VENUS

Edited by

D. M. HUNTEN, L. COLIN,

T. M. DONAHUE, and V. I. MOROZ

With the assistance of

MILDRED SHAPLEY MATTHEWS

With 69 collaborating authors

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27. THE BOW SHOCK AND THE MAGNETOSPHERE OF VENUS ACCORDING TO MEASUREMENTS FROM VENERA 9 AND 10 ORBITERS

K. I. GRINGAUZ
USSR Academy of Sciences

Some features of the magnetosphere of Venus which were revealed by magnetic and plasma measurements aboard Veneras 9 and 10 are similar to the well-known peculiarities of the Earth's magnetosphere. They are: a well-developed outgoing shock wave; a current of plasma immediately behind the shock wave front, which perfectly satisfies the hydromagnetic theory; a wake of the magnetosphere protracted slightly along the Sun-Venus axis; and a plasma layer in the middle of the magnetic wake, which separates the two strands of antiparallel lines of force.

Although measurements of the magnetic field and plasma near Venus have been conducted since 1968 by Venera 4 (Gringauz et al. 1968; Dolginov et al. 1968), Mariner 5 (Bridge et al. 1967), Venera 6 (Gringauz et al. 1970), and Mariner 10 (Bridge et al. 1974; Ness et al. 1974), prior to 1975 some authors did not regard the findings as convincing. For example, Wallis (1972) believed that the bow shock does not exist near Venus, while Russell (1977) conceded that the shock wave near the planet is not an outgoing wave. These opinions changed after the Venera 9 and 10 magnetic and plasma measurements in 1975–1976, which gave information on many interactions of the shock wave and magnetosphere of Venus.

This chapter employs the following definition of the magnetosphere: a limited region of space with a magnetic field which, due to the existence of the planet within it, differs in magnitude, direction, and regularity from both the interplanetary field and the magnetic field in the transitional zone behind the front of the near-planetary shock wave, if this exists (Gringauz 1981). This definition is somewhat different from earlier ones, but it can be used for

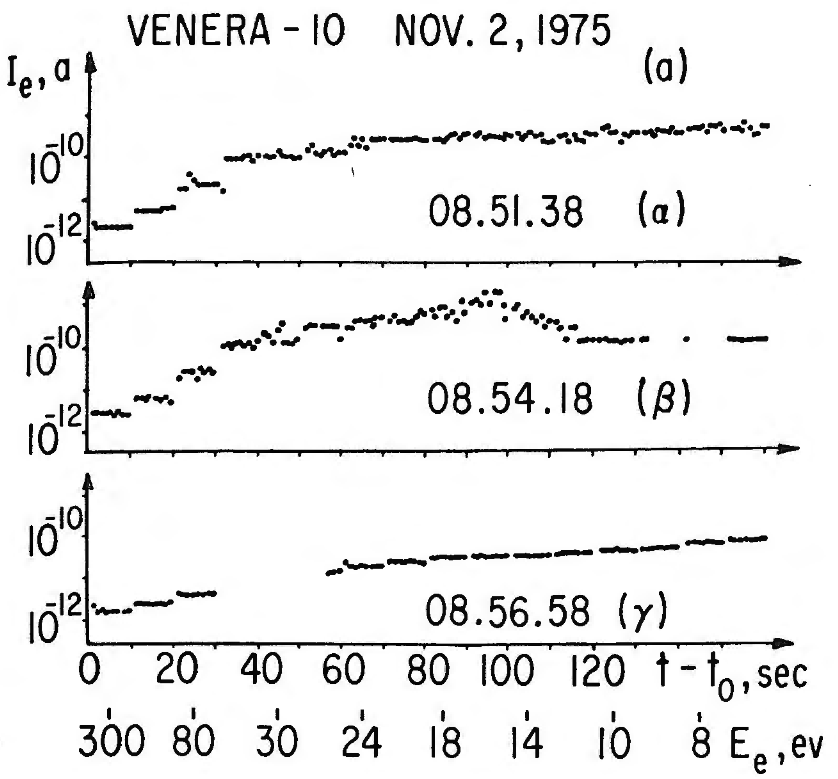

Fig. 1. Charged particle spectra obtained when crossing the near-planetary shockwave front: electron retardation curves from Venera 10, 2 October 1976.

all planets, and it avoids such terms as pseudomagnetosphere and quasi magnetosphere.

I. THE SHOCK WAVE NEAR VENUS

Measurements of the magnetic field near Venus by Veneras 9 and 10 were conducted by means of 3-component fluxgate magnetometers (Dolginov et al. 1976; Dolginov 1977), while measurements of the plasma were made by wide-angle plasma detectors, Faraday cylinder and planar electron analyzer with deceleration potential (Gringauz et al. 1976*a,b*) and by narrow-angle electrostatic analyzers (Vaisberg et al. 1976*b,c*).

