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ABSTRACT

The results of the Soviet and American spacecraft plasma and magnetic experiments showed that a bow shock of Venus forms as a result of the direct interaction of the solar wind with the ionosphere. The shape and the position of Venus bow shock, in general, correspond to a very weak dissipation of the solar wind energy in the ionosphere.

The magnetic and plasma measurements showed that Venus has the plasma-magnetic tail in some features similar to the tails of the planets having intrinsic magnetic field. However, the measured magnetic field near the planet is strongly influenced by IMF; may be this fact is the evidence of induced magnetosphere. Some results of laboratory simulation and computer experiments are also in favour of such induced magnetosphere.

The interaction with the ionosphere manifests itself in the existence on the night side of the boundary region where the solar wind inflow into the optical umbra of the planet is observed.

Some other observed results which were interpreted as the evidence of solar wind-ionosphere interaction in the presence of induced magnetic field are discussed.

Introduction

Venus can be considered as one of the most fundamentally studied (after the Earth) planet of the Solar system.

The soviet and american space vehicles such as satellites, landers and fly-by missions acquired vast information about the atmosphere, ionosphere, plasma and magnetic field near Venus.

The review of Bauer et all. (1977) "The Venus ionosphere and solar wind interaction" contained the brief description of the current state of this problem. The concluding remarks of this review are that at present we have already known "what occurs" near Venus "without giving clues as to why, to what extent and under what conditions" it occurs.

Among the main unsolved problems Bauer et al. indicated the following:

1. Is there an intrinsic magnetic field?
2. How do ionospheric currents contribute to the deflection of the solar wind and how much of the solar wind is absorbed by the planetary atmosphere?
3. How important is the solar wind in forming the dayside ionopause and what is the mechanism of momentum transfer from the solar wind to the upper ionosphere?
4. What is the cause of the variability of the dayside ionopause height?
5. Is there a magnetotail and what are its properties?

a) what is the mechanism responsible for the solar wind plasma inflow into the tail; is there a rarefaction region due to the magnetosheath plasma expansion to the nightside cavity or is the boundary layer formed?

b) is it possible in the latter case to consider the boundary layer properties similar to those of the Earth plasma mantle and, therefore, to consider the mechanisms of their formations also similar or the boundary layer is formed due to intermixing the ionospheric and solar wind plasmas?

c) are there a plasma sheath, substorms and other phenomena in the Venus wake region typical of the Earth magnetotail?

6. What is the cause of the variability of the electron density profile in the nightside ionosphere and what produces one or two peaks in the profile?

The Venera-9 and -10 experiments clarified many questions from mentioned above. Before the Pioneer Venus program begins it is of interest to summarize all results we have recently obtained by the Venera-9 and -10 experiments and to attempt to answer the questions mentioned above on the basis of all the available experimental data and theoretical investigations.

1. Nature of the measured magnetic field near Venus

The nature of the magnetic field measured near Venus was the basic question among those raised as a result of the experiments by Mariner-2, Venera-4, Mariner-5 and Mariner-10. Dolginov and other authors (1968) of the magnetic experiments on-board Venera-4 estimated the upper limit of the dipole moment of the weak intrinsic magnetic field of Venus as 1/3000 M_E (M_E - the Earth dipole moment).

The estimations by Dolginov et al. (1969) based on the Venera-4 measurements and the Mariner-5 data brought about the value $M_V \approx (5 \text{ to } 8) \times 10^{21}$ gauss·cm^3 and the upper limit on the surface field of 2 to 4 γ .

Russell (1976a) revised and gave a new interpretation of the Venera-4 magnetic data and defined the upper limit of the magnetic moment as $M_E \sim 6.5 \times 10^{22}$ gauss·cm^3 corresponding to a surface field of about 30γ. The magnetic moment according to Russell's estimations was northward (i.e. opposite to the direction of the Earth magnetic moment); and magnetic field in wake behind Venus should be "from the Sun" in the northern hemisphere and "to the Sun" in the southern hemisphere independent of IMF direction. The data of Mariner-5 which had crossed the planet wake in the northern hemisphere confirmed Russell's assumption (1976b). The Venera-4 data which from Russell's point of view confirmed his assumption (1976b) actually contradicted it.

The Venera-9 and -10 measurements of the magnetic field were mainly carried out at the nightside of the planet and the pericentre altitude was much higher than the ionopause altitude at the dayside. During the evolution of orbits the pericentres shifted from the nightside to the dayside and the planetary wake was crossed at greater distances ($\sim 7\ R_V$). The detailed description of these magnetic measurements was presented by Dolginov et al. (1976, 1977). There were about 30 sessions of observations including 7 sessions with the corrected data of the simultaneous observations in the solar wind and the planetary wake at distances from 1.5 to 2.5 R_V. The observations in the wake at distances from 5 to 7 R_V were carried out only by the Venera--10 during 4 sessions.

The preliminary analysis of the Venera-9 and -10 data led the authors (Dolginov et al., 1977) to the conclusion that the elongation of the field along the Sun-Venus direction $(|B_x| \gg \gg |B_{y,z}|)$ is the main feature of its topology in the near and distant regions of the Venus tail. There are two lobes of field lines with the direction "to the Sun" and "from the Sun" separated by a region where the magnetic energy density has a deep minimum similar to that as it occurs "in the neutral sheet" of the Earth magnetosphere. The plasma properties in this layer are also similar to those in the Earth plasma sheath. Plasma measurements (Verigin et al., 1977) showed that at these distances (1.5 R_V) as well as at $4R_V$ the sign reverses of a B_X-component was accompanied by bursts of energetic ions ($\geqslant 2$ kev), e.g. on 25.11.75 (Fig. 1) (Verigin et al., 1977). The magnetic field in the wake at distances up to 2.5 R_V had a transverse component of the order of 5γ when the radial component was zero.

Dolginov et al. (1977) explained the totality of their experimental data for near and distant regions of the tail by the existence of the intrinsic dipole magnetic field of the planet with the north pole located in the northern hemisphere. The dipole magnetic moment has been estimated as $M_V \approx 3 \times 10^{22}$ gauss·cm^{-3} (the surface field of about 10γ). It was pointed out that the field had a prevailing direction "from the Sun" in the northern hemisphere and "to the Sun" in the southern hemisphere.

However, in the near tail (1400 to 2500 km) the following peculiarities were observed. In some cases the direction of Bx-component, measured during the entry of the vehicle deeply into the shadow, remained the same as in the solar wind and only further when the vehicle was approaching the planet, the direction of Bx-component was becoming adequate to a depole configuration independently of Bx sign in the solar wind.

There were also the cases when the field measured in the tail had everywhere the opposite direction as compared with the dipole direction expected in this hemisphere (see, e.g. Fig. 2, 30.10.75, Venera-9). Measurements from Venera-4 that had been approaching the planet in the northern hemisphere indicated that the magnetic field up to distance 200 km was directed "to the Sun" as well as IMF measured by the Mariner-5. This fact contradicted to the expected direction of the dipole field in the northern hemisphere. As may be seen from Fig. 3 (the Venera-9 and -10 data) the directions of Bx-component in the northern and southern hemispheres often differed from the expected for the dipole field. Dolginov et al. (1977) indicated that the "superposition" of IMF and the intrinsic field of Venus might be a possible reason of the observed picture. Another possible reason might be associated with the effects of current system induced by the solar wind in the ionosphere. Eroshenko, one of the authors of the magnetic experiments, attempted to reveal these effects using the data of the simultaneous measurements of IMF and the magnetic field in the planet cavity obtained by Venera-9 and -10 (Dolginov et al., 1977). The analysis was carried out under assumption that if the variations of the magnetic field components inside the cavity are due to induction effects, the field properties near the planet should depend on the transverse $B_\perp$ -component of IMF.

Fig. 4 shows the directions of both Bx-radial component measured along sections of seven trajectories in the cavity (view from the Sun) and the transverse component $B_\perp$ of IMF (arrows) measured 30, 20, 10 and 0 minutes (numbers 1, 2, 3, 4) before the measurements in the cavity. The dotted line aa' shows the plane normal to one of $B_\perp$ vectors. It is seen from

Fig. 4 that:

1) Bx with different directions are observed in the southern hemisphere at various periods of time;
2) aa' divides the tail into two hemispheres with different directions of Bx, Bx being directed "from the Sun" in that hemisphere where the vector $B_\perp$ is located.

Fig. 5 presents the data of all seven sessions of observations in the rotating coordinate system ($B_\perp$-axis is directed along the transverse component of IMF, X_{SE}-axis - to the Sun and Z' forms with X_{SE} and $B_\perp$ the right-hand coordinate system). Evidently, the B_x direction in the tail is defined by $B_\perp$: $Bx < 0$ ("from the Sun") to the right from aa' in that hemisphere where $B_\perp$ is located and $Bx > 0$ ("to the Sun") to the left from aa'. Certain asymmetry of the picture relative to a-a' axis is explained by Eroshenko by a possible aberration effect and measurement errors. Another explanation of this effect could evidently be the influence of a weak intrinsic planetary dipole magnetic field with the neutral sheet lying close to the ecliptic plane.

As seen from Fig. 4 the found dependence of Bx on $B_\perp$ remains valid if the time interval τ between the measurements of $B_\perp$ and Bx is not more than 20 minutes. Sometimes for $\tau \approx 30$ min this dependence is not already true and, therefore, Eroshenko considers $\tau \approx 30$ min as the upper limit of the time-delay between the variations of $B_\perp$ IMF and the field reconstruction in the tail. This value is consistent with his numerical estimation of the time of the magnetic field diffusion through the ionosphere $\tau = 4\pi \sigma L^2 \approx 30$ min with $\sigma \approx 1$ to $2\times10^{-2} M_0/m$ and $L \approx 400$ km (characteristic linear scale of the ionosphere). Using the plasma data obtained by Vaisberg and Greengauz groups Eroshenko calculated $E_\infty = -\frac{1}{c}\left[\vec{V} \times \vec{B}\right]$ in the solar wind and analyzed the dependence of the averaged value of the field in the cavity $|B_{mean}|$ on E_{∞} for all seven sessions of observations (see Fig. 6). The value of $|B_{mean}|$ in the tail tends to grow with E_{∞}.

The correlation, Eroshenko obtained between the direction of IMF and the direction of the field in the near tail means that the induction effects are prevailing in forming the magnetic field in the wake behind Venus. Thus the analysis of the magnetic measurements data in the tail shows that the permittable upper limit of the intrinsic venusian magnetic field value is lower than that previously estimated without taking into account the contribution of external sources.

2. Contribution of ionospheric currents to the formation of the obstacle near Venus and the value of the solar wind absorption by the ionosphere

a) Contribution of ionospheric currents to the formation of the obstacle.

Rather simple considerations show that the conducting plasma shell of the planet may be an obstacle for the solar wind plasma since the magnetic field of the solar wind and, therefore, particles of the interplanetary plasma "frozen" into it, can not penetrate into such shell. The magnetic field of the solar wind in such case should be deformed in the interaction region and a typical "magnetic cushion" forms. In the case of finite conductivity of the ionosphere the IMF partially penetrates into the ionosphere. As a result an electric current is induced in the ionosphere and its circuit is closed by current in the solar wind. The total magnetic field of induced currents together with the magnetic "cushion" is usually called an induced magnetosphere.

The possibility of the induced magnetosphere formation near nonmagnetic planets was first suggested by Dessler (1968), Johnson and Midgley (1968). Further some calculations were performed (Cloutier and Daniell, (1973), Cloutier, (1976), Daniell and Cloutier, (1977), Horning and Schubert, (1974)) and the laboratory (Andreanov and Podgorny, (1976)) and numerical simulations (Lipatov, 1976, 1977, 1978) of the induced magnetosphere formation were carried out for the dayside of a nonmagnetic planet with a ionosphere similar to the Venus ionosphere.

Cloutier and Daniell (1973), Cloutier (1976), Daniell and Cloutier (1977) presented the approximate model of the distribution of currents in the Venus ionosphere induced by the solar wind.

The electric field of the solar wind $E_\infty = -\frac{1}{c}\left[\vec{V}_\infty \times \vec{B}_\infty\right]$ existing in the coordinate system fixed with the planet can generate an electric current in the Venus ionosphere which in turn induces the magnetic field B_{ind}. If the total solar wind flux within the tube having a cross-section $\sim L^2$, where $L \approx 10^4$ km is a characteristic linear scale for the planet, comes into contact with the planetary obstacle, the potential difference across such an obstacle can reach $\sim$ 40 kv (V_∞ = 400 km/sec and $B_\infty = 10\gamma$). Since the solar wind in the post shock region is deflected by the obstacle the intensity of the plasma flux coming into contact with the obstacle defining the potential difference depends on the character of solar wind and obstacle interaction. Spreiter et al. (1970) assumed that the ionopause is an unpenetrable obstacle and, therefore, there is no electrical contact between the solar wind and the ionospheric plasma. The early experimental data obtained near Venus (Bridge et al., 1974; Ness et al., 1974) showed that the position of the shock is in well agreement with the Spreiter et al. assumption. The calculations by Cloutier et al. (1969), Mitchel (1971) and Cloutier (1976) also showed that the Venus ionosphere is evidently almost an unpenetratable obstacle.

Based on this concept Daniell and Cloutier (1977) while calculating the currents and potentials in the ionosphere (Fig.7) used for $\vec{E}_n = -\frac{1}{c}\left[\vec{V}_\tau \times \vec{B}_\tau\right]$ the values of V_τ and B_τ in the post shock region from Spreiter et al.' model where the ionopause was considered to be the equipotential surface and $V_n = B_n = 0$, $E_\tau = 0$ on it. Then, they assumed that E_n is continuous on the ionopause and only the insignificant part of the solar wind is absorbed by the ionosphere. The ionosphere conductivity was calculated using a neutral atmosphere model and a given value of the magnetic field $B_{ind} \sim 20\gamma$ in the ionosphere. The calculated magnetic field value was then adjusted to the given value of B_{ind}. The boundary of the magnetosphere induced by a current flowing in the conductivity maximum of the ionosphere was determined from the condition that the field B_{ind} of this current should conceal the post shock solar wind magnetic field on the planetary surface. It follows from Figs 7a and b that the ionopause is not already an equipotential surface and the potential difference across the poles applied to the ionosphere is about 20 to 30 v. Certainly, since the calculations of Daniell and Cloutier were not self-consistent their model gave only a qualitative picture of the current distribution. However, it permits the solar wind absorption by the ionosphere to be estimated, and, evidently, these estimations are rather close to reality since they are based on Spriter et al. model which, as mentioned above, is in good agreement with the experimental data. As it has been shown above the total-potential difference applied to the ionosphere in case of an undisturbed solar wind flux is about 40 kv. Since according to Daniell and Cloutier $\varphi \approx 20$v only 0.05% of the solar wind flux should be absorbed.

The direct numerical simulation of the interaction between the solar wind and the dayside stationary (without convection) Venus ionosphere with finite conductivity was performed by Lipatov (1976, 1977, 1978). In his model of 1978 the concentration of magnetic field lines is obtained near the ionopause (magnetic cushion). The finite conductivity of ionosphere causes the magnetic field diffusion into it and the formation of a magnetohydrodynamical boundary layer. The typical thickness of this "stagnation" region with the magnetic field of the "cushion" several times stronger than the solar wind magnetic field is comparable to the ion gyroradius in this field. Fig. 8 gives the distributions of density, field lines and plasma flow lines in the equatorial (XZ) and meridional (YZ) planes in Lipatov's model. It is seen from this Figure that plasma flow lines go round the region of the intense magnetic field. In regions with the relatively weak magnetic field the plasma inflowing the ionosphere partially draws in the magnetic field; it occurs at high latitudes (see Fig. 8) for B_∞ direction chosen by Lipatov. Evidently, the magnetic field from the "cushion" region should be swept away by the solar wind to the nightside forming the elongated magnetotail.

Fig. 9 presents the qualitative picture of the current distribution in the dayside ionosphere that is in good agreement with the induced field distribution measured in the near tail by Venera-9 and -10 (presented by Eroshenko). Eroshenko suggests that field lines of the magnetic field induced by a transverse component of IMF stretch towards the nightside and close in the wake behind the planet. Fig. 9 also agrees with the current distribution obtained by Daniell and Cloutier (Fig. 7) and with Lipatov's qualitative picture.

