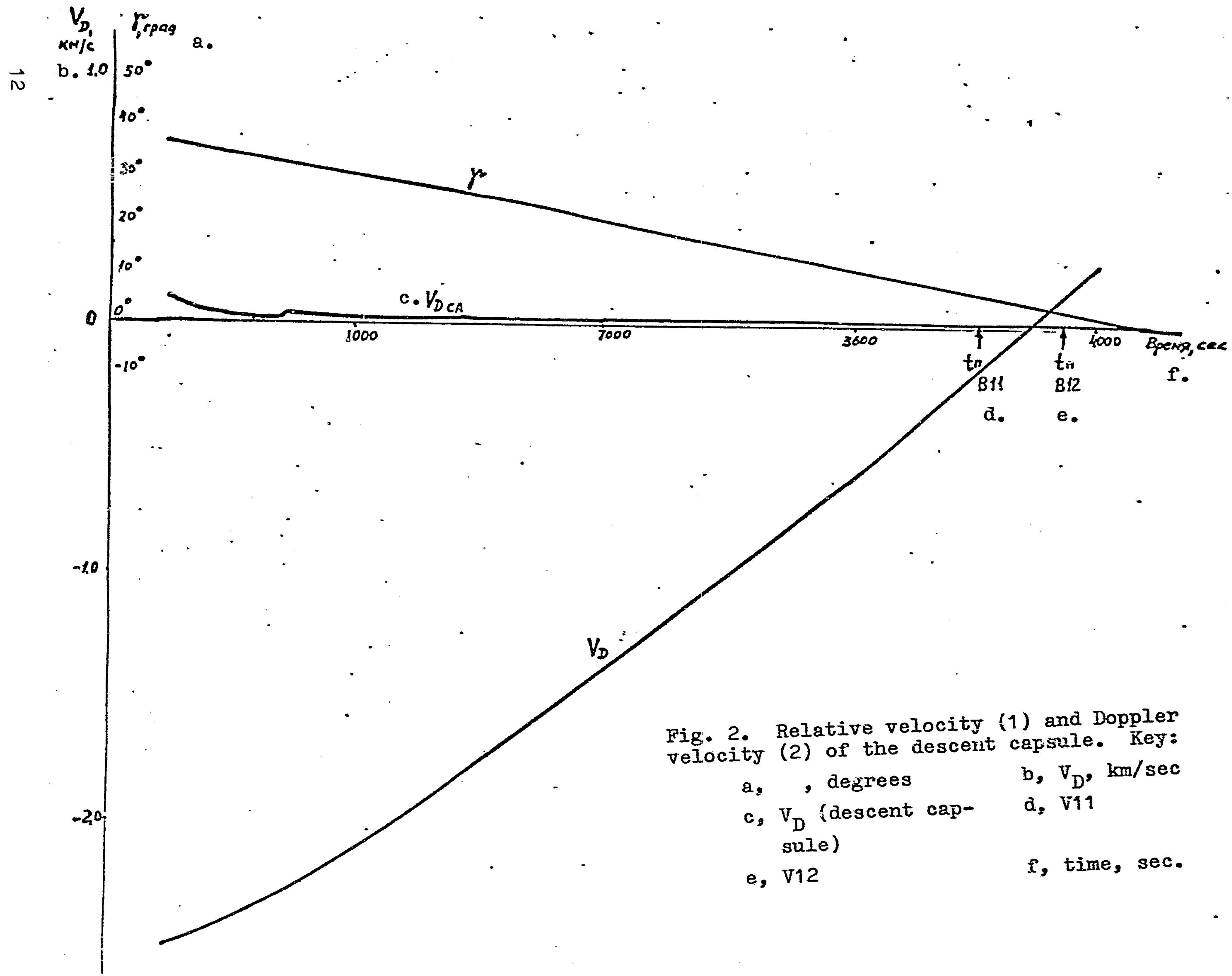

Fig. 2. Relative velocity (1) and Doppler velocity (2) of the descent capsule. Key:

a, , degrees
b, V_D, km/sec
c, V_D (descent capsule)
d, V11
e, V12
f, time, sec.