All these measurements demonstrated the existence of a distinct and permanent shock wave around Venus. Figure 1 shows sample curves of electron deceleration from data obtained by Venera 10 on 2 October 1976, when the spacecraft was entering the unperturbed solar wind from an area near the planet. Curve α was obtained in a transitional region (the deceleration poten-

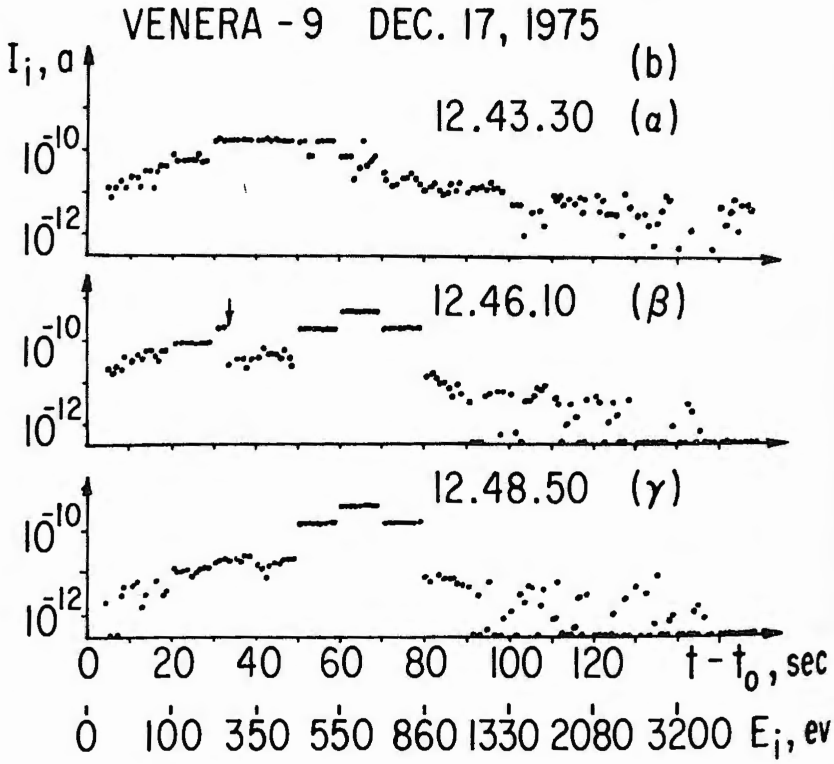

Fig. 2. Charged particle spectra obtained when crossing the near-planetary shockwave front: energy spectra of ions from data of the Faraday cylinder on board Venera 9, 17 December 1976.

tial diminishes, taking on fixed values, at each of which the collector current is measured 10 times). The deceleration curve γ was obtained in the solar wind. Curve β was obtained by intersecting the front of the shock wave; the transition from a deceleration curve of type α to type γ type takes place on segment S (see Fig. 2), corresponding to the shock wave front. This lasts ~ 20 s, corresponding to a thickness of ~ 150 km for the front, if the front was not moving during the measurements.

Figure 2 shows the energy spectra of ions, found by a Faraday cylinder mounted on board Venera 9 on 17 December 1976. Here the transition from the spectrum of type α to that of type γ is virtually a jump lasting 1 s, and the thickness of the shock wave front may be estimated at ~ 8 km, if the front is immobile. However, cases were observed in which the changes in the energy spectra and particles of the magnetic field in the space around the planet took place very slowly and gradually, with large fluctuations, and the thickness of the shock wave front could then be estimated as 2000–3000 km. The broad