The results of laboratory experiments on the simulation of the Venus induced magnetosphere are of great interest; these experiments were first carried out by Andreanov and Podgorny (1976) and are now under way by Podgorny and his colleagues.

In these experiments an artificial ionosphere formed by the vaporisation products of the wax sphere placed in the flow of the hydrogen plasma with the frozen-in magnetic field. This artificial ionosphere turned out to be an obstacle with which the flow interacted. The induced magnetosphere was observed in the dayside of the artificial ionosphere with magnetic field lines directed along its boundary (Andreanov, Podgorny, 1976). These experiments were also carried out for the wax sphere night side. Arrows on Fig. 10a show the measured directions of the magnetic field in the vicinity of the wax sphere. The reorientation of the magnetic field vectors in the incoming flow is clearly seen near the symmetry plane at the nightside. It is evident that such a field configuration is typical of the magnetotail.

Since in this experiment short pulses of the incoming plasma flow (10 to 20 msec) were used the magnetic field disturbances could be caused not only by the electric field $\vec{E} = -\frac{1}{c}[\vec{V} \times \vec{B}]$ but also by the induction field component $\frac{\partial B}{\partial t}^{\circ}$. The relative significance of these effects was revealed in additional experiments using a metallic sphere. The disturbances in the vicinity of the metallic sphere and near the same sphere but surrounded by a glass shell were compared. In the latter case only the induction mechanism $\frac{\partial B}{\partial t}$ worked. Fig. 10b shows the magnetic field flow disturbance only due to $\vec{E} = -\frac{1}{c}[\vec{V} \times \vec{B}]$ that agrees with Eroshenko's interpretation (Dolginov et al. (1977).

It is evident that the last laboratory experiments of Podgorny and his colleagues illustrate that the Venus magnetosphere induced by the electric field $\vec{E} = -\frac{1}{c}[\vec{V} \times \vec{B}]$ may possess a magnetotail stretching up to ten planet radii. These results are in good agreement with the picture of the magnetic field observed in the Venus tail by Venera-9 and 10.

b) Absorption of the solar wind by ionosphere

As mentioned above, the position and the shape of the shock front depend on the obstacle properties. The data obtained for 33 crossings of this front by Venera-9 and -10 (Verigin et al., 1977) confirmed that the front position is really in good agreement with Spreiter et al. calculations (1970) for $H/r_0 \approx$ ≈ 0.01 to 0.02. Thus, the statistically rich experimental data obtained on Venera-9 and -10 as well as the previous experimental data indicate that there is no significant solar wind energy dissipation in the Venus upper atmosphere (Fig. 11). At present these data are the only that confirm the assumption about the negligible absorption of the solar wind by the ionosphere.

Russell (1976c, 1977) suggested that the solar wind absorption by Venus ionosphere could reach 30%. In this case the shock front may significantly approach the planetary surface and the bow shock become attached. Russell's assumption was based on his calculations of the subsolar point distances for both the shock and the ionopause. Experimental points of shock front crossings by Venera-4 and -6, Mariner-5 and -10 and only two points of the Venera-9 and -10 crossings were approximated by a surface of revolution a conical section with a focus located in the planetary center. It should be noted that Russell's results are somewhat formal in spite of the fact that he critically revised all the previous experiments. Nevertheless Romanov et al. (1977) confirmed Russell's assumption and interpreted the results of the ion measurements with narrow-angle analyzers on board Venera-10 (19.04.76) as a case of extraordinary close shock front position (zenith angle $\chi = 69^{o}$). The ion spectra observed in magnetosheath showed multicomponent structure with one of the components being weakly thermalized and decelerated solar wind. The authors assumed that in this case the bow shock might be attached and correspond to the case of low ionopause height obtained by the radio-occultation data. However, the direct comparison with the simultaneous radio-occultation data was failed; according to the data of electron and ion plasma observations by wide-angle analyzers on board Venera-9 and -10 the shock front on 19.04.76 was crossed at greater distance from the planet than according to data obtained by narrow-angle analyzers and the shock front position was also in agreement with that calculated by Spreiter et al. (1970) (see the point of front crossing for the minimum value of χ on Fig. 10 (Verigin et al., 1977)).

The conclusion that the solar wind flow in the ionosphere can be of the same order of magnitude as in the magnetosheath was made by Bauer and Hartle (1974) who suggested the model describing a dayside Ne(h)-profile obtained during the radio-occultation of Mariner-10. The low height of the ionopause on the dayside Ne(h)-profile, according to their opinion, could be explained by the effect of a direct inflowing of the solar wind.

It is difficult to estimate the real value of the solar wind absorption by Venus atmosphere until the direct measurements of the dayside atmosphere temperature, composition as well as the magnetic field in the subsolar region are carried out and the role of B_{ind} in the pressure balance on the ionopause is known.

However, the estimations of high absorption by the ionosphere given in papers mentioned above does not seem convincing because of the following: 1) experimental data about the shock front position are in good agreement with gas-dynamical calculations for an unpenetratable obstacle; 2) Russell's assumption of a high solar wind absorption may be matched with any model of an induced magnetosphere (Daniell and Cloutier, 1977; Lipatov, 1977, 1978) if only the ionosphere conductivity is damaged (by several orders of magnitude) that does not agree (see below) with the properties of the upper Venus ionosphere and atmosphere obtained in the radio-occultation experiments and in the simulation calculations that agree with the experimental data.

Indeed, if B_{ind} takes part in the interaction of the Venus ionosphere with the solar wind the increase of the solar wind flow must make B_{ind} higher. As it can be estimated in accordance with Daniell and Cloutier (1977) the increase of B_{ind} up to 80γ (instead of 20 γ they used) the pressure balance being sustained the solar wind absorption remains equal to 0.1%, i.e. significantly less than that of Russell's. From Lipatov's calculations (1977, 1978) it follows also that the increase of the solar wind flow leads to the increase of a "field pumping" effect on the dayside and of a boundary layer thickness and to removal of an obstacle boundary from the planet together with the shock front.

Thus, the experimental data and the results of theoretical calculations permit the following conclusions to be made: i) ionospheric currents induced by the solar wind are evidently essential for the interaction mechanism of the solar wind with Venus and are of prime importance for the distribution of magnetic field in the wake behind the planet; and (ii) on the dayside the absorption of the solar wind by the atmosphere must be of the order of fractions of per cent or of one per cent but not tens of per cent.

3. On the mechanism of solar wind momentum transfer to the ionosphere and pressure balance on the ionopause

As mentioned above the direct contribution of the magnetic field B_{ind} to the pressure balance on the dayside ionopause is still unknown because of the lack of the corresponding experimental data. However, the existence of B_{ind} clarifies the question under discussion about the mechanism of momentum transfer from the solar wind to the ionosphere.

The dayside ionosphere boundary, the ionopause, was constantly observed on thirteen profiles obtained during radio occultation experiments from Venera-9 and -10 (Ivanov-Kholodny et al., 1977, 1978) as a sharp decrease of Ne-density by the order of magnitude at distance of 50 to 100 km.

The solar wind streaming pressure on the ionopause with $n_\infty = 10\ \text{cm}^{-3}$ and $V_\infty = 400\ \text{km}\cdot\text{sec}^{-1}$ is about $K\rho_\infty V_\infty^2 \approx 2.5 \times 10^{-8}\ \text{din/cm}^2$. Besides B_{ind} only the pressure of the ionospheric plasma can practically make contribution to the pressure balance on the Venus ionopause.

The experimental data about T_e and T_i in the Venus ionosphere are not still available but it is evident that if B_{ind} does not contribute significantly to the pressure balance the temperature of the ionosphere plasma $T_e + T_i$ must be ~ 1.5 ev in order to provide the proper pressure balance the measured density in the ionosphere near the ionopause being equal to $N_e \approx 10^3$ to $10^4\ \text{cm}^{-3}$. It is impossible to provide such high temperatures of the ionospheric plasma only by ionospheric internal sources of heating. In order that high temperatures are provided by the solar wind energy transfer to the ionosphere it is necessary that an anomalous heating mechanism is present in the ionosphere and a heat conduction near the ionopause is low. The small thickness of the ionopause $d_i \lesssim 10^2$ km exceeds the solar wind momentum transfer to the ionosphere due to gas-kinetic and Coulomb collisions (gas-kinetic and Coulomb free path lengths of the solar wind particles in the upper Venus atmosphere at the ionopause height λ_g and $\lambda_c \approx 10^6$ to 10^5 km with $n_n \approx 10^4$ cm^{-3} (Broadfoot et al., 1974, Chan and Nagy, 1977), i.e. are much greater than the ionopause thickness.

In principle, the solar wind momentum transfer to the ionosphere and the anomalously low heat conduction near the ionopause could be provided by a collective deceleration of the solar plasma flux while interacting with the ionospheric plasma due to, e.g., a two-stream instability.

However, since such plasma instabilities lead not only to the momentum but also to the energy transfer the interaction should be extremely inelastic. The latter should contradict to the available experimental data about the shock front position well described by the elastic interaction model (see Section above) and to the data (to be discussed below)about the steady dayside ionosphere boundary.

Thus, the solar wind momentum must evidently be transferre to the ionosphere through the magnetic field. In this case the Larmor's radius of ions $r_{\lambda i} \sim \frac{V_\infty mc}{eB_{ind}} \approx 100$ km (for B_{ind} $\sim 40\gamma$) which is comparable with the ionopause thickness become a characteristic scale for such an interaction. The existence o a horizontal induced magnetic field in the upper ionosphere mus automatically result in decreasing the transverse heat conducti and sustaining the high plasma temperature in it.

The laboratory experiments mentioned above on the simulation of the solar wind interaction with Venus (Andreanov and Podgorny, 1976) perfectly illustrated the importance of the magnetic field $B_{ind.}$ to the processes of momentum transfer from the solar wind to the ionosphere. In these experiments the induced magnetosphere with magnetic field lines directed along the artificial ionosphere boundary was observed. However, the induced magnetic field appeared to be insufficient to deflect the flow and the plasma momentum was mainly transferred directly to the ionosphere. The momentum transfere mechanism itself worked only in the presence of the magnetic field frozen-in the artificial solar wind, i.e. in the presence of B_{ind}. A shock wave and a sharp boundary of the obstacle in the plasma flow without the frozen-in magnetic field was not observed.

Thus, though the contribution of the magnetic field $B_{ind.}$ to the pressure balance on the ionosphere dayside boundary is still unknown it is obvious that the induced magnetic field defines the formation of a sharp boundary between two plasmas and the momentum transfere from the solar wind to the ionosphere.

4. The cause of the variability of the dayside ionosphere height

Experimental $N_e(h)$-profiles in the dayside Venus ionosphere prior to Venera-9 and -10 were obtained by means of radiooccultation measurements in fly-by missions of Mariner-5 (Stenford's group, 1967) and Mariner-10 (Howard et al., 1974).

As known, the heights of the upper boundary of the ionosphere h_i for these profiles were rather different ($\sim$ 500 km from the Mariner-5 data and $\sim$ 350 km from the Mariner-10 data).

Besides this the Mariner-5 profile had an elongated region of, evidently, constant electron density over the main maximum.

Since $N_e(h)$-profile from Mariner-5 corresponded to a lower solar zenith angle ($\chi = 33^{\circ}$) than that from Mariner-10 ($\chi = 67^{\circ}$) the ionopause height decrease with the increasing o χ was not in agreement with the expected dependence $h_i(\chi)$ (Spreiter et al., 1970, Bauer, 1973) which followed from the Newtonian approximation for the solar wind streaming pressure $K\rho_{\infty} V_{\infty}^2 \cos^2\chi$.

Since $\rho_{\infty} V_{\infty}^2$ was a bit higher, according to preliminar data of Mariner-10[*)], than that for the Mariner-5 experiment, an assumption was made that on increasing the streaming pressur of the solar wind the latter drawn in ionosphere photoions at altitudes where the pressure balance was not satisfied. As a result the shape of $N_e(h)$-profile is distorted due to ionosphe particle downstream transfere with a velocity of about 10 km/s As mentioned above, this assumption allows the significant absorption of the solar wind by the Venus' ionosphere to be estimated (Bauer and Hartle, 1974).

From these data one might conclude that the dayside ionosphere is being compressed by the solar wind with the increasi of its streaming pressure.

To check the last conclusion it is of great interest to analyse ionopause positions on thirteen dayside $N_e(h)$-profil obtained for $\chi \lesssim 90^{\circ}$ during the radio occultation experiments

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[*)] According to the data on electron component of the solar wind was preliminary; the final value of V_{∞} is not available at this time (Bridge et al., 1976).

carried out on Venera-9 and -10 (Aleksandrov et al., 1977, Ivanov-Kholodny et al., 1978). Fig. 12 shows the latitudinal dependence (or the dependence on a solar zenith angle) of a ionopause height according to the radiooccultation data from Venera-9 and -10 and from Mariner-5 and -10.

As seen from Fig. 12 h_i is steadily increasing with the increasing of χ for $\chi \leq 80^{\circ}$ and somewhat decreases for $\chi \geq 80^{\circ}$. The Mariner-10 value of h_i is consistent with the dependence plotted on Fig. 12, but the Mariner-5 value falls out of it.

According to the Venera-9 and -10 data an "ionosheet", the region with approximately constant Ne over the ionization maximum (Fig. 12c), was observed only for $\chi > 70^{\circ}$. This fact contradicts to the Mariner-5 data ($\chi = 33^{\circ}$). Aleksandrov et al. (1976) in their first publications presented the Ne (h) -profile for $\chi = 14^{\circ}$ (Venera-10, on 2.11.77) with the "ionosheet" and the ionopause at altitude 500 to 540 km. However, in their recent paper (Ivanov-Kholodny et al., 1977) the ionopause height was estimated to be about 260 to 270 km for the corrected profile and $\chi = 14^{\circ}$. The interpretation of the radiooccultation data, as known, meets certain difficulties in taking into account the contribution of the interplanetary and the terrestrial ionosphere plasma density to the measured total electron content along a propagation ray-path. Evidently, difference in Ne(h)-profiles for $\chi = 14^{\circ}$ mentioned above, may be explained by these difficulties.

The Mariner-5 data interpretation also meets similar difficulties. In addition, because of caustic formations the data between the 250 and 500 km altitude were not obtained.

Therefore, the Mariner-5 data will not be taken into consideration and the corrected Venera-9 and -10 data will be used below. Then all observed values of h_i (including the value from the Mariner-10 data) are well described up to $\chi = 78^\circ$ by $h_i(\chi)$-dependence obtained from the pressure balance of t ionosphere with the solar wind streaming pressure $K\rho_\infty V_\infty^2 \cos^2$ (Spreiter et al. (1970)). The scale height H for Ne(h)-profi beneath the ionopause up to $\chi = 68^\circ$ was about 20 km and for $\chi > 73$-74° H reached the value from 100 to 200 km, i.e. t "ionosheet" was being formed (see Fig. 12c). Hence, the experimental values of H were also in agreement with the small values of H/r_0 equal to about ~ 0.01 obtained by Spreiter et al. (1970). It should be noted that Cloutier and Daniell ionospheric current model (1973) is, in general, in good agreement with the results obtained by Venera-9 and -10. Cloutier a Daniell (1973) based on the Spreiter et al. model (1970) obta ed the abrupt change in the character of the latitudinal dependence of induced currents for $H/r_0 \approx 0.01$ and $\chi \approx 75$ to 80°, i.e. approximately for the same latitudes where the Venera-9 and -10 data had shown a peculiarity in the steady increase o h_i with the increasing of χ.

It should be emphasized that the Venera-9 and -10 radio-occultation data given in Fig. 12a were obtained in different days and even on different months and under various conditions in the solar wind. The preliminary analysis of the ionopause height dependence on the solar wind streaming pressure carried out by Breus and Verigin for some measurements of Ne(h)-pr files and $\rho_\infty V_\infty^2$ (with short time intervals about 20 to 30 between these measurements) did not reveal the regular depende of h_i on $\rho_\infty V_\infty^2$ (Table 1).