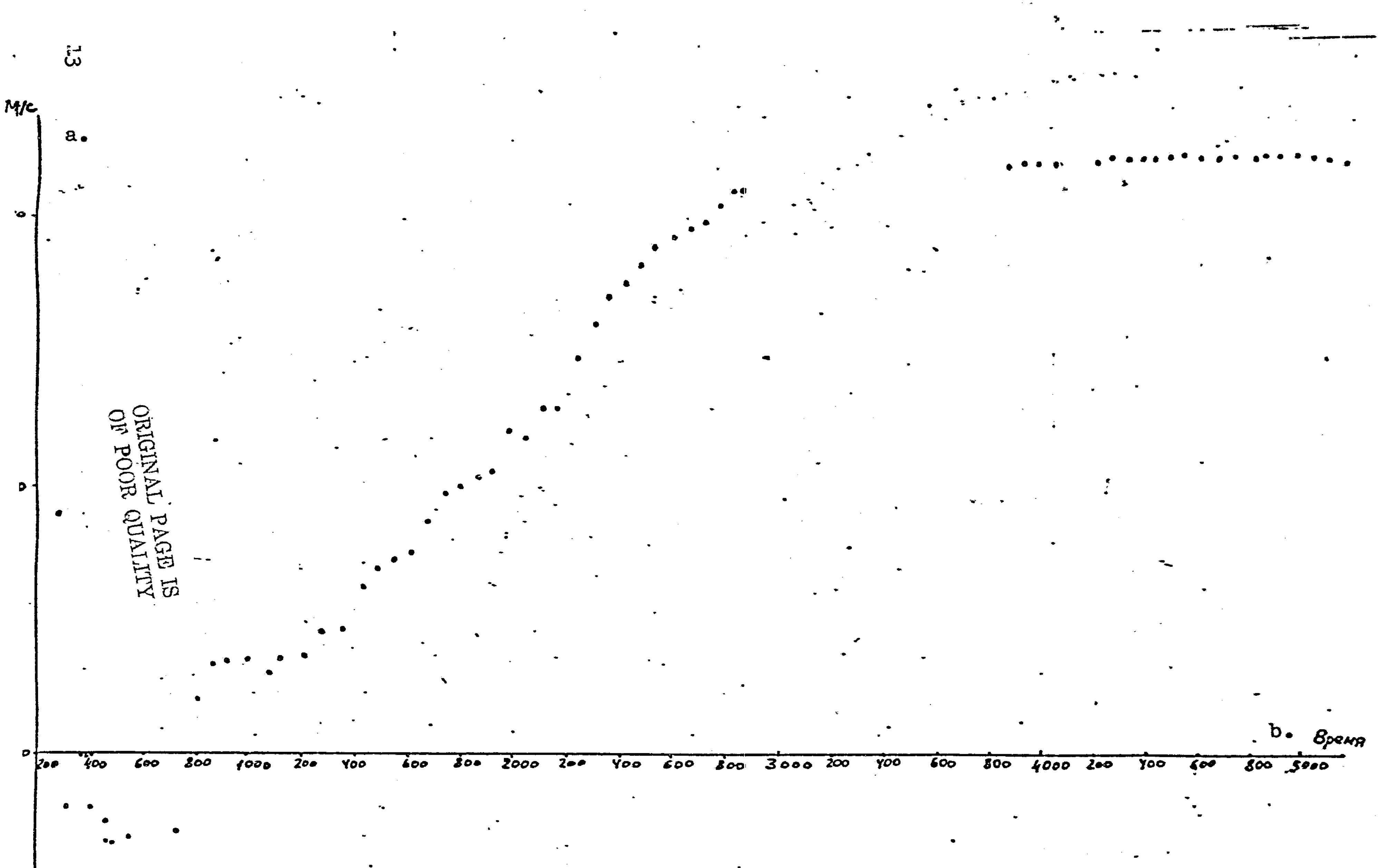

Fig. 3. (following page). The Doppler remainder of Venera-12. Key:

a, m/sec b, time

c, V11 d, V12

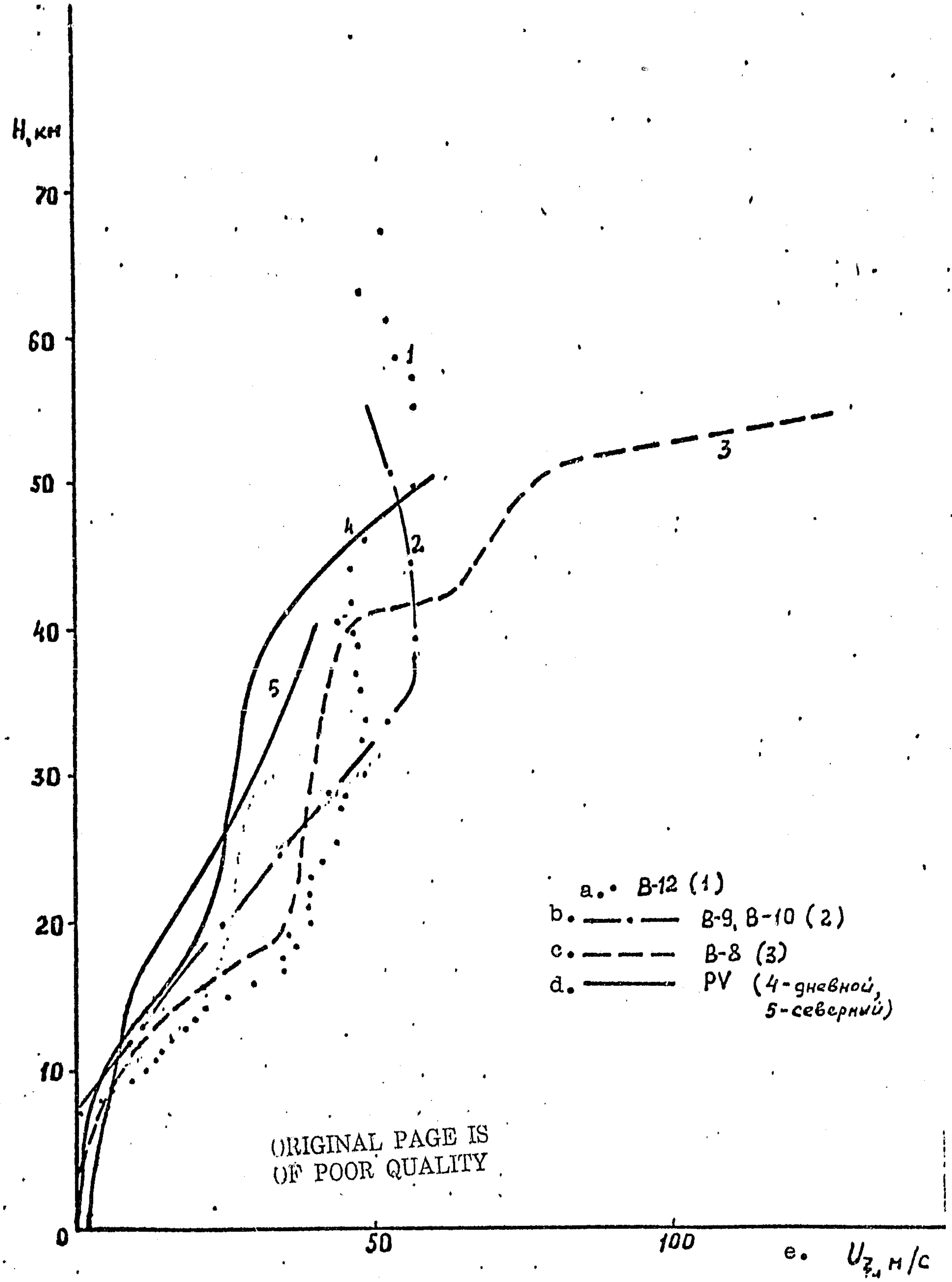

Fig. 4. Wind speed profile from the measurements of Venera-12 (dots), Venera-8 (1), and Venera-9,10 (2). Key: a, V-12 (1); b, V-9, V-10 (2); c, V-8 (3); d, PV (4 - day, 5 - evening); e, U_z m/sec.