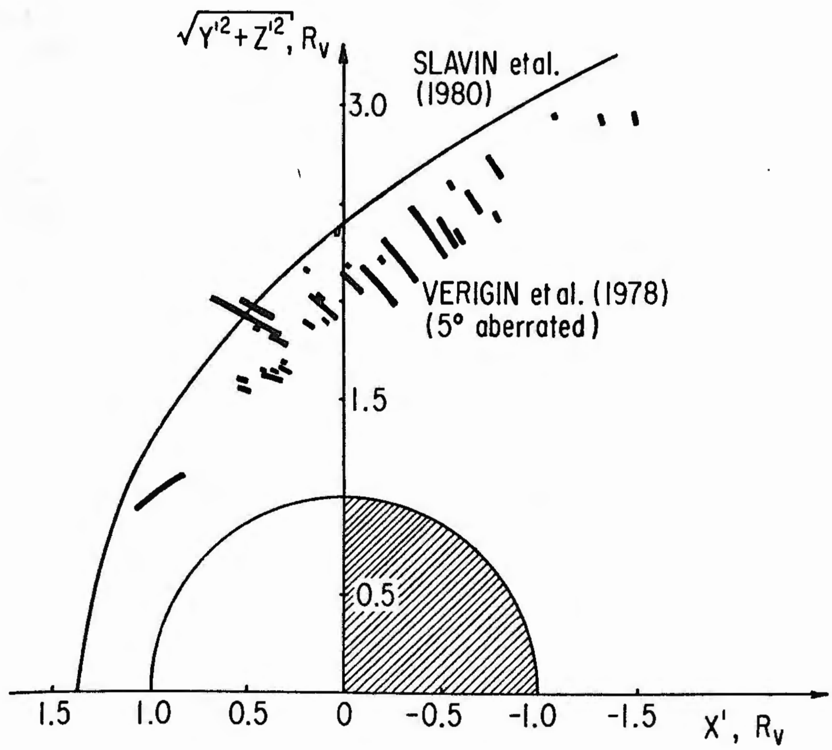

Fig. 3. Positions of crossings of the bow shock according to data of wide-angle plasma detectors on board Veneras 9 and 10 (end of 1975, 1976), and mean position of the front of the bow wave according to data of the PVO (end of 1978, 1979). From Verigin et al. (1978).

diffuse fronts correspond to the orientation $\mathbf{B}_I$ of the interplanetary magnetic field, near the local normals to the surface of the front $\mathbf{n}_{loc}$, while the sharp fronts correspond to angles between $\mathbf{B}_I$ and $\mathbf{n}_{loc}$ which are closer to 90°.

The results of measurements of the position and width of the near-planetary shock wave front obtained by Veneras 9 and 10 have been summarized by Verigin et al. (1978), the authors of the experiments with wide-angle plasma detectors in Fig. 3 in which the broad fronts are shown to occur at ~ 30% of the intersections. It is evident from Fig. 3 that the position of the shock wave during the measurement period by Veneras 9 and 10 (end of 1975, and 1976) was rather stable. This figure also shows the mean position of the near-planet shock wave from Pioneer Venus orbiter data, according to a paper by Salvin et al. (1980), who emphasized that the position of the shock wave is highly variable compared with the data of Verigin et al. (1978). Slavin et al. believe that this discrepancy can be explained by the different phases of solar activity during which the Venera and Pioneer measurements were conducted.

Using data from 2 crossings of the front by Mariner 5 orbiter, Greenstadt (1970) was the first to point out the dependence of the local structure of the shock wave front near Venus on the angle between $\mathbf{B}_l$ and $\mathbf{n}_{loc}$. Bridge et al. (1976) have indicated that, in the Mariner 5 and Mariner 10 crossings of the near-planetary shock wave, the positional uncertainty of the shock wave front was ~ 3000 km, i.e. on the order of the size of the obstacle. Since the rate of propagation of disturbances in a magnetized plasma is greatest in the direction perpendicular to **B**, not only the structure but also the distance of the shock wave front from the obstacle depends on the angle between $\mathbf{B}_l$ and $\mathbf{n}_{loc}$. Precisely this dependence of the local structure and distance of the shock wave front on the angle defined by $\mathbf{B}_l$ and $\mathbf{n}_{loc}$ was responsible for the asymmetry of the shock wave front in the plane perpendicular to the Sun-Venus line (according to Romanov et al. 1978), and for the asymmetry in the 3-dimensional structure of the near-planetary shock wave (Smirnov et al. 1981). In my opinion, this same effect partially explains the discrepancy in the determinations of the position and variability of the shock wave by Veneras 9 and 10 and by Pioneer Venus orbiter (cf. Fig. 3); because the orbital inclination of Veneras 9 and 10 to the plane of the ecliptic is much less than that of the Pioneer Venus orbiter, the angles between $\mathbf{B}_l$ and the local normals to the shock wave front are larger for Pioneer, i.e. the vector $\mathbf{B}_l$ is mainly situated in the plane of the ecliptic (Gringauz 1981).

II. THE MAGNETOSPHERE OF VENUS

At present, all researchers agree on the absence of a currently measurable internal magnetic field at Venus (see Chapter 25). This problem may be of interest for planetary dynamo processes, but not for the physics of the Venus magnetosphere.

Prior to Veneras 9 and 10, no spacecraft had explored the optical shadow of Venus. Indicators of the penetration of the spacecraft into the magnetosphere of Venus were considered to be (as in the case of the Earth's magnetosphere): abrupt increase in the magnetic field B, and a reduction in its fluctuations; and reduction of the fluxes of plasma, accompanying the growth of B, when the magnetic pressure exceeds the plasma pressure. In the wake of the magnetosphere, an additional indicator is the extension of B along the Sun-Venus line.