Table 1

$\chi°$	h_i, km	$\rho_\infty V_\infty^2$, 10^{-8} din/cm^2
46	285 to 295	1.4
58	280 to 300	5.6
74	370 to 480	4.2
87	545 to 565	7.1

The stable position of the boundary relative to the variations of $\rho_\infty V_\infty^2$ means that either B_{ind} determines the pressure balance on the ionopause, or the increase of $\rho_\infty V_\infty^2$ makes the ionosphere heater near the ionopause, that occurs with the participation of B_{ind}.

In case when plasma instabilities are forming a boundary, as discussed above, from general considerations it is obvious that the boundary position should depend on what distance is located the region where the conditions necessary for switching on the main instability are fulfilled. The boundary position should depend on the parameters of the solar wind flux and the obstacle; and in the general case it should be shifted, when the incoming flux characteristics change. It seems rather doubtful that the mutual exclusion of the effects of various parameters involved in this process occurs in such a way that the boundary remains motionless.

Interesting results were obtained in the Venus dayside ionosphere models by Negy et al. (1975) and Chen and Negy (1978) concerning the contribution of the ionospheric plasma to the pressure balance on the ionopause. Chan and Negy developed the self-consistent model of the distribution of ion components, Ne, Te and Ti, in the ionosphere for various conditions of the solar wind momentum transfer to the ionosphere. Ne(h)-profiles they obtained are in good agreement with the experimental ones near the main peak of ionization; and temperatures Te + T_i $\sim$ 1000 to 1700°K for $\chi \sim 60^\circ$ correspond to the scale-heights obtained by Venera-9 and -10 in the upper ionosphere (see above). However, such low temperatures can not provide the pressure balance with the solar wind and it means that the induced magnetic field may evidently make a significant contribution to the pressure balance.

Chan and Negy also showed (1978) that velocities of the vertical transport of ionospheric particles $\sim$ 10 km/sec at the upper boundary (as Bauer and Hartle suggested (1974)) due to the direct effect of the solar wind do not permit within the framework of their model the ledge on the Ne(h)-profile observed at 180 km to be obtained. According to Negy et al. calculations (1975) the existence of such peculiarity could also be explained by the vertical transport of ionospheric mass upward and its horizontal transport toward the terminator from the subsolar region with the velocity of about 10 km/sec. However, such velocities for vertical transport are too great. Therefore, Chan and Negy (1978) assumed the possibility of particle transport downward with 10 cm/sec at all ionosphere levels up to the main peak of ionization but not only at the upper boundary as assumed by Bauer and Hartle (1974). However, these considerations are not checked yet calculations.

Thus, the radio occultation data obtained for the dayside ionosphere and the ionopause position h_i permit, at present, the following conclusions to be made:

1) the ionopause height h_i in the dayside ionosphere regularly depends on a zenith angle χ for $\chi \leq 80^{\circ}$; variations of h_i approximately correspond to the pressure balance in a Newtonian approximation and to the ionopause position described by Spreiter et al. calculations (1970) for $H/r_0 \sim 0.01$ and $r_0 = 6350$ km;

2) this dependence is in a good agreement with the position of both the shock front and the magnetotail boundary observed in the plasma and magnetic experiments (Greengaus et al., 1976, Vaisberg et al., 1976);

3) the decrease of h_i for great values of χ can be associated with the transient conditions near the terminator since the ionization is practically absent on nightside Ne(h)-profiles even for $\chi = 102^{\circ}$ at altitudes higher than 150 km;

4) the "ionosheet" - an extended region over the main peak of ionization with approximately constant Ne - was formed for $\chi > 70^{\circ}$;

5) the dependence of the ionopause position on a zenith angle with a peculiarity at $\chi = 80^{\circ}$ does not evidently contradict the calculations of the latitudinal dependence of induced currents in the Venus ionosphere (Cloutier and Daniell, 1973);

6) the stable position of the ionopause with different streaming solar wind pressures means that either B_{ind} is of prime significance in the pressure balance or B_{ind} increases with the increasing of $\rho_{\infty} V_{\infty}^{2}$ and, as a consequence, the ionospheric temperature near the ionopause becomes higher;

7) the above conclusions are not final because of some am-

biguity of radio occultation data and the discrepancy between the $h_i(\chi)$ dependence and the Mariner-5 data.

Many assumptions could be made about the nature of the "ionosheet". It can be assumed that it either consists of the ionospheric plasma (e.g. of helium ions) or the solar wind particles entering according to Lipatov (1978) into this region at the induced magnetosphere flanks or it is simply the internal (ionospheric) part of the boundary layer that develops at certain distances from the stagnation point. These new problems should be studied in future.

5. Plasma-magnetic tail

In contrast to previous experiments Venera-9 and -10 succeeded in obtaining the detailed distribution of ion and electron components and the magnetic field in the planetary wake deeply in the optical umbra. These measurements showed that Venus has a plasma-magnetic tail with its characteristic properties.

a) Boundary layer and the plasma inflow mechanism into the tail.

Outside a tail boundary in the magnetosheath and inside the optical umbra of the planet there were observed different phenomena indicating that the solar wind plasma inflow into the planetary tail, was being distributed along stretched magnetic lines forming a plasma-magnetic tail. At the dayside ionosphere boundary various instabilities decreasing the heat and electric conductivity of this region and accelerating the solar wind momentum transfer to the ionosphere (i.e. causing the viscous interaction of two plasmas) can be developed. As a result the boundary layer is forming extending from the stagnation point both into the ionosphere and into the magnetosheath. Different mechanisms forming such a boundary layer were suggested by Spreiter et al. (1976), Lipatov (1977-1978), Perez-de Tejada and Dryer (1976), Cloutier (1976), Hartle and Wu (1973),Hartle et al. (1976).

The boundary layer (or the corpuscular penumbra as called by Greengauz et al., 1976)) observed by Venera-9 and -10 (Vaisberg et al., 1976; Greengauz et al., 1976 and Verigin et al., 1977) is located asymmetrically relative to the calculated ionopause position $H/r_0 \simeq 0.01$ (Spreiter et al., 1970). Its thickness is about 1000 km near the terminator at the distance of about 2,000 - 4,000 km in the tail and its height over the surface near the terminator is about 800 km. At greater distances the boundary layer is broadening and its main part occupies the zone under the calculated ionopause (see Fig. 13, Verigin et al., 1977).It means, as Perez-de-Tejada and Drier (1977) have noted, that the viscous mechanism is responsible for the boundary layer formation when the solar wind plasma interacts with that of the ionosphere.

The Venus tail with its boundary layer extends at great distances. Some peculiarities in the properties of electrons with energies from 13 to 715 ev were observed by Mariner-10 at distances up to $80R_V$ in the wake. These peculiarities coincided with the expected characteristics of the external part of the boundary layer lying in the magnetosheath (Yets et al., 1977). Lepping and Behanon (1976) observed (Mariner-10 data) variations of the magnetic field typical of the case when the space vehicle passed through the planetary wake at distances $100\ R_V$.

The spectra with several maxima within different energy intervals and with one "major" maximum at the lowest energy E_{min} were recorded by means of wide-angle ion analyzers in the boundary layer at distances of about (2 to 5)R_V from the planet. The ion flux magnitude and E_{min} systematically decreased when the vehicle was moving from the bow-shock into the penumbra region (see Fig. 13, 19.04.76, Venera-9).

In the corpuscular penumbra there was observed an average decreasing of flux, density (more than by the order of magnitude), velocity (more than by a factor of 2 to 3) and a small (by a factor of 1.5) decreasing of ion and electron temperatures. According to these data the characteristic decrease of a bulk velocity in comparison with that in a magnetosheath corresponds to an external edge of the boundary layer.

The data of wide-angle analyzers (Greengauz et al., (1976)) do not allow an unambiguous conclusion to be made about the constant existence of the boundary layer since the time of boundary layer crossing is comparable to the time of full ion spectrum registration (160 sec, i.e. 1100 km).

Vaisberg et al. (1976) observed double-peak spectra over the sharp ionopause, in the region of "rarefaction wave" (as it was called in their first publications) or in the external part of the boundary layer (according to recent publications) (Romanov et al., 1977, Perez-de-Tejada, Dryer, Vaisberg, 1977). They observed the double-peak spectra under the ionopause too.

The sharp boundary within the boundary layer was always observed according to Vaisberg et al. (1976) and Romanov et al. (1977). It corresponded to the ionopause position for $H/h_0 \approx 0.01$ (Spreiter et al. (1970); the directed fluxes of the solar wind decelerated and thermalized plasma (E 1.9 to 2 kev and $T \sim 70-$ -100 ev) which were slower and heater than fluxes in the magnetosheath were recorded in the external part of the boundary layer. The plasma fluxes with energy of directed motion of about 150 ev ($V \sim 100$ to 200 km/sec) were observed under the ionopause. While approaching a tail axis the flux energy was decreasing up to $E_0 \sim 50$ ev and the flux magnitude was becoming lower than the analyzer sensitivity threshold. Vaisberg et al. (1976) and Romanov et al. (1977) assume that the low-energy plasma observed in the tail under the ionopause is of planetary origin. However, the ionopause is not an unpenetrable boundary. The noticeable component normal to the tail axis of a velocity vector is observed (according to the data of electrostatic analyzers) in the boundary layer for energetic and for low-energy components of the fluxes (see Fig. 4 of Vaisberg et al.' paper, 1976).

According to the data of wide-angle analyzers at close distances a distinct inflow of the solar wind electrons into the tail region was also observed both in the boundary layer (corpuscular penumbra) and deeply in the optical umbra (see Fig. 14, Verigin et al., 1977).

Besides the cases when plasma intermixing(double-peak spectra) was observed in the boundary layer Romanov et al. (1977) observed the cases when plasma intermixing was absent at distances from 1 to 2 R_V and in the remote regions of the tail, $\sim 5R_V$. In such cases bursts of energetic particles with $E \gtrsim 2$ to 9 kev at this boundary and the turbulent region of the plasma and the magnetic field above this boundary were observed.

These phenomena according to Romanov et al. (1977) were thought to be the manifistation of instabilities.

The revised results of the Mariner-5 measurements of ions with the higher time resolution allowed Bridge et al., (1976) the boundary to be registered between the region with the directed solar plasma fluxes and the cavity with the thermalized, according to the authors' interpretation, plasma not recorded by an analyzer.

Thus, the following properties of the plasma-magnetic tail near Venus are of importance:

1) this tail involves the boundary layer having a boundary within it, which separates plasmas with different properties: over the boundary the plasma is evidently of the solar wind origin disturbed by the interaction with the obstacle; under the boundary it is cooler and has smaller bulk velocity than outside. The latter plasma can be assumed to be an accelerated or heated plasma of planetary origin;

2) the plasma inflow into the tail near the terminator is observed;

3) sometimes the intermixing of external and internal plasmas is observed;

4) the gradual variation of plasma properties in the tail while approaching to its axis was recorded;

5) sometimes the sharp boundary without intermixing is observed which is accompanied by bursts of energetic particles at the boundary and by turbulisation of plasma and magnetic field over it.

The authors of the experiments with wide-angle analyzers (Verigin et al., 1977) noted the similarity of the boundary layer near Venus with the diffuse magnetosphere boundary near the Earth. As is known, the gradual broadening of the boundary layer, or the plasma mantle, until it touches the plasma sheath, the intermixing of plasmas and appearance as a result of double-peak spectra are observed in the remote regions of the Earth magnetotail (Breus and Gringaus, 1977).

However, in spite of the obvious similarity of these phenomena near the Earth and Venus they are, evidently, of different origin. The mechanisms of the plasma mantle formation and the sources of plasma sheath particles near the Earth are yet under discussion. The close contact of the solar wind with the Venus ionosphere and the distinct effects of the induced magnetic field in the tail provide conditions on the obstacle boundary rather different from those on the Earth magnetosphere boundary.

b) Are there a plasma sheet, substorms and other phenomena in Venus wake region typical of the Earth magnetotail?

As it can be seen from Fig. 13 there exists a region under the corpuscular umbra near the planet up to distances of 3 to $4R_V$ where regular ion fluxes were not observed and only in 30% of telemetry samples (see the spectrum obtained in 4^h27^m, Fig. 13) the ion spikes in various energy intervals were recorded. The detection of ion bursts deeply in the umbra with energies $\geqslant 2$ kev not observed neither in the magnetosheath nor in the corpuscular penumbra is an interesting peculiarity of this region. As it has been already noted the boundary layer broadening when moving into the tail from the terminator, plasma instabilities and other mechanisms can explain plasma penetration deeply into the optical umbra but they do not explain the existence of ion fluxes in it with energies not observed in the vicinity of the corpuscular penumbra. To explain this fact it is evidently necessary to suggest some mechanism of ion acceleration deeply in the corpuscular umbra of the planet.

As it has been shown in Section 1 the effects of magnetic field induction and its reconstruction in the tail with changing of $B_\perp$ IMF distinctly manifest themselves in the umbra region. Frequent field reconstructions and resulting variations of the neutral sheet plane position (see Fig. 4) may cause acceleration of the low-energy plasma in various regions of the corpuscular umbra. As it was mentioned above in the remote tail regions (Fig. 1) accelerated ion fluxes with $E \geqslant 2$ kev ($T \sim 10^3$ ev) were observed near the neutral plane when B_x-component of the magnetic field in the wake reversed its sign. Similar effects are observed in the Earth plasma sheath (Verigin et al., 1977). The narrow-angle electrostatic analyzer measurements in the remote tail (Vaisberg et al., 1977) showed periodic increases of the mean energy of the low-energy plasma (energy interval from 50 to 500 ev) separated by short periods of low number flux or its disappearance. Mean period of such events was about 8 min and they were accompanied by short time decreases of the magnetic field. The periods of plasma acceleration coincided with the intervals between negative pulses of the magnetic field. Romanov et al. (1977) noted the similarity of the events observed with the situation during a substorm in the Earth plasma sheath.

Previously, Russell (1976c) analysing the preliminary magnetic field data (Dolginov et al., 1976) obtained during one of the Venera-9 passages in the optical umbra suggested this hypothesis.

As mentioned in Section 5a specific differences between Venus and Earth magnetotails associated with different types of interaction of the solar wind with these planets do not permit to treat the Venus and Earth magnetosphere phenomena as completely identical This question requires further investigation.

6. What is the cause of the variability of the electron density profile in the nightside ionosphere?

The following phenomena can evidently provide an intense and irregular source of the Venus nightside ionosphere: the existence of an elongate magnetotail where the solar wind plasma inflows deeply into the optical umbra, plasma acceleration manifesting itself in pulsations of the plasma and the field and in the appearance of high-energy particles in the neutral sheet, constant existence of electron fluxes with energies more than several tens of ev in the optical umbra.

The assumption that the solar wind can be a source of the Venus nightside ionosphere was suggested immediately after reducing first data obtained by Venera-4 (Gringauz et al., 1968; Gringauz and Breus, 1970; Breus, Gringauz, 1972) and by Mariner-5 (McElroy and Strobel, 1969; Bauer, 1973). In that time there were no direct experimental data about the Venus magnetotail, the solar wind fluxes in the umbra, and the boundary layer. Therefore it was rather difficult to imagine how such fluxes could penetrate up to an ionization maximum deeply in the optical umbra far from the terminator. Nevertheless, it has been pointed out that approximately 2 to 10% of the solar wind energy should be enough for maintaining the observed nighttime ionization. This assumption seemed most reasonable while all other assumptions came across serious problems in explaining nightside Venus ionization (McElroy and Strobel, 1969; Bauer, 1973).

After the Mariner-10 (Howard et al., 1974) and the Venera-9 and -10 radio occultation experiments (Aleksandrov et al., 1976b) it became evident that the Venus nightside ionosphere is unusually variable: the profiles have either one or two ionization

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As it has been shown in Section 1 the effects of magnetic field induction and its reconstruction in the tail with changing of $B_\perp$ IMF distinctly manifest themselves in the umbra maxima the value of Ne in the upper maximum prevailing as a rule that in the lower. The thickness of a maximum region was about 15 km but sometimes it appeared to be extremely small. The corresponding scale-height was from 1 km to 13 km with an averaged value $\overline{H}_p$ 5 km.

The irregular variations of the nighttime ionosphere were naturally associated with the influence of electron fluxes detected in the tail. Gringaus et al. (1976, 1977 a, b) using the Venera-9 and -10 electron data for the optical umbra together with Ne(h)-profiles almost simultaneously obtained by the radio occultation technique constructed the model of the nightside ionosphere ionization by directed electron fluxes. Comparison of N_{em} variations in the upper maximum of the nightside ionosphere with those of the electron fluxes revealed their clear correlation (Fig. 15).