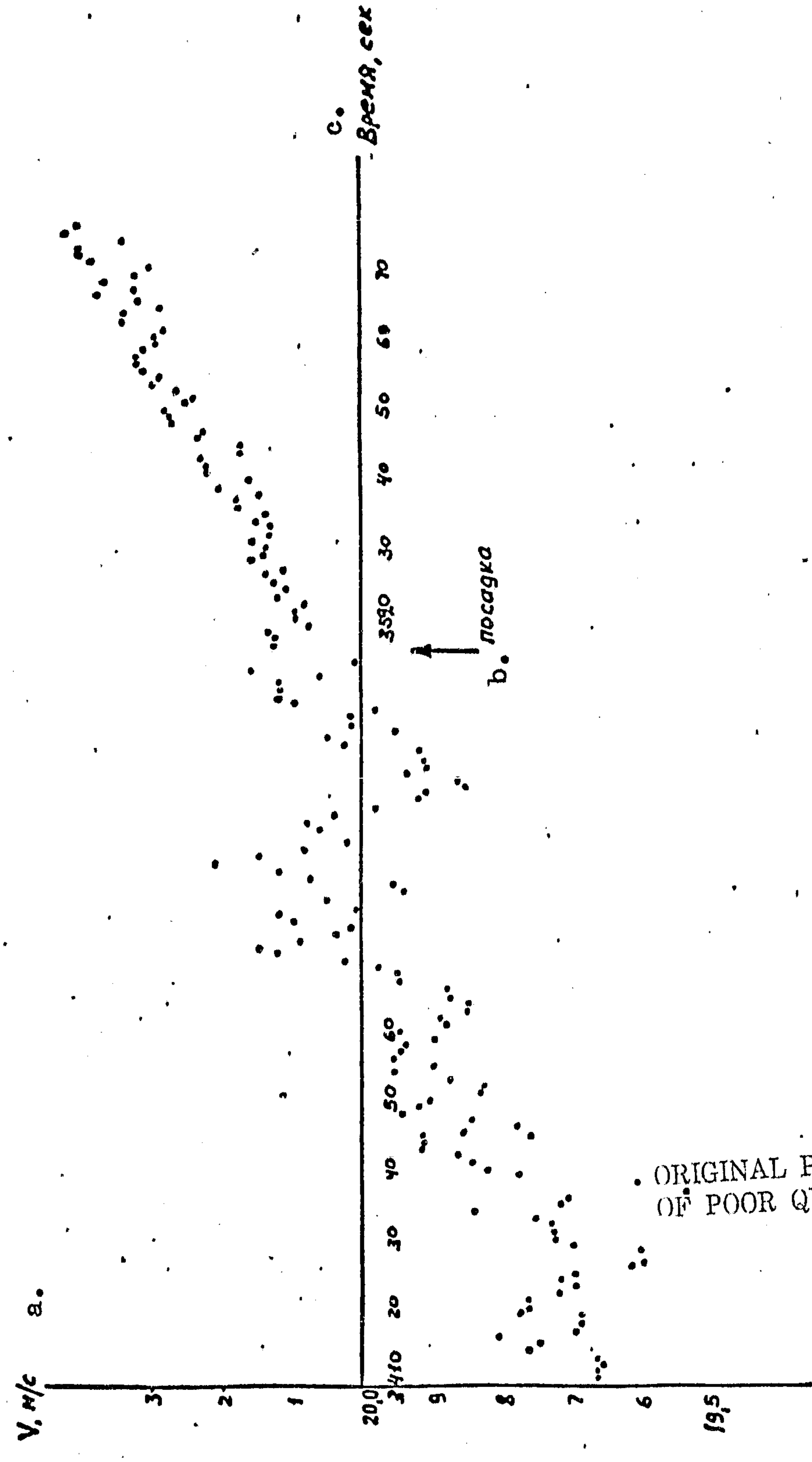

Fig. 5. Doppler remainder of Venera-12 near the touchdown point. Key: a, V, m/sec; b, touchdown point; c, time, sec.