The closest that Veneras 9 and 10 came to the planet's surface was 1500 km. To date (1981) the richest data on the magnetic field and plasma at low altitude (< 1 $R_♀$) has been obtained from the Pioneer Venus orbiter. On the other hand, information on the structure of the magnetic field and plasma at great height above the night side of the planet has come largely from Veneras 9 and 10. The Venera measurements are summarized on the basis of the experiment with wide-angle plasma detectors, Fig. 4 (Gringauz 1981; Verigin et al. 1978). Region A is the transitional zone behind the shock wave front;

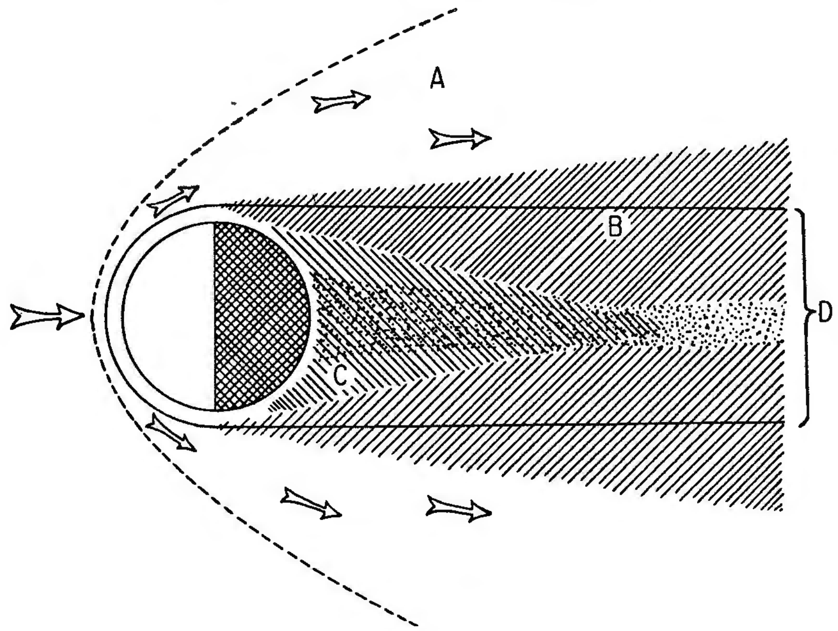

Fig. 4. Plasma-magnetic formations in the nightside portion of space around Venus: A, transitional region; B, boundary layer (particulate penumbra); C, particulate shadow; D, wake of the magnetosphere.

in it, the speed of the plasma is rather well described by hydrodynamic analyses made under the assumption that the obstacle is impervious to the solar wind (Spreiter 1976). Region B is a particulate penumbra or boundary layer (Gringauz et al. 1976*b*; Verigin et al. 1978), in which the plasma fluxes are reduced and the speed of the plasma V_i is less than that in the nondissipative model of Spreiter ($V_i \leq 0.75\ V_o$, where V_o is the speed of the undisturbed solar wind). This region, as is seen from Fig. 4, extends into the optical shadow of the planet. Verigin et al. (1978) noted that the retardation of the plasma flow in region B is caused by the quasi-viscous interaction between the solar plasma of the transitional region and the obstacle (i.e. the ionospheric plasma). As early as 1970 Spreiter et al. pointed out the possibility of formation of a broad layer by this cause. Verigin et al. (1978) have shown that the experimental data obtained in this region by the wind-angle detectors are in qualitative agreement with boundary-layer analyses (Perez-de-Tejada et al. 1977).

A segment of region B adjoining the terminator was apparently observed by the retarding-potential analyzer on board the Pioneer Venus orbiter (Spenner et al. 1980). For future study of the physics of region B, energy-mass ion analyzers would be very useful, but unfortunately these instruments were not on board Veneras 9 and 10, or the Pioneer Venus orbiter.