The Ne(h)-profiles calculated by Gringauz et al. (1977) were based on the neutral atmosphere model composed of CO_2 and with $T_{n\infty} \approx 200^{\circ}$K. Neutral density in this model at the level of the ionization maximum was $n_n \approx 2x10^9$ cm^{-3}. This value contradicts to that of Venus atmosphere models suggested by Marov and Ryabov (1974) and by Izakov (1976) where $n_n \approx 2 \cdot 10^9$ cm^{-3} corresponds to altitudes of 170 km and 165 km, respectively.

However, the analysis of neutral temperature measurements in the Venus nighttime atmosphere recently published gives lower temperatures than those used by Gringauz et al. (1977). For example, $T_n \approx 100^{\circ}$K at h = 250 km with $\chi \geqslant 90^{\circ}$ according to Anderson (1976) who revised the results of airglow emission observations on board Mariner-5. According to data obtained by Ivanov-Kholodny et al. (1977) during the Venera-9 and -10 radio occultation experiment $T_n = 100^{\circ}$K ($\overline{H}_p = 5$ km) in the nightside ionosphere at h = 120 to 140 km. Finelly, $160 < T_n < 200^{\circ}$ at h = 140 km with $\chi = 180^{\circ}$ in Dickinson and Ridely's model (1975) where all up to date experimental results were taken into account.

Some discrepancies between the calculated (by Gringauz, (1977)) and experimental number densities in ionization maximum and between their heights is evidently associated with the ambiguity of the neutral atmosphere model used, with the uncertainty of maximum heights estimated from radio occultation data (±10 km) and with the fact that observations of electron fluxes and Ne(h)-profiles were not simultaneous (with time difference ~10 to 20 min). The characteristic time of Ne(h) establishment in the ionosphere $\tau \approx (\alpha N_{em})^{-1} \approx 6$ min (with $N_{em} \approx 7 \times 10^3$ cm^{-3} and α-coefficient of dissociative recombination for $CO_2 \sim 3.8 \times$ $\times 10^{-7}$ cm^{-2} sec^{-1}).

However, the electrons with energies considered cannot reach the second maximum of ionization. Its existence can be explained, for example, by meteor ionization in the Venus atmosphere (Butler and Chamberlain, 1976; Krasnopolsky, 1978). The intensity of such a meteor source can, in principle, be sufficient for creating ionization at the level with $n_n \approx 10^{12}$ to 10^{13} cm^{-3}. These values of the altitude and the density are consistent with the position of the second ionisation maximum being approximately 20 km lower than the upper maximum with $n_n \approx 10^9$ cm^{-3} if $\overline{H}_p$ is set ~3 km.

Krasnopolsky (1978) suggests the model including photoionization of the atmosphere by the scattered radiation of Heλ584Å (~10R) and charge-exchange of atomic sulphur S with O_2^+ in order to explain the upper maximum of ionization $N_{em} \sim 7 \times 10^3$ cm^{-3} for one of radio occultation profiles (Aleksandrov et al., 1976). He estimates the upper limit of the electron flux magnitude that can also be a source of ionization. These estimations were based on the fact that his data of the Venera-9 and -10 spectroscopic observations (during 6 sessions of measurements) had not shown any airglow emission with $\lambda = 5577Å$ produced by the electron fluxes. The upper limit obtained by Krasnopolsky is approximately by the order of magnitude less than the electron flux measured by Gringauz et al. (1976, 1977). The cause of this discrepancy should be analyzed. According to Krasnopolsky, the sensitivity threshold for his spectrometer at $\lambda = 5577Å$ was $I = 4R$. With $N_{em} \approx 7x10^3$ cm^{-3} and $T_n \approx 250^o$ the estimated emission intensity at $\lambda = 5577Å$ was $I_R = 2R$ for a recombination reaction $O_2^+ + e \rightarrow O + O$ (1) (with $O(^1S) \sim 10\%$). The upper limits of electron fluxes were estimated under assumption that the emission intensity I_e they caused at $\lambda = 5577Å$ did not exceed $I - I_R$ in the process $CO_2 + e \rightarrow CO + O(^1S) + e$ (2). For the process efficiency 0,1 used in these estimations the electron flux appeared to be $\sim 1.3 \times 10^7$ cm^{-2} sec^{-1}. However, with $N_{em} \approx 1.6 \times 10^4$ cm^{-3} and $T_n \approx 100^oK$ experimentally observed in other cases (Ivanov-Kholodny et al., 1977) the estimation of the emission intensity at $\lambda = 5577Å$ (made in the way similar with Krasnopolsky's one for a recombination reaction (1)) resulted in the value $I_R \approx 25R$. Such emission intensity Krasnopolsky should have observed if the sensitivity threshold of his spectrometer was $\sim 4R$. May be, the deterioration of the equipment sensitivity noted by Krasnopolsky led to the threshold value more than 4R. In this case the estimation of the upper limit of electron fluxes becomes underrated. The electron fluxes $\sim 10^8$ cm^{-2} sec^{-1} measured by Gringauz et al. (1976) and Verigin et al. (1977) may cause the emission intensity at $\lambda = 5577Å$ $\sim 15R$ if the efficiency of the excitation process by electron impact (2) is taken 0,1, used by Krasnopolsky. The specification of this process efficiency and the sensitivity threshold of the spectrometer may probably eliminate the discrepancy of Krasnopolsky's estimations with the experimental data about the electron fluxes measured by Gringauz et al.

It should be noted that Cehn and Nagy (1977) suggested the model of the nighttime ionosphere ionization by electron fluxes of arbitrary values (e.g. with energy of 400 ev and the flux 10^7 cm^{-2} sec^{-1}) because the Venera-9 and -10 data and Gringauz et al.'s papers were not available to them (1976, 1977 a,b). Their model described fairly well one of the nighttime profiles obtained during the Venera-9 and -10 radio occultation experiments. It also followed from their calculations that other sources of ionization, for example, the transport of light ions from the dayside into the nightside ionosphere (Bauer, 1973) could not maintain the existence of the irregular but significant nightside ionization near Venus.

Thus, the electron fluxes measured in the planetary umbra by Venera-9 and -10 are served as rather intense and irregular source of ionization. The irregularity of this source is in good agreement with the variable nature of the upper maximum of ionization in the nightside ionosphere. The second maximum of ionization can probably be created by metallic ions of the meteor matter ionized by the scattered radiation L_α and L_β or transported from the dayside ionosphere.

Conclusions

The results of plasma and magnetic field measurements obtained by Venera-9 and -10 permitted to answer more definitely the questions raised by the Mariner-5, -10 and Venera-4, 6 experiments.

One of such disputable questions was the question about the nature of the Venus magnetic field and its value. The magnetic field measured in the Venus wake turned out to be dependent on the interplanetary magnetic field orientation, at least, up to distances of 2.5 R_v and the induction effects are of prime importance in forming the field in the wake. This fact makes it necessary to decrease the upper limit value of the Venus intrinsic magnetic field estimated earlier without taking into account the contribution of external field sources.

Currents induced by the solar wind in the dayside ionosphere and the magnetic field B_{ind} they produced are of great importance in forming an obstacle for the solar wind near Venus. So far there are no experimental data concerning the magnetic field at the planetary dayside and the contribution of B_{ind} to the pressure balance remains unknown. The experimental data about a characteristic thickness of the ionosphere boundary-ionopause, the dependence of ionopause height on solar zenith angle, the stability of the boundary position - all these facts indicate that either the induced magnetic field is an obstacle or it makes a significant contribution to the pressure balance on the ionopause undirectly reducing the transverse heat conductivity near the ionopause.

The experimental data about the solar wind properties in the transition layer behind the shock front, the shock front position and the position of the obstacle boundary are in good agreement with gas-dynamical calculations describing the interaction of the solar wind with the unpenetrable obstacle. From these data it follows that the solar wind absorption by the Venus ionosphere should be negligible.

The investigations of plasma and the magnetic field properties at the planetary nightside revealed the existence of plasma-magnetic tail with the boundary layer extended up to distances of $\sim 80R_V$. Up to $7R_V$ within the boundary layer the plasma-magnetic tail boundary was observed. In the vicinity of this boundary the effects of viscous interaction between two plasmas manifested themselves: inflow of the fluxes from the outer region into the inner one, intermixing of the solar wind and the wake plasmas.

Sometimes, no intermixing of fluxes with different properties and their mutual penetration were observed. However, such observations of the sharp plasma-magnetic tail boundary were accompanied by observations of extremely turbulized magnetic fields and the plasma over the boundary as well as the energetic particle bursts at the boundary. The existence of such events is probably associated with the local effects of plasma instabilities with short time increments insufficient to smear the boundary in the tail.

In the magnetosheath the Mariner-10 observed the depletion of high-energy electron with $E_e > 150$ ev (Bridge et al., 1974) that was explained by the direct interaction between the solar wind and the dayside Venus atmosphere. It occurs in regions where magnetic field tubes with electron fluxes from the magnetosheath penetrate deeply into the atmosphere the density and the composition of which can provide necessary ionization. The same phenomenon was frequently observed by Venera-9 and -10 (Verigin et al., 1977) and the depletion effect was evidently independent of IMF orientation relative to the local shock front normal. Further investigations as well as the comparison of observations of the sharp tail boundary, of the electron flux depletion in the magnetosheath and of the solar wind properties are necessary.

Energetic particles accelerated up to energies not observed in the boundary layer were recorded in the optical and corpuscular planetary umbra. Sometimes the periodic variations of plasma flux intensity and of magnetic field reminding the corresponding phenomena in the Earth plasma sheath were registered. It is interesting to note that the plasma and magnetic field distributions near Venus formally resemble those near the Earth: both planets have plasma-magnetic tails, boundary layers or the plasma mantles, neutral sheets, plasma sheaths with variations of the field and the plasma and Venus ionopause formally reminds the Earth plasmapause. However the close contact of the solar wind with Venus ionosphere, the fundamental role of induction effects on the magnetic field distribution near Venus make one to conclude that mechanisms of these phenomena near Venus and Earth are different and need further investigations.

The existence of plasma acceleration in the Venus tail neutral sheet, of electron fluxes and meteor component in the planetary optical umbra may evidently provide for the adequate and irregular source of the Venus nightside atmosphere ionization consistent with the irregular character of observed nighttime Ne(h)-profiles. The Venera-9 and -10 data and the ideas suggested above should evidently be checked in future experiments.

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FIGURE CAPTIONS

Fig. 1 Observations of ion fluxes with energies 2 kev (b,c) in the Venus wake (Verigin et al.,1977) at the region of sign reversal of the magnetic field B_x-component (Dolginov et al.,1977) on board Venera-9 on 25.11.75.

S - crossing of the shock front. Dotted line - components of IMF measured by Venera-10.

Fig. 2 Magnetograms of the magnetic field and the Venera-9 orbit projections with regions where they have been registered on 30.10.75. B_x-magnetic field component in an undisturbed solar wind (dotted line for Venera-10) - is directed towards the Sun ($B_x > 0$). The field is directed from the Sun (B_x 0) in the wake before the beginning of the magnetosheath (on the left up to the arrow with MR) in the southern hemisphere that is contrary to the direction of the assumed dipole magnetic field (Dolvinol et al., 1977).

Fig. 3 Projections of 17 Venera-9 and -10 orbits onto the YZ plane with directions of B_x-component measured in the wake (Dolginov et al.,1977). Numbers denote different orbits.

Fig. 4 Variations of B_x-magnetic field component direction (view from the Sun) in the wake. Near the Venera-9 and -10 orbit projections conventional symbols showing the direction of B_x-component are plotted: ⊙-$B_x > 0$ (towards the Sun), - $B_x < 0$ (from the Sun), ● -$B_x = 0$. Arrows denote vectors of the transverse IMF component measured in the undisturbed solar wind 30, 20, 10 and 0 min (numbers 1, 2, 3, 4) before measurements in the cavity; dotted line aa' denotes the plane normal to one of the vectors $B_\perp$ and corresponds to a neutral sheet plane of the induced magnetic field.

Fig. 5 Variations of B_x-component direction in the wake (according to Fig. 4) plotted in the rotating coordinate system X_{SE} $B_\perp Z'$ where $B_\perp$-axis coincides with the direction of the transverse IMF component and Z'-axis forms with X_{SE} and $B_\perp$ the right-hand coordinate system.

⊗ - $B_x < 0$ (from the Sun, ⊙ -$B_x > 0$ (towards the Sun), aa' - the neutral layer plane of the induced field.

Fig. 6 Dependence of the mean magnetic field in the wake $|\overline{B}_{av}|$ on the electric field in the solar wind E_∞. The latter was calculated by Eroshenko using data of plasma analyzers obtained by Gringauz et al., Vaisberg et al. V_∞ and B_∞ were obtained in 20 min before measurements in the wake.

Fig. 7 Distributions in the Venus ionosphere of i) electric potential; ii) current lines calculated using potential data presented in Fig. 7a for Daniell and Cloutier's model (1977); iii) conductivity and magnetic field in the ionosphere for the subsolar point used in calculations.

Fig. 8 Distributions of i) density; ii) magnetic field; iii) current lines in meridional (YZ) and equatorial (XZ) planes in Lipatov's model (1978). Dotted lines indicate the ionosphere with a depth $\delta_H \sim r_i \gg r_e$ (r_e and r_i are respectively electron and ion Larmor radii in the undisturbed solar wind).

Fig. 9 Qualitative scheme of the Venus induced magnetic field distribution. The transverse IMF component lies in the ecliptic plane and its direction coincides with the positive direction of y_{SE} (Eroshenko, 1978).

Fig. 10 Results of the magnetic wake of the induced magnetosphere simulation in laboratory experiments carried out by Podgorny and his group. a) The induced magnetosphere having a wake formed due to interaction between the flux with the frozen-in magnetic field and the wax sphere. The incindent plasma flux evaporates wax, ionizes evaporation products, forming an artificial ionosphere and interacts with it. b) The effect of disturbance in the wake of an artificial magnetosphere associated only with the electric field $E \sim -\frac{1}{c}[\vec{V} \times \vec{B}]$. The effect of $\frac{\partial B}{\partial t}$ is excluded by comparison of experimental results obtained for a metallic sphere and for that surrounded by a glass shell.

Fig. 11 The shock front position near Venus according to data about solar wind ion and electron components measured by means of wide-angle analyzers on board the Venera-10 (Verigin et al., 1977) during 33 crossings. Dotted line shows the front position calculated by Spreiter et al. (1970) for $H/r_0 = 0.01$ and the stagnation point height over the surface equal to 500 km. For three front crossings (shown by arrows) values of $\rho_\infty V_\infty^2$ were the following:

a) 1.4×10^{-8} dyne/cm^2 (28.10.75);
b) 4.2×10^{-8} dyne/cm^2 (11.11.75);
c) 8.4×10^{-8} dyne/cm^2 (28.10.75);

i.e. the distance up to the front either remained constant or increased with the increasing of the solar wind streaming pressure.

Fig. 2 The ionopause heights h_i obtained on board Venera-9 and -10 by means of the radio occultation method (Ivanov-Kholodny et al., 1978):

a) $h_i(\chi)$ – dependence where χ is a solar zenith angle at the conventional point of radio-beam contact with the planetary surface. Dotted line and circle show the similar results of Mariner-5 and -10.

b) $h_i(\chi)$ -dependence (given in Fig. 12a) in polar coordinates;

c) Ne(h)-profiles 1) 28.10.75; $\chi = 46^\circ$;
2) 23.11.75 $\chi = 83^\circ$.

Fig. 13 Distribution of ion component in the interaction region according to the data of wide-angle modulation analyzers obtained by Venera-9 (01.10.76) and -10 (19.04.76) (Verigin et al.). Ion spectra are presented with calculted parameters v_i, T_i and n_i, appropriate to different regions of the trajectory. The region of the corpuscular penumbra or the boundary layer is shaded.