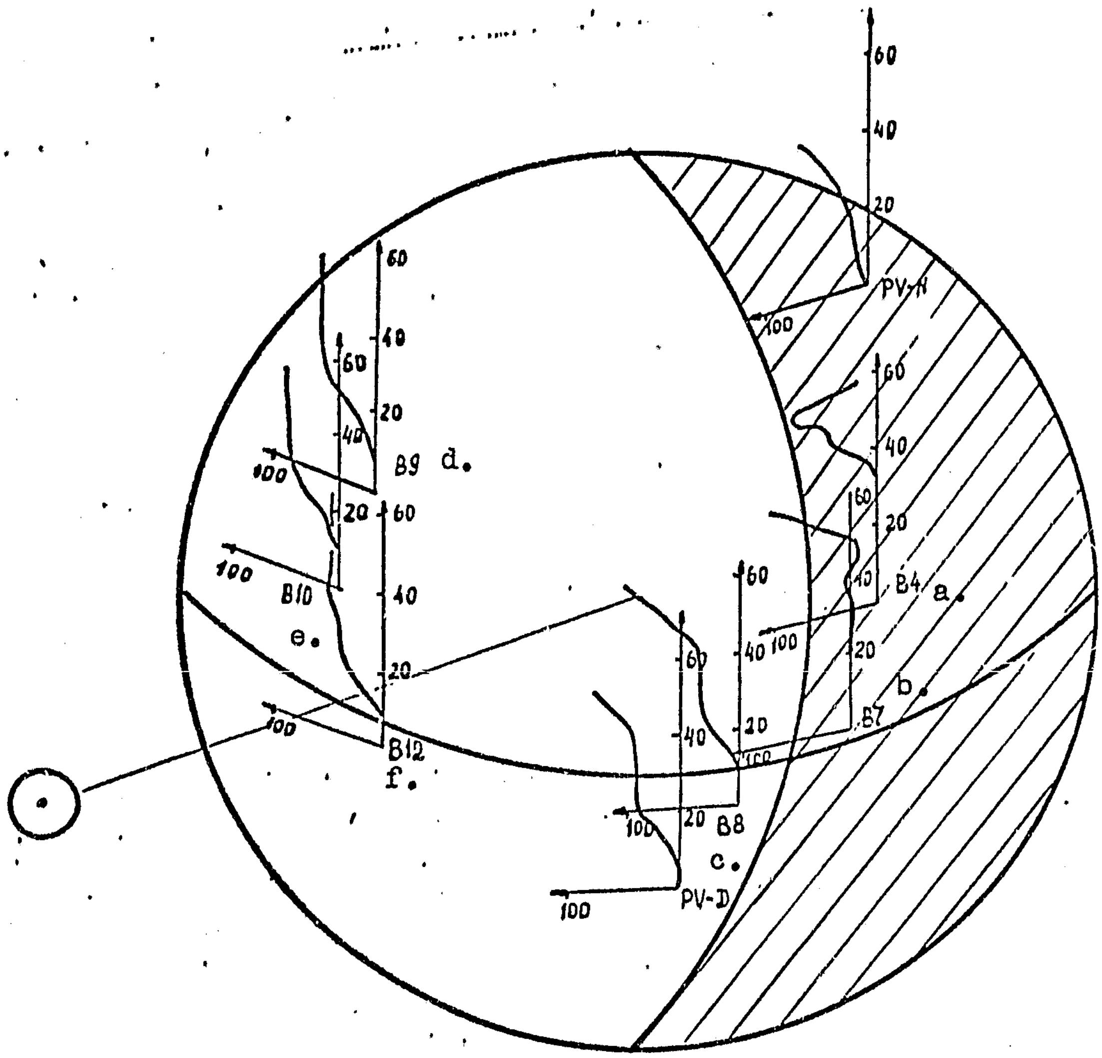

Fig. 6. General diagram of the wind speed profiles in the atmosphere of Venus. Key: a, V4; b, V7; c, V8; d, V9; e, V10; f, V12.

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