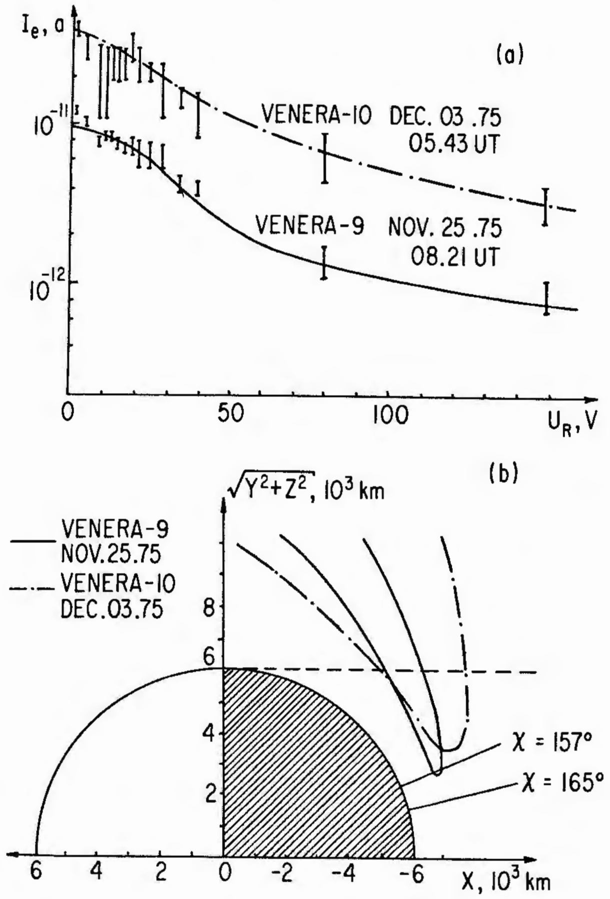

Fig. 5. (a) Examples of retardation curves for the electrons directed at the planet in the optical shadow of the latter, and (b) coordinates of Veneras 9 and 10 where the above retardation curves were obtained.

Region C (Fig. 4) is a particulate shadow, in which the Faraday cylinders on board Veneras 9 and 10 did not record regular ion fluxes from the transitional zone within the limits of their sensitivity (Gringauz et al. 1976*a*; Verigin et al. 1978). This region is roughly the shape of a cone with a base of radius $R_♀ + H_{ipt}$, where $R_♀$ is the radius of Venus and H_{ipt} is the height of the ionopause at the terminator, and the height of the cone is $\sim$ 4 to 5 $R_♀$. A similar evaluation of the dimensions of the particulate shadow (called a cavity by the authors) is given by Intriligator et al. (1979), using the Pioneer plasma analyzer data. Despite the absence of regular ion fluxes (Gringauz et al. 1976*a*; Verigin et al. 1978), electron fluxes always exist in the particulate shadow, though they are extremely variable; cf. the integrated spectra (retardation curves in Fig. 5). Furthermore, in the particulate shadow sporadic ion fluxes

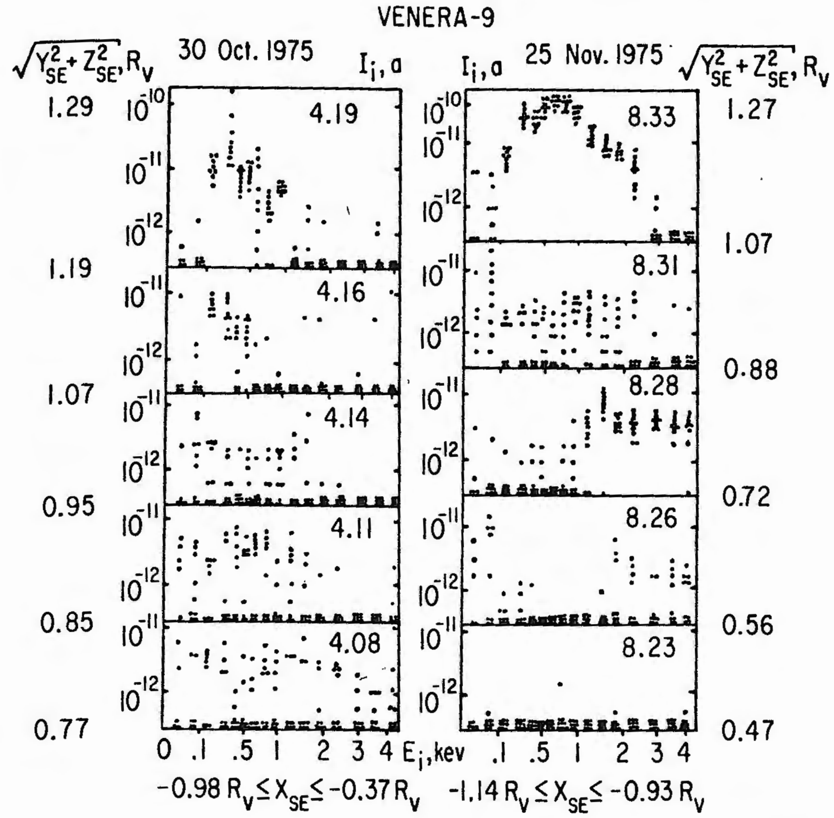

Fig. 6. Energy spectra of ions obtained when the Venera 9 spacecraft crossed from the particulate shadow into the transitional zone on 30 September 1975 and 25 October 1975.

are observed with energies E up to E_{max}, the maximum that can be registered by the Faraday cylinders (i.e. up to 4.5 keV); there may be sporadic fluxes of ions with $E > E_{max}$.