Fig. 14 Distribution of electron fluxes with $E_e \geqslant 10$ eV in the Venus tail. For four passes of Venera-9 and one pass of Venera-10 positions of the satellites are shown by different marks on their orbits when electron fluxes with $E_e \geqslant 10$ eV in 2; 1; 0,5; 0.25; 0.12 times differ from electron fluxes with $E_e > 10$ eV in the solar wind for each pass. Thick lines connecting the same marks show the surface on which the ration between electron fluxes with $E_e > 10$ eV and the flux in the solar wind remains constant. These data correspond to measurements with approximately the same solar wind velocities ($310 \leq V_i \leq 360$ km/sec). It is clearly seen that with $\sqrt{y^2+z^2} > 6.500$ to 7.000 km the distribution of $\dot{j}_e/\dot{j}_{e\infty}$ qualitatively agrees with the distribution calculated by Spreiter et al. (1970, 1976). In the region $X < 10,000$ km and $\sqrt{y^2+z^2} < 6.500$ to 7.000 km the inflow of electron fluxes into the corpuscular penumbra is distinctly seen. Far from this region in the tail the flux lines are stretching along the direction of the magnetic field.

Fig. 15 a) Calculated (1) and (2) and experimental Ne(h)-profiles (3) and (4) obtained on November 25 and December 3, 1975 after measurements (in 12 min and 18 min) of electron spectra by a radio occultation method.

b) Comparison of the $\mathcal{N}_{em}$ data obtained in the radio occultation experiment with values of $\mathcal{N}_{em}^{c}$ calculated using electron fluxes data in appropriate sessions (Gringauz et al., 1977).

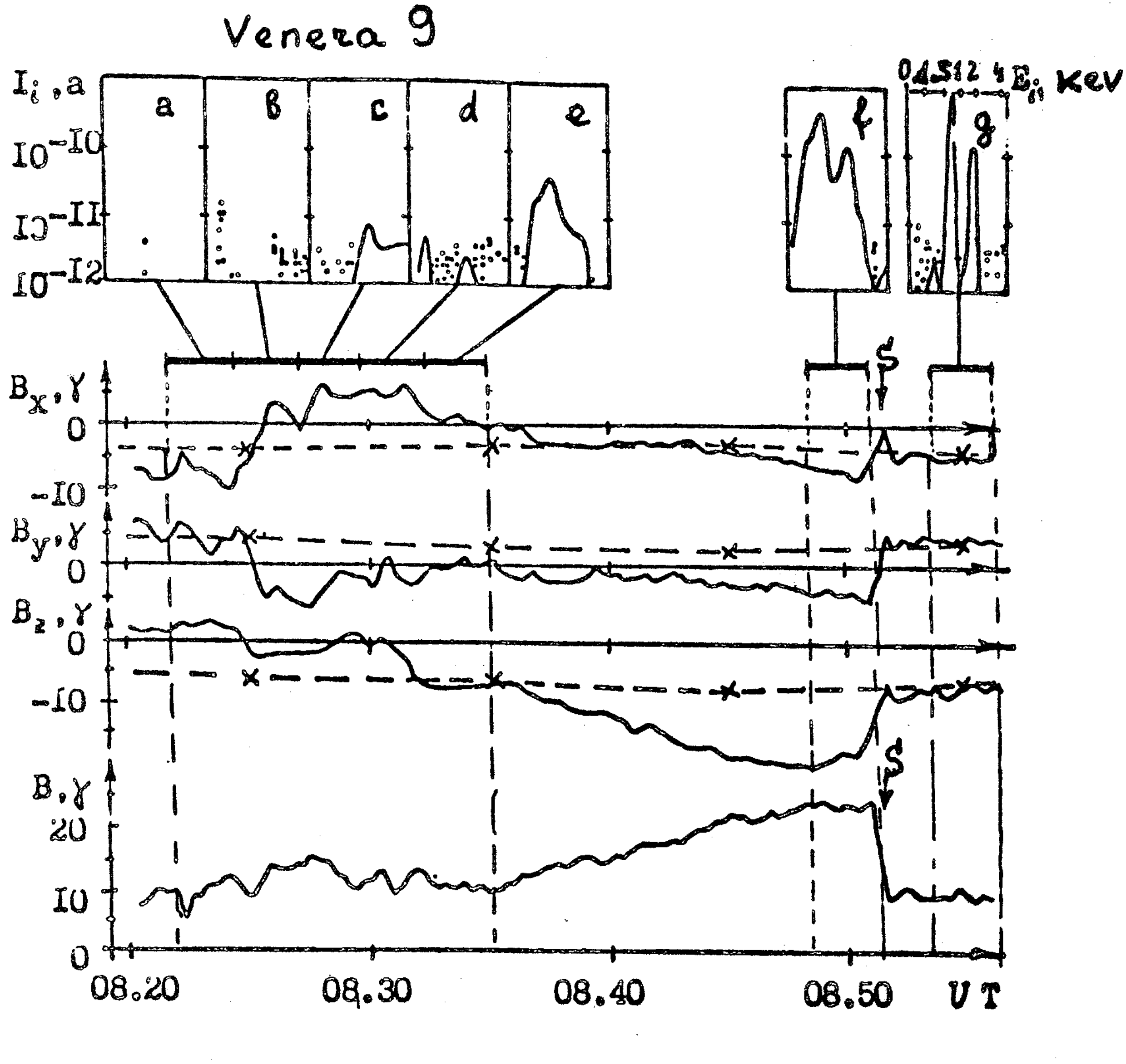

Venera 9
I_i, a
10^-10
10^-11
10^-12
a
b
c
d
e
f
g
0 0.5 1 2 4 E_i, keV
B_x, γ
0
-10
B_y, γ
0
B_z, γ
0
-10
B, γ
20
10
0
S
S
08.20
08.30
08.40
08.50
UT

Fig. 1

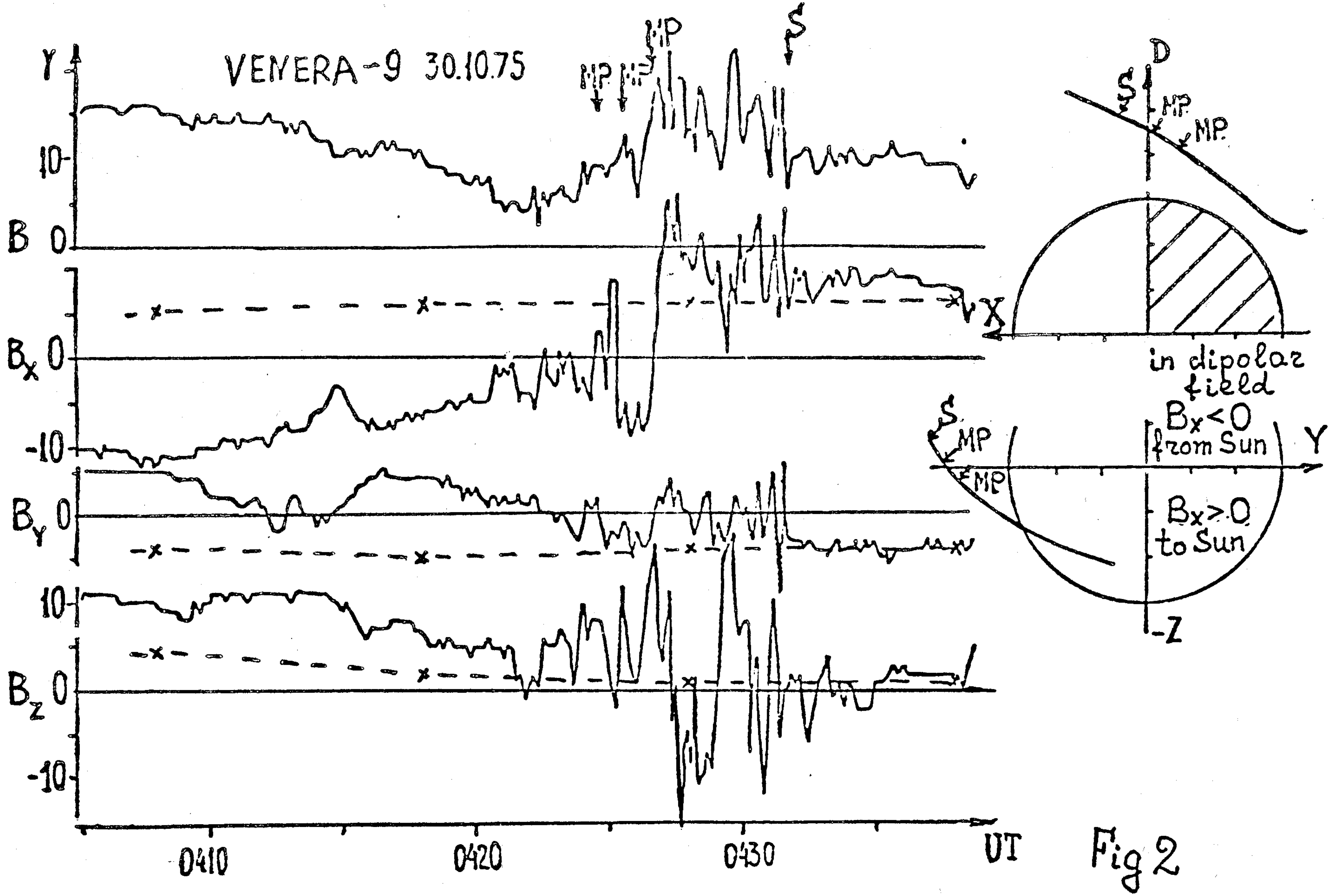
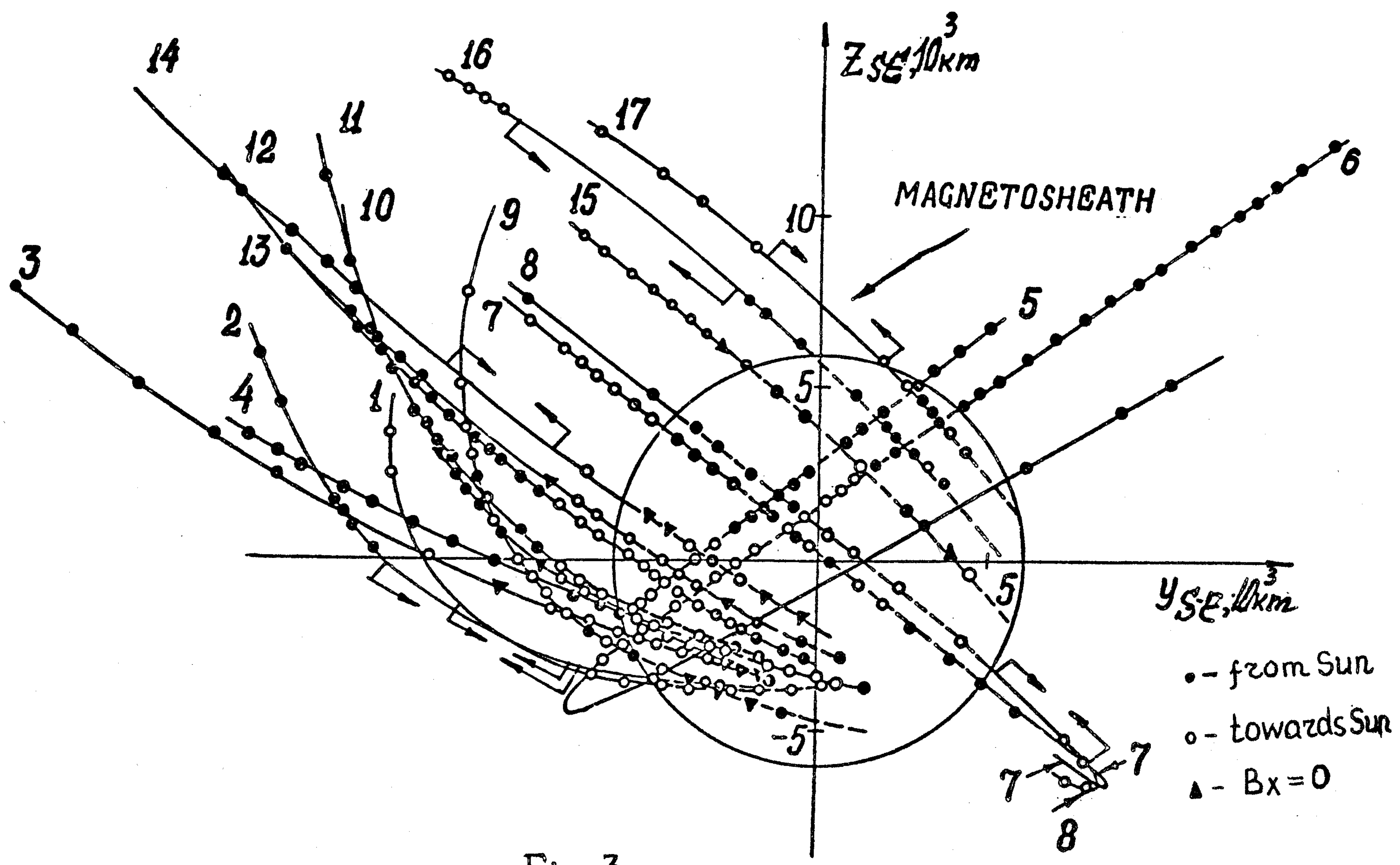

VENERA-9 30.10.75
MP
MP
MP
S
B
B_x
B_y
B_z
Y
10
0
-10
0410
0420
0430
UT
X
D
S
MP
MP
in dipolar field
B_x<0 from Sun
B_x>0 to Sun
Y
-Z

Fig 2



$Z_{SE}, 10^3 km$
$Y_{SE}, 10^3 km$
MAGNETOSHEATH
10
5
-5
5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
7
7
8
● - from Sun
○ - towards Sun
▲ - Bx = 0

Fig 3

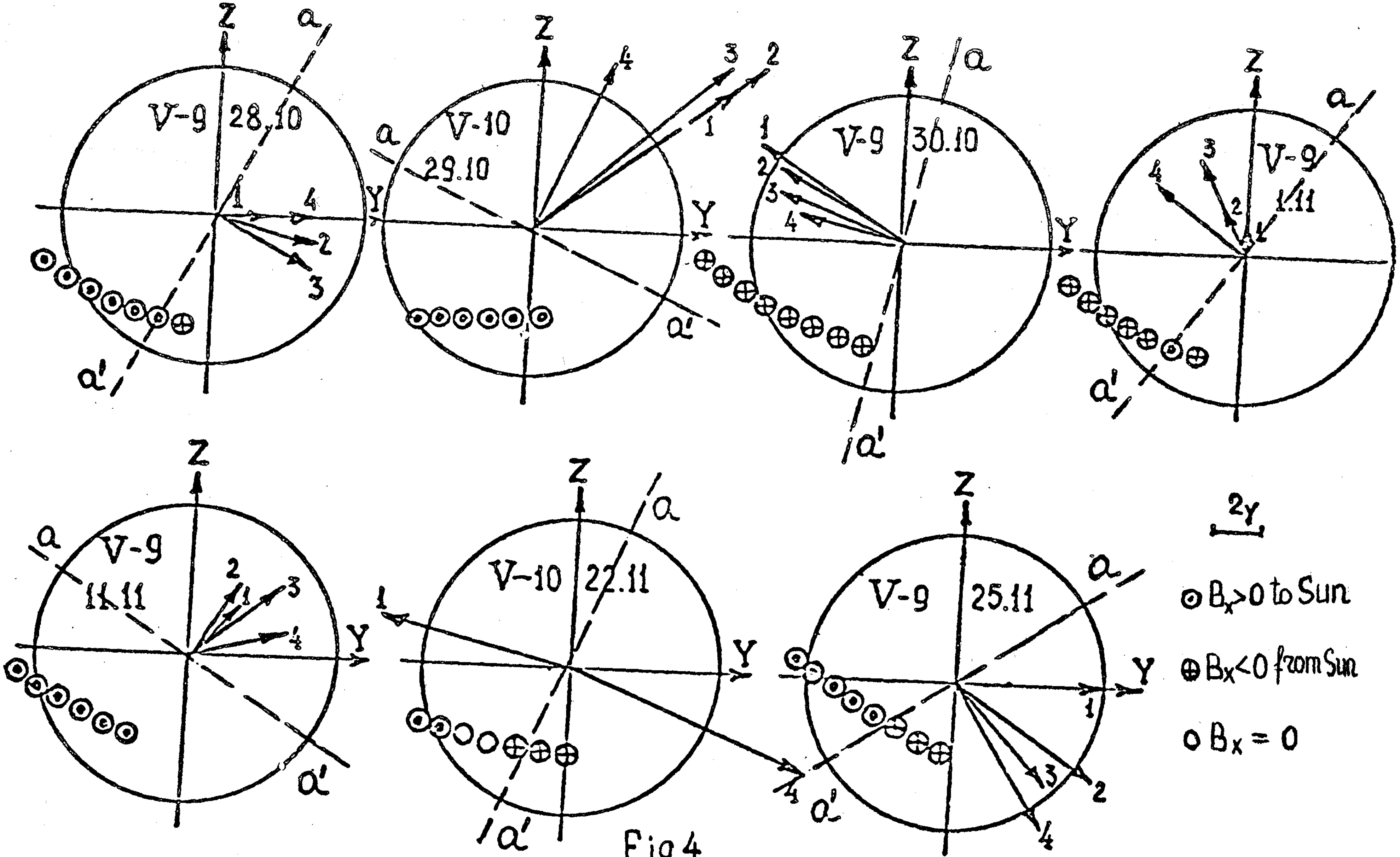

V-9 28.10
V-10 29.10
V-9 30.10
V-9 1.11
V-9 11.11
V-10 22.11
V-9 25.11
Z
Y
a
a'
1
2
3
4
2γ
⊙ $B_x>0$ to Sun
⊕ $B_x<0$ from Sun
○ $B_x = 0$

Fig 4

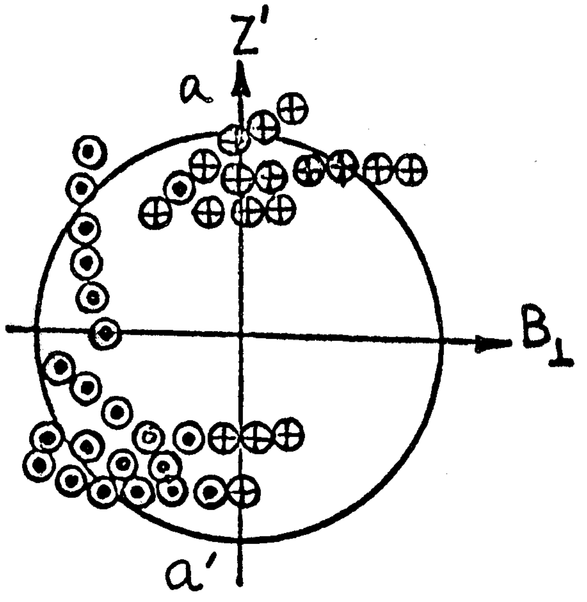


Fig. 5

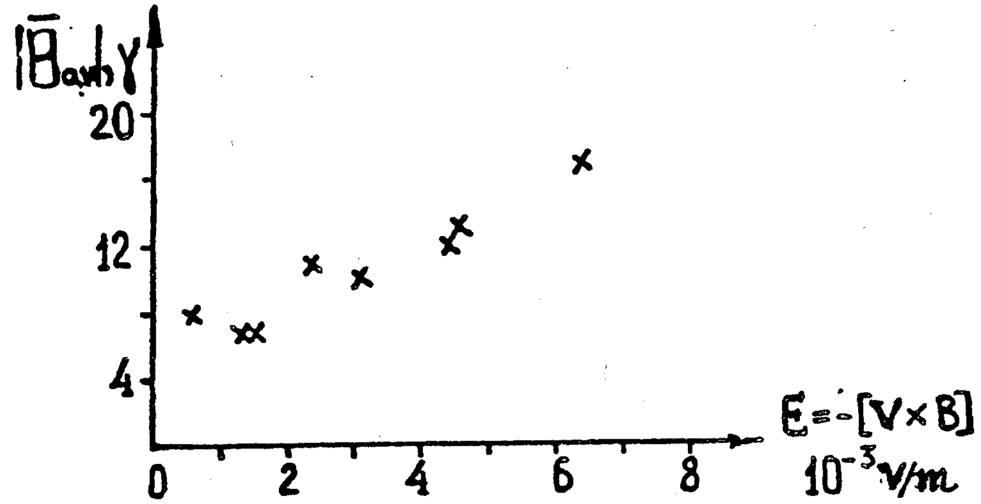


Fig. 6

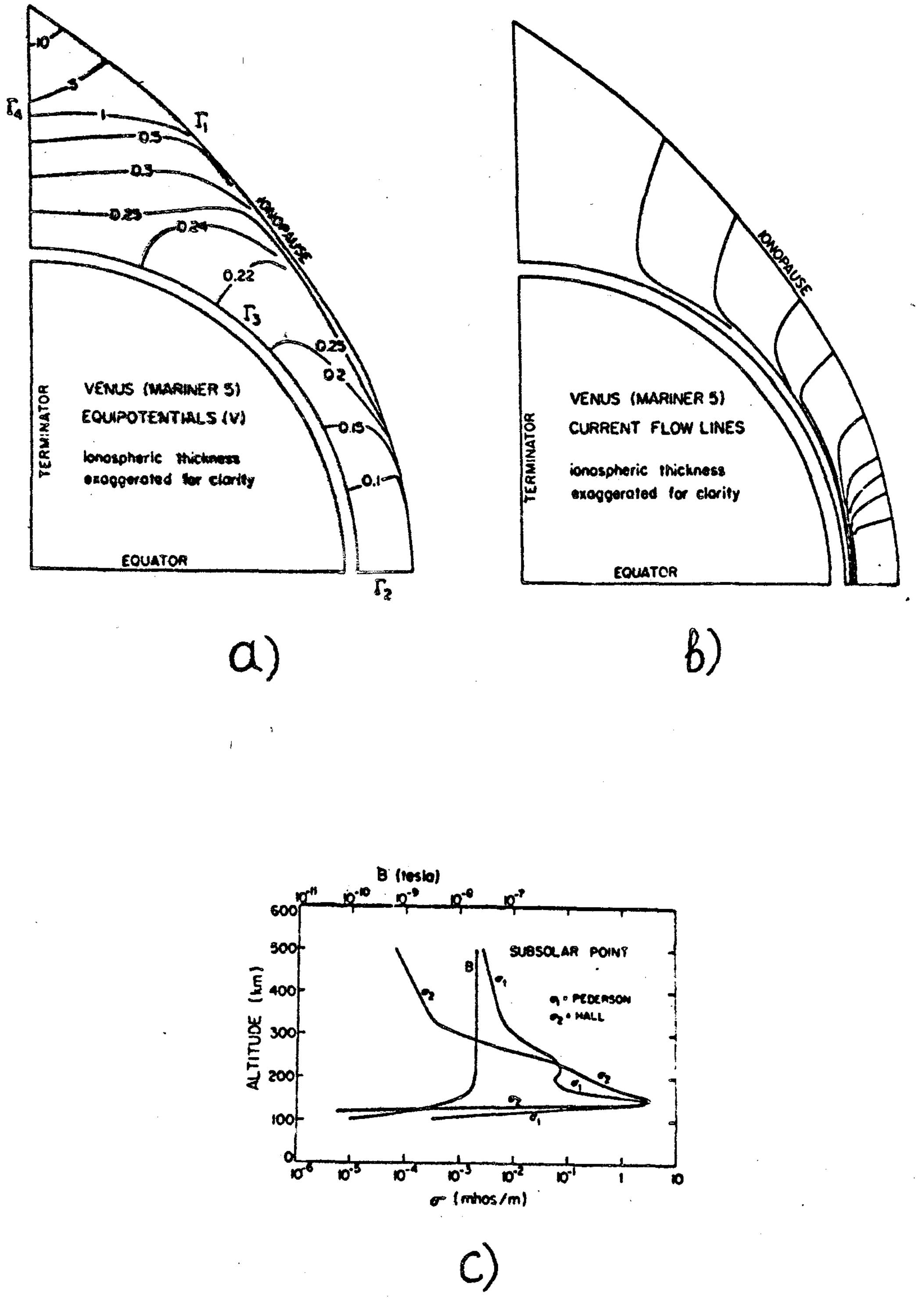

10
3
Γ_4
1
0.5
Γ_1
0.3
0.25
0.24
IONOPAUSE
0.22
Γ_3
0.23
0.2
0.15
0.1
Γ_2
TERMINATOR
VENUS (MARINER 5)
EQUIPOTENTIALS (V)
ionospheric thickness
exaggerated for clarity
EQUATOR
a)
IONOPAUSE
TERMINATOR
VENUS (MARINER 5)
CURRENT FLOW LINES
ionospheric thickness
exaggerated for clarity
EQUATOR
b)
B (tesla)
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
SUBSOLAR POINT
σ_1 = PEDERSON
σ_2 = HALL
B
σ_1
σ_2
ALTITUDE (km)
0
100
200
300
400
500
600
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
σ (mhos/m)
c)