Figure 6 shows sample energy spectra of the ions according to the data of a Faraday cylinder oriented toward the planet along the Sun-Venus line, when Venera 9 was moving from the particulate shadow into the transitional layer (Gringauz et al. 1976*a*). In each energy interval, 10 measurements per second of the total current were made. Many points lie on the abscissa, although in ~10% of the measurements there were significant fluxes of ions with energies of 2 to 4 keV in the particulate shadow. Ions of such energy are not observed in the transitional layer, and apparently are a consequence of acceleration processes occurring in the particulate shadow or at great distances in the wake of the magnetosphere, in region D. Region D (Fig. 4) is the wake of the

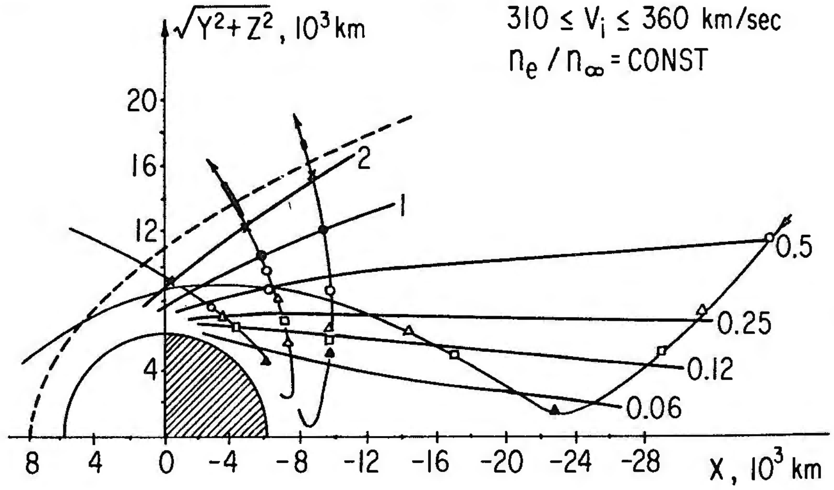

Fig. 7. Distribution of plasma concentration in the nightside portion of Venus's magnetosphere and in the transitional zone.

magnetosphere of Venus (similar to the wake of the geomagnetic sphere); it is characterized by a predominence of magnetic over plasma energy, two antiparallel strands of magnetic lines of force extended along the Sun-planet axis (x-axis), and a plasma layer in the middle of the wake (Dolginov et al. 1970; Verigin et al. 1978; Romanov et al. 1977). However, in contrast with Earth's magnetosphere, the orientation of the neutral layer and plasma layer varies with the change in component $\mathbf{B}_l$ in the plane YZ. The diameter of the wake of Venus's magnetosphere somewhat exceeds the diameter of the planet.

Figure 7 (Verigin et al. 1978) shows the distribution of the plasma concentration n_e in the nightside space around the planet, according to the data of retarding-potential electron analyzers; $n_{e\infty}$ is assumed the same as in interplanetary space. Figure 8 shows two consecutive measurements of ion spectra by Venera 10 passing from the transitional zone into the wake of the magnetosphere. The decrease in plasma flux at the wake boundary corresponds to an increase in **B**, while B_y and B_z are reduced. Figure 9 (Verigin et al. 1978) shows ion spectra and vectors **B**, as measured within the magnetosphere of Venus near the point where the x-component of **B** changes sign. The change in sign of B_x corresponds to the appearance of particles with energies of 1 to 3 keV in the ion spectrum. These are absent from the neighboring spectra within the magnetosphere, and evidently are related to a plasma layer of the venusian magnetosphere qualitatively similar to the plasma layer of the Earth's magnetosphere.