Fig. 7

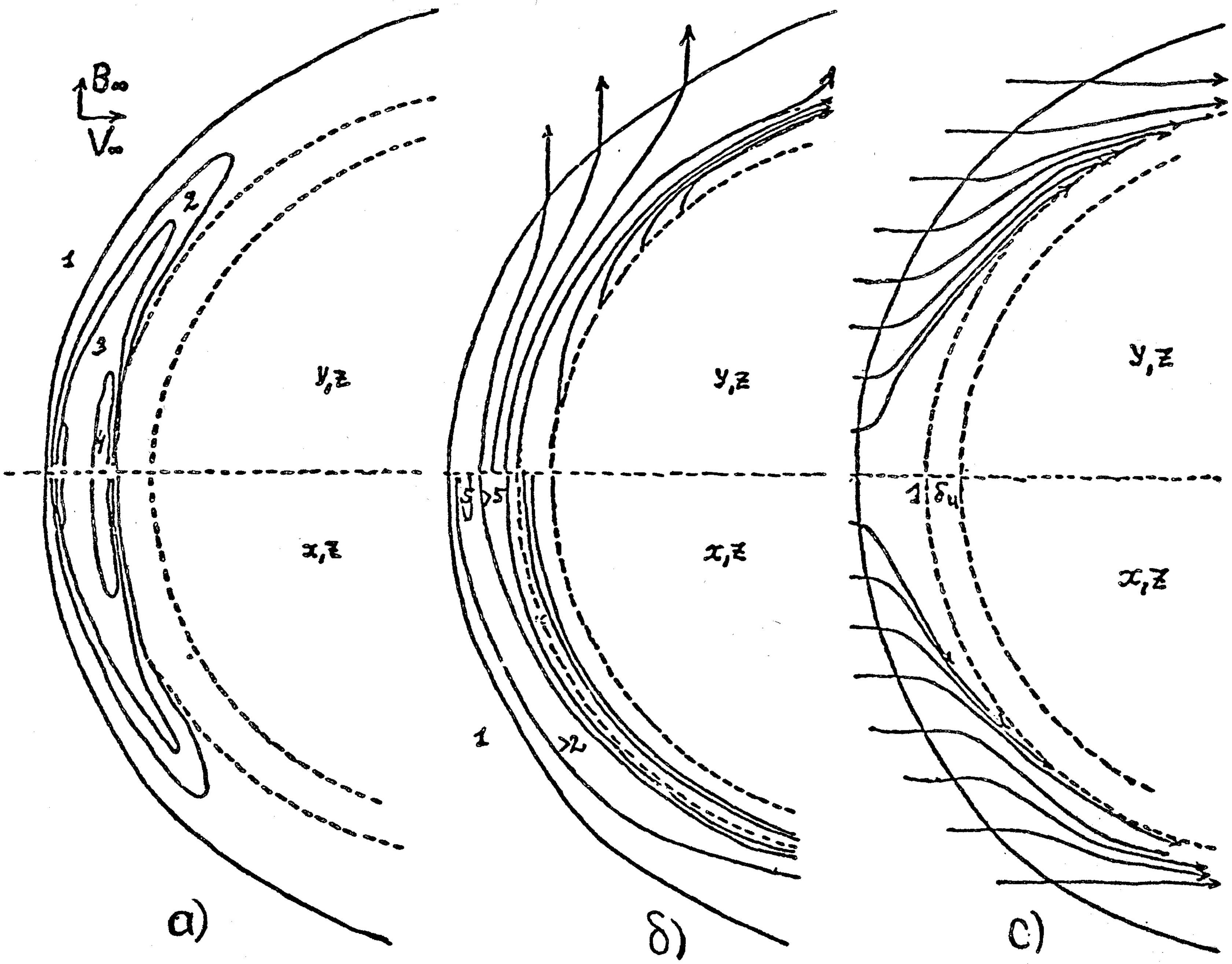


Fig 8

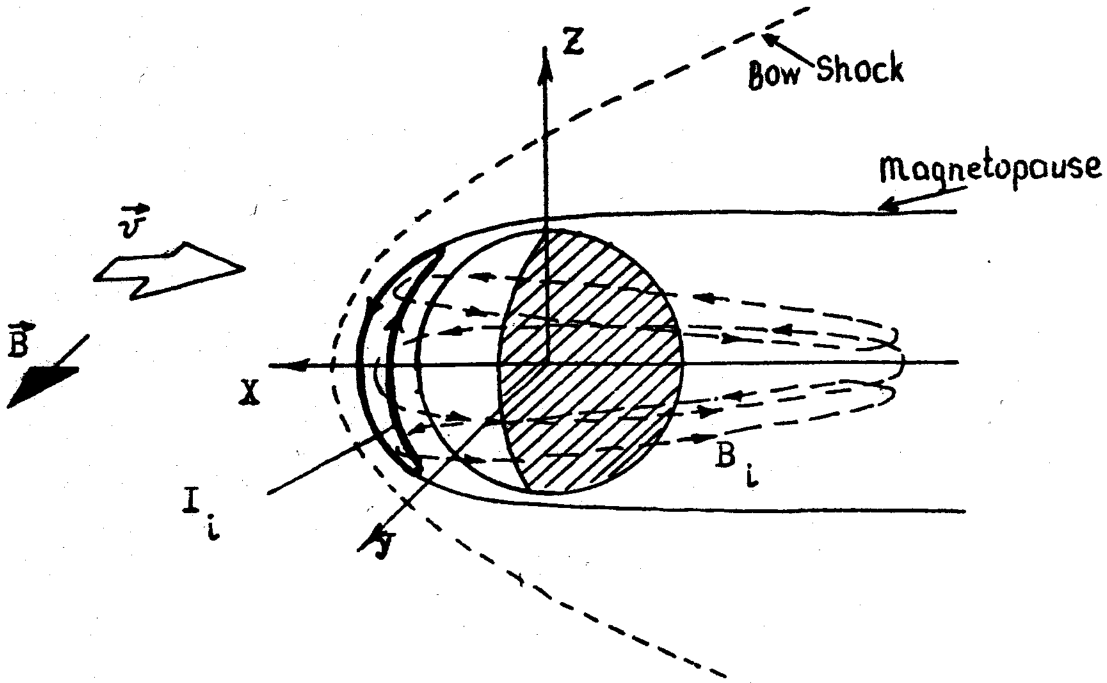


Fig 9

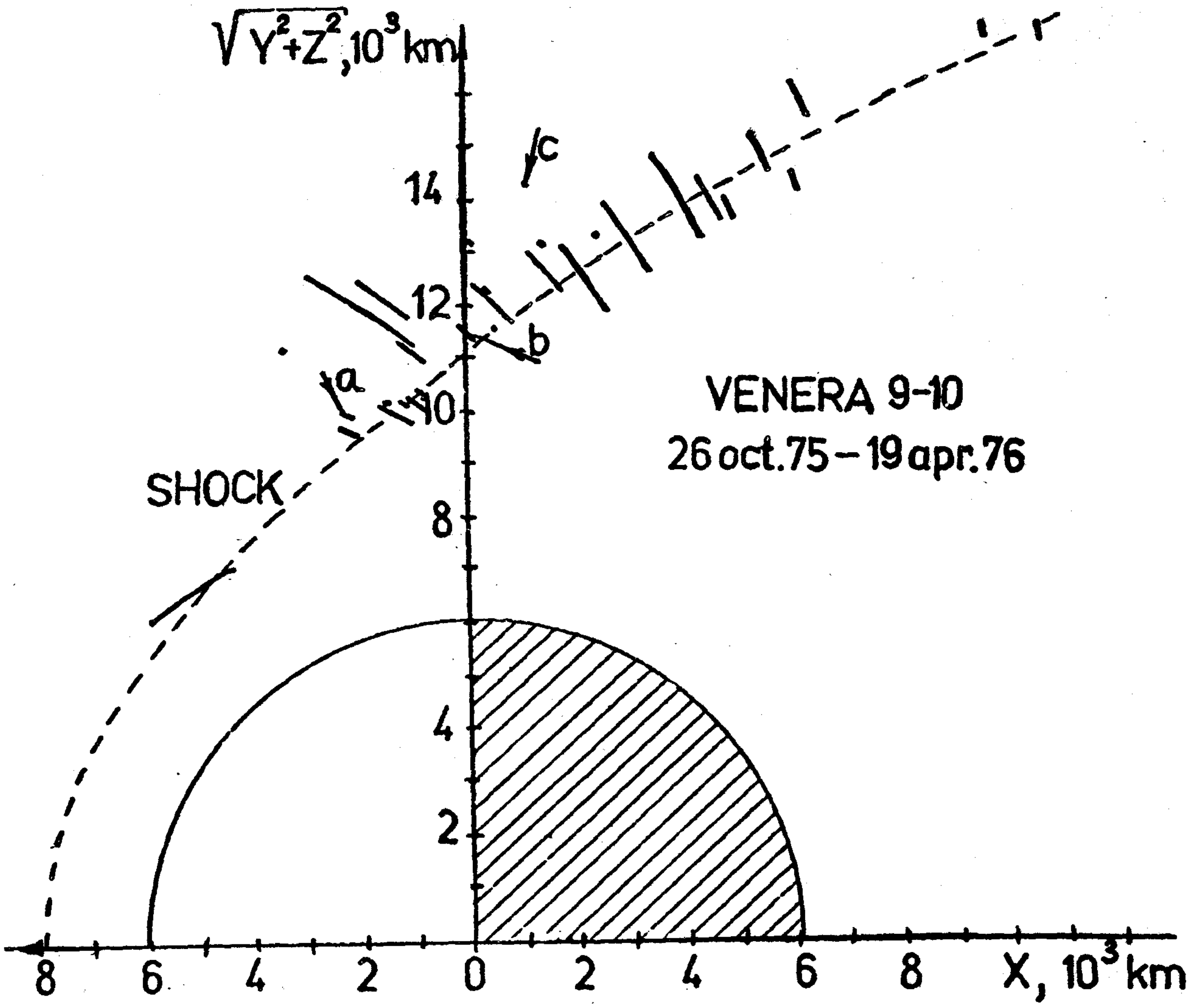

$\sqrt{Y^2+Z^2}$, 10^3 km
14
12
10
8
4
2
c
b
a
r
SHOCK
VENERA 9-10
26 oct.75 – 19 apr.76
8
6
4
2
0
2
4
6
8
X, 10^3 km

Fig 10

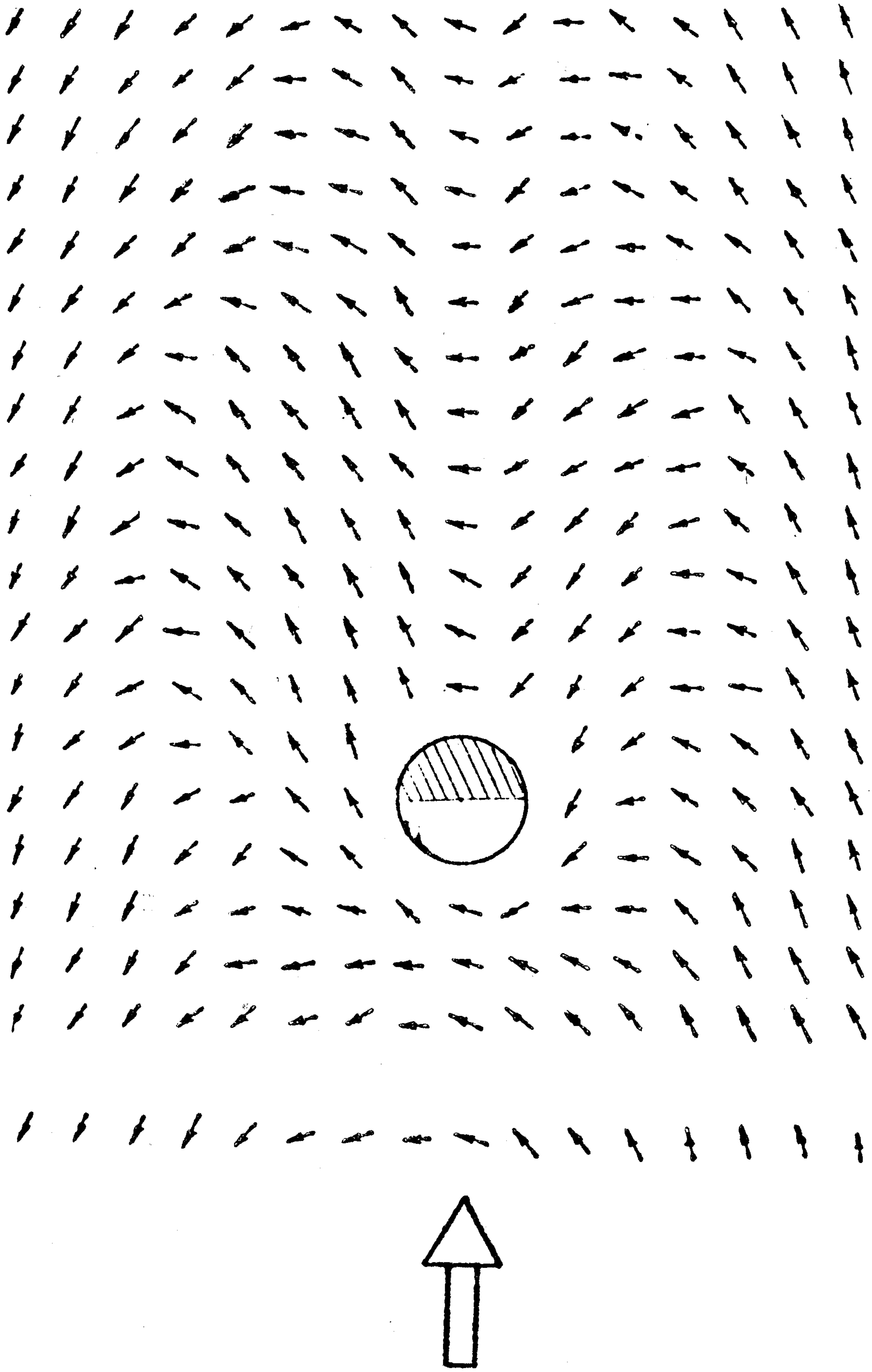


Fig 10a

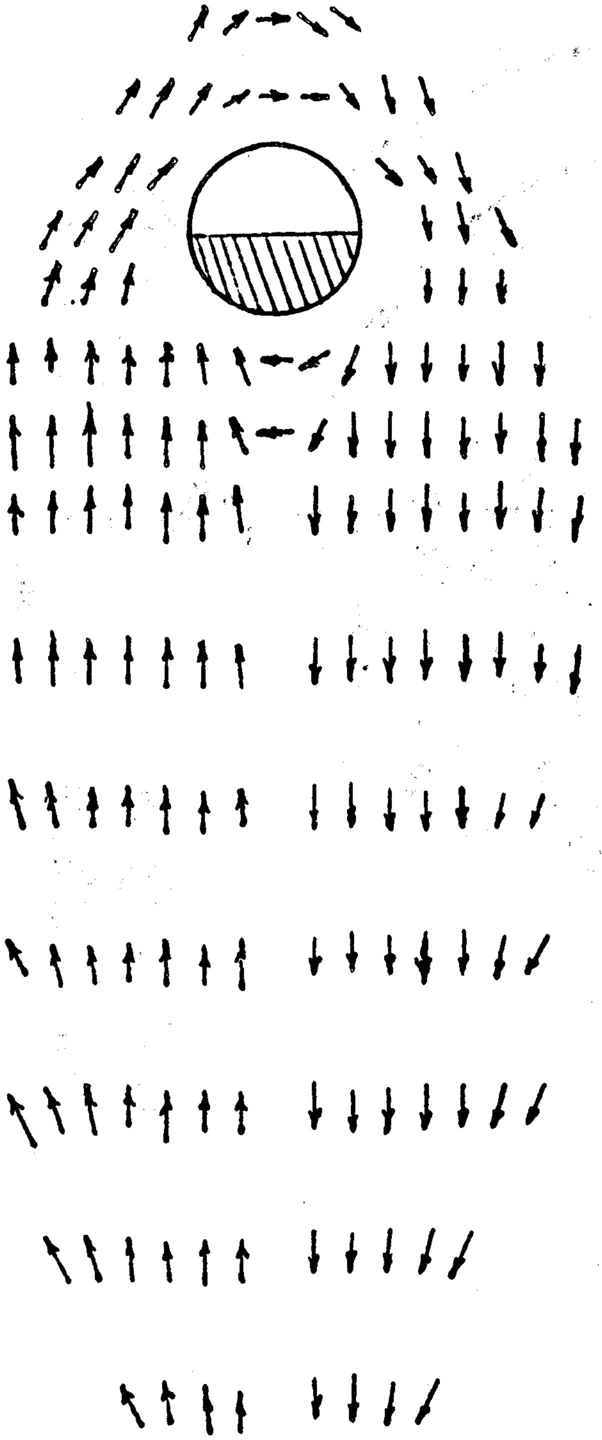


Fig 10b

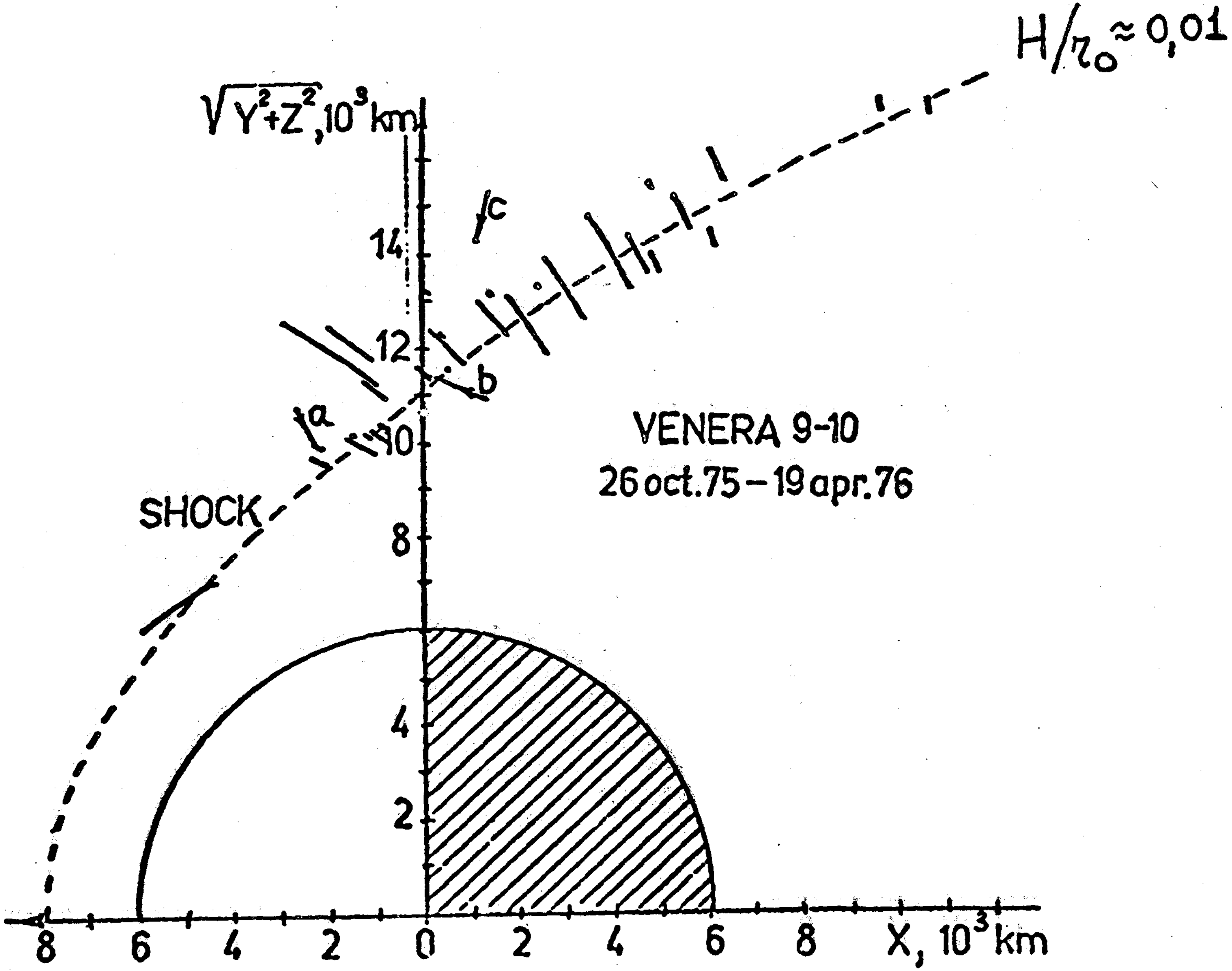

$H/r_0 \approx 0{,}01$
$\sqrt{Y^2+Z^2}$, 10^3 km
14
12
10
8
4
2
c
b
a
SHOCK
VENERA 9-10
26 oct.75 – 19 apr.76
8
6
4
2
0
2
4
6
8
X, 10^3 km