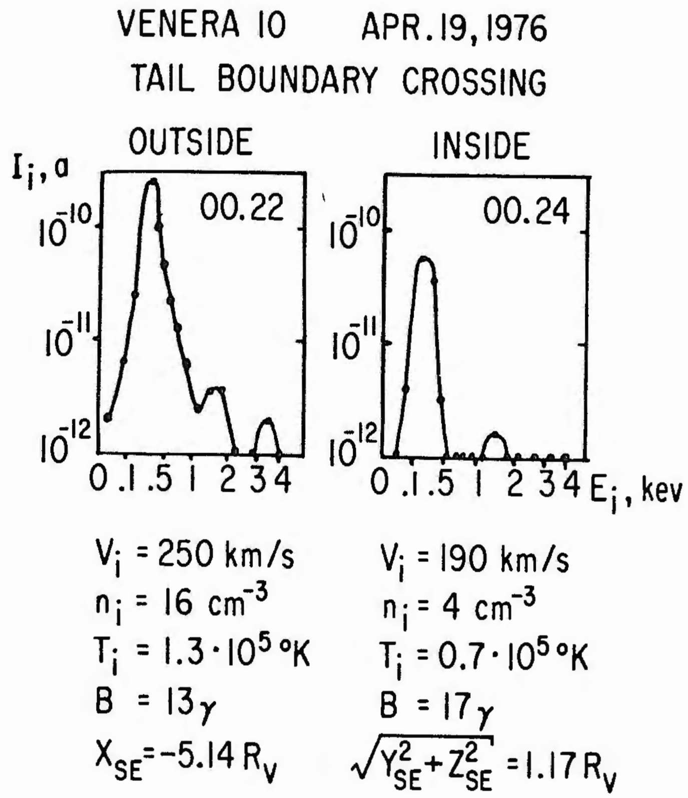

Fig. 8. Ion spectra obtained on crossing the boundary of the magnetospheric wake of Venus.

III. THE CORRELATION BETWEEN THE MAGNETOSPHERE AND IONOSPHERE OF VENUS

Figure 10 shows a simplified current system corresponding to the magnetic fields near Venus (Gringauz 1981). The dayside portion of this current system creates a magnetic barrier, discovered above the dayside ionosphere in Pioneer measurements, and injects current into the upper layer of the dayside ionosphere, which is closed across the plasma of the transitional zone (Elphic et al. 1980*a*). The current structure in the nightside portion is similar to that in the cross section of the geomagnetosphere wake (Θ-structure).

Part of the fluxes of electrons with energy <300 eV directed toward the planet, and measured in the particulate shadow (Fig. 5), evidently strongly influence the formation of the nightside ionosphere of Venus. The electron concentration n_e in the ionosphere of Venus was measured by the Venera 9

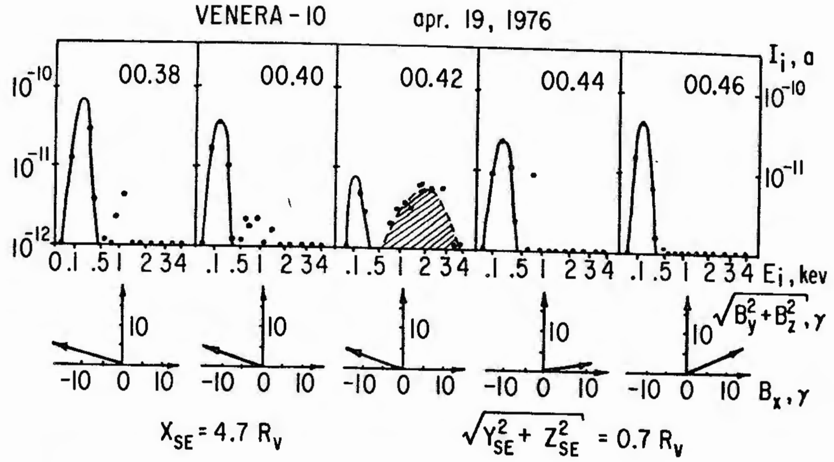

Fig. 9. Variation of the ion spectra for the change in direction of the magnetic field in the magnetospheric wake: appearance of the plasma layer.