Fig. 11

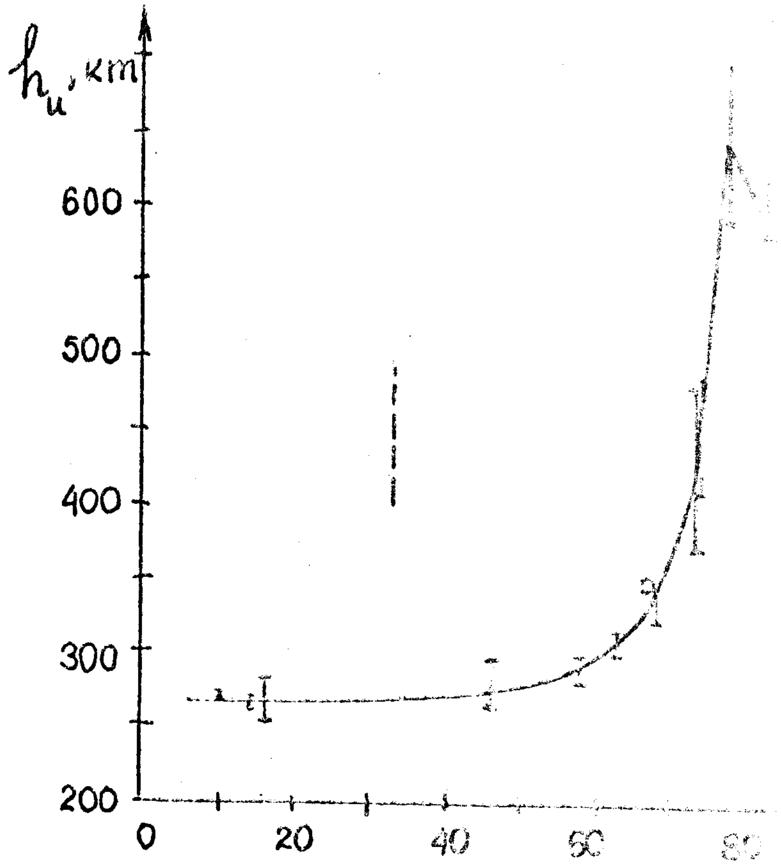


Fig. 12a

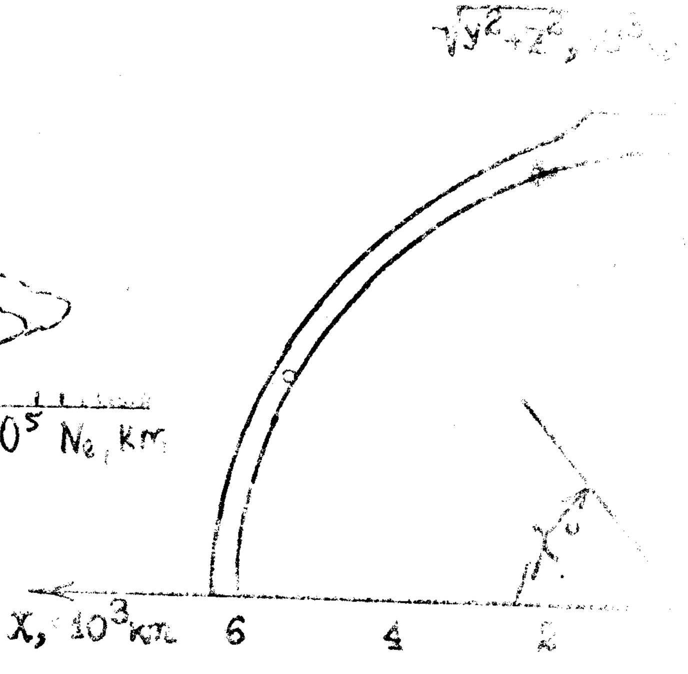


Fig. 12b

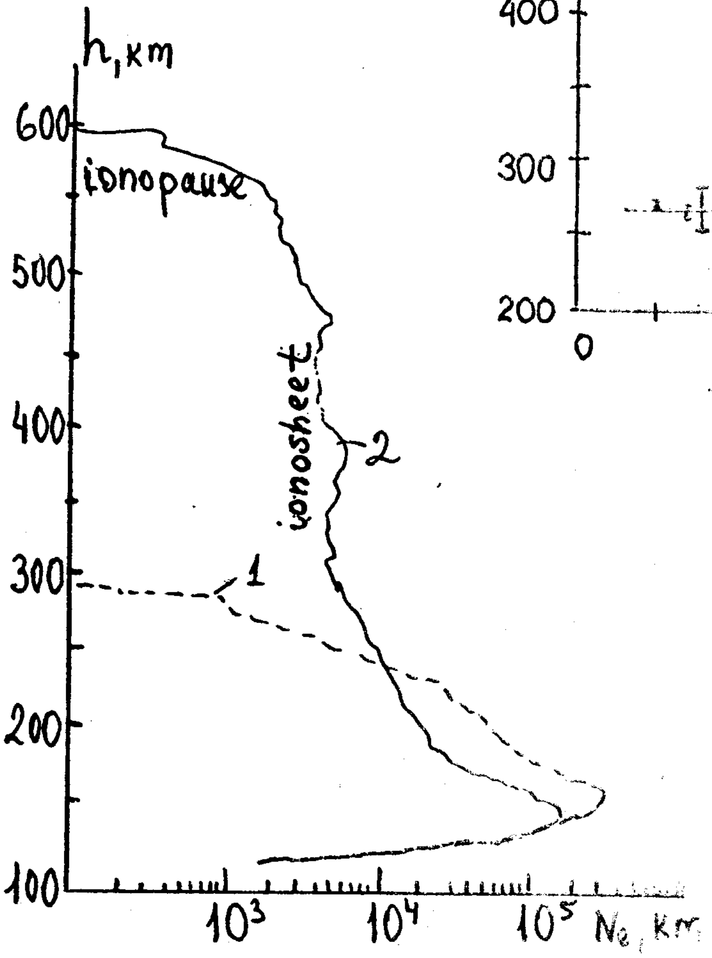


Fig. 12c

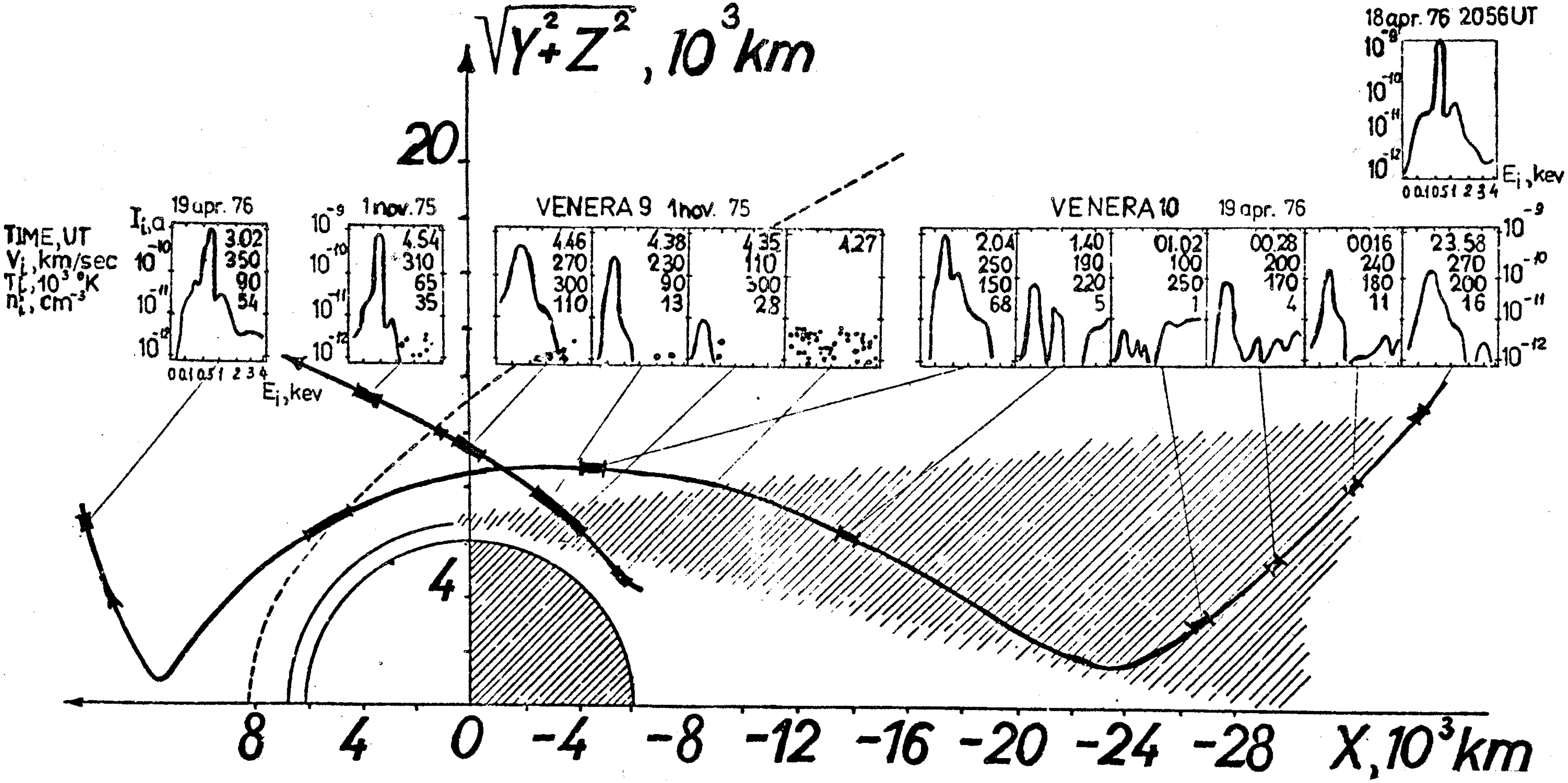

$\sqrt{Y^2+Z^2}$, 10^3 km
X, 10^3 km
20
4
8
4
0
-4
-8
-12
-16
-20
-24
-28
TIME, UT
V_i, km/sec
T_i, 10^3 °K
n_i, cm^{-3}
I_i, a
E_i, kev
19 apr. 76
3.02 350 90 54
1 nov. 75
4.54 310 65 35
VENERA 9 1 nov. 75
4.46 270 300 110
4.38 230 90 13
4.35 110 300 28
4.27
VENERA 10 19 apr. 76
2.04 250 150 68
1.40 190 220 5
01.02 100 250 1
00.28 200 170 4
0016 240 180 11
23.58 270 200 16
18 apr. 76 2056 UT
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0 0.1 0.5 1 2 3 4

Fig. 13

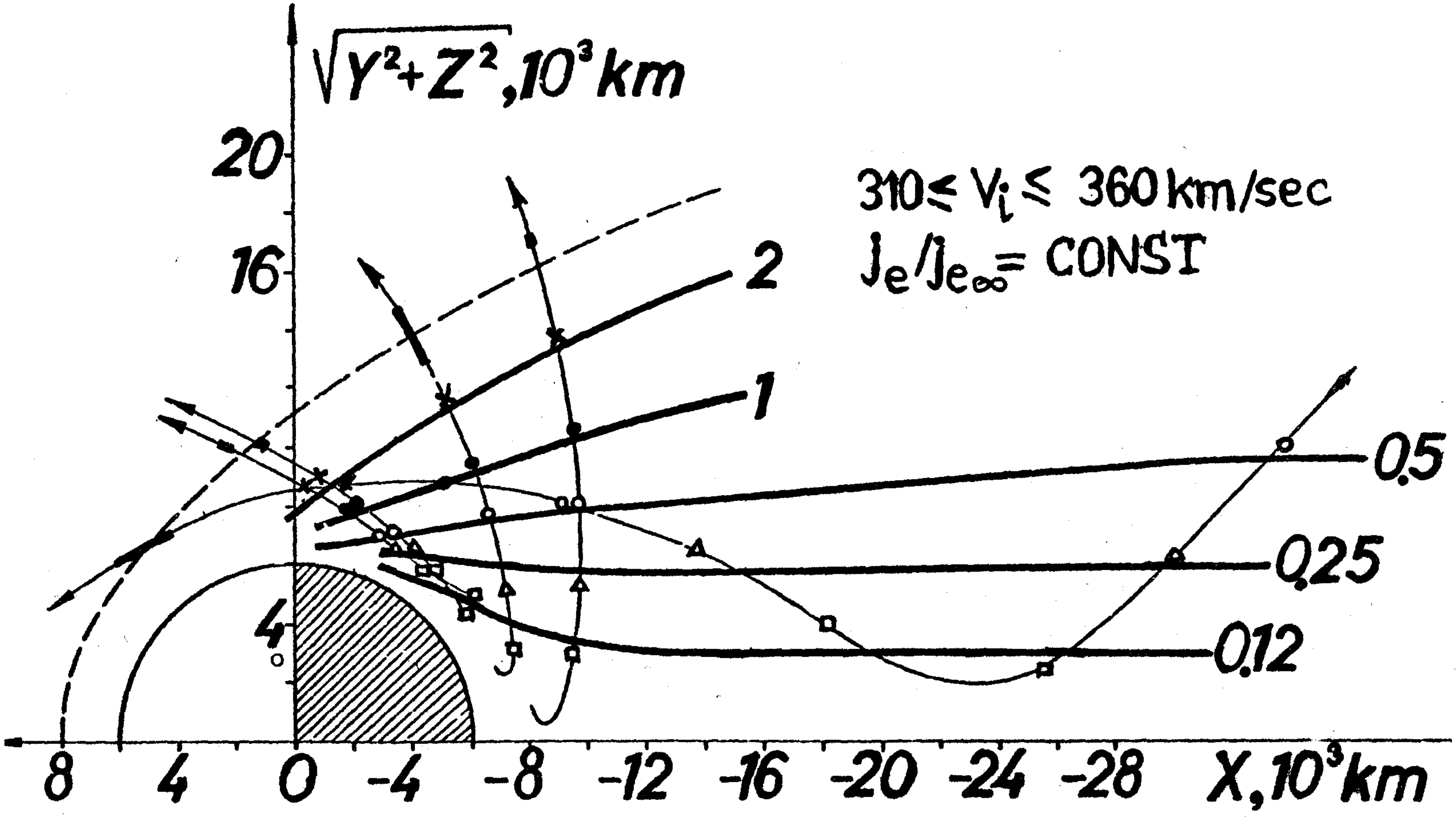

$\sqrt{Y^2+Z^2}$, 10^3 km
20
16
4
8
4
0
-4
-8
-12
-16
-20
-24
-28
X, 10^3 km
$310 \leq V_i \leq 360$ km/sec
$J_e/J_{e\infty}$ = CONST
2
1
0.5
0.25
0.12

Fig 14

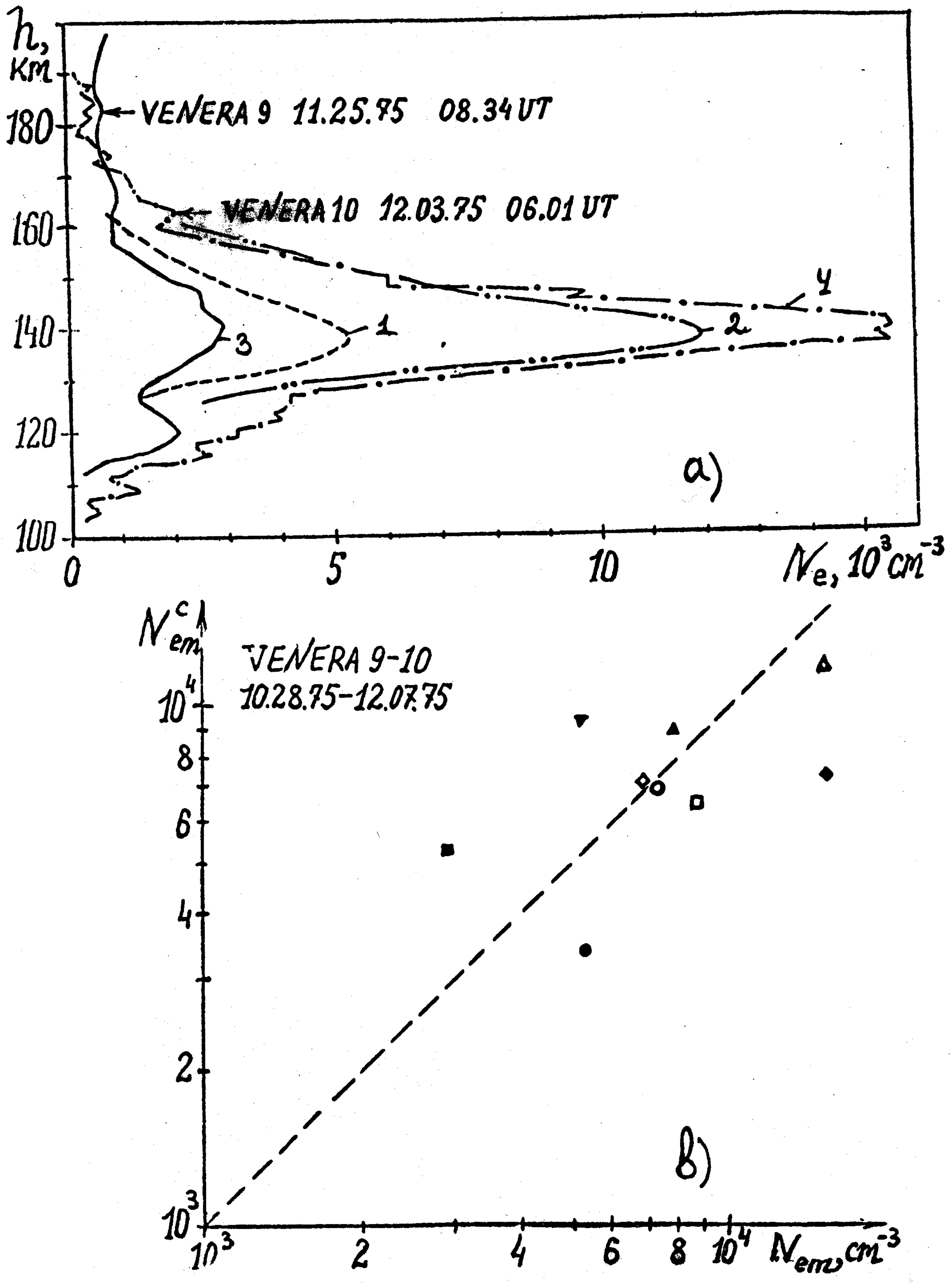

h, km
180
160
140
120
100
0
5
10
Ne, 10³ cm⁻³
VENERA 9 11.25.75 08.34 UT
VENERA 10 12.03.75 06.01 UT
1
2
3
4
a)
Nᶜem
VENERA 9-10
10.28.75-12.07.75
10⁴
8
6
4
2
10³
10³
2
4
6
8
10⁴
Nem, cm⁻³
b)

Fig 15