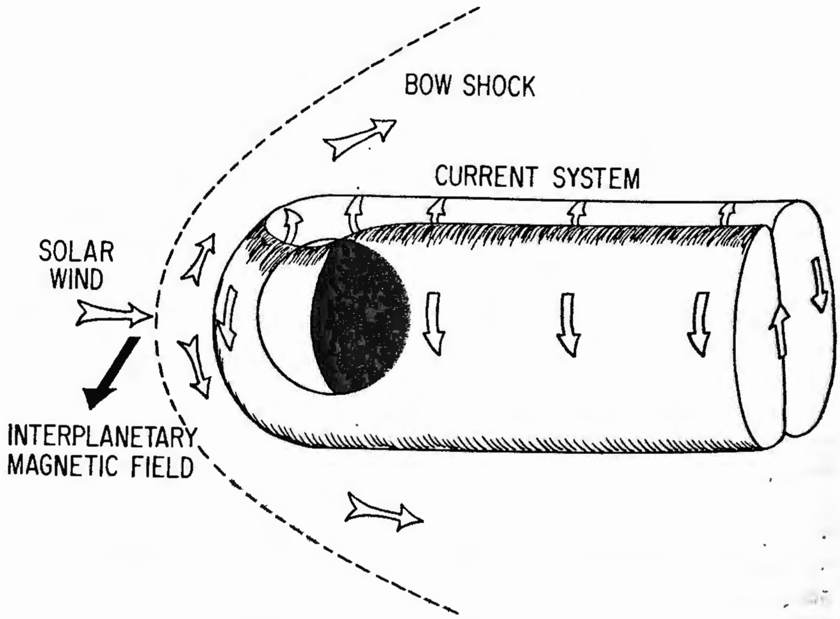

Fig. 10. Simplified current system in the magnetosphere of Venus constructed on the basis of available observations.

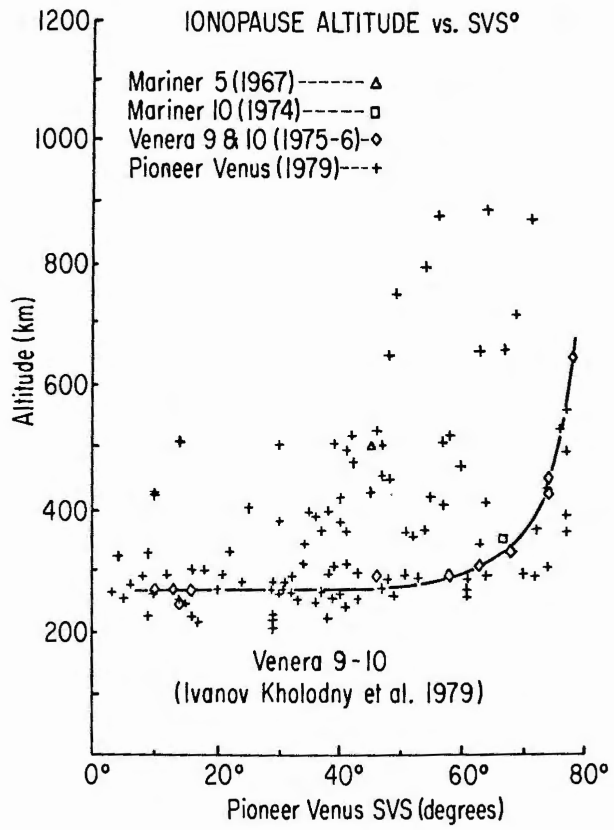

Fig. 11. Diurnal ionopause, from data of a radio occultation experiment on board Veneras 9 and 10, and data from the Pioneer Venus orbiter.

and 10 radio occultation experiment (Aleksandrov et al. 1976*b*; Ivanov-Kholodnyy et al. 1977). The measurements confirmed the existence of the ionopause as a characteristic and permanent feature of the dayside ionosphere of Venus; it was previously observed by the Mariner 5 flyby (Mariner Stanford group 1967) and the Mariner 10 flyby (Fjeldbo et al. 1975). The measurements from Veneras 9 and 10 established that the height of the ionopause increases with solar zenith angle; this tendency was confirmed by Pioneer Venus observations (cf. Figs. 11 and 12; Elphic et al. 1980*a*).

The nightside ionosphere of Venus, according to radio occultation data from Veneras 9 and 10, has a principal maximum n_e at the fixed height ~140 km. The value of $n_{e(max)}$ varies considerably with time. Often, but not always, this principal maximum is attended by another smaller maximum. A comparison of the time variations in the electron fluxes measured in the particulate

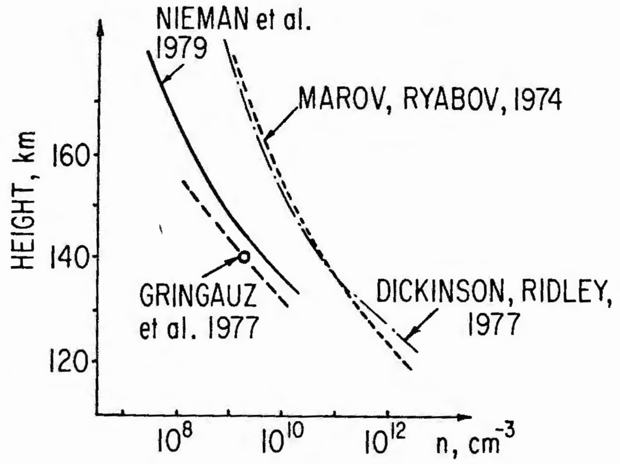

Fig. 12. Models of the neutral atmosphere of Venus with density at 140 km altitude from analyses in 1977 using electron measurements from Veneras 9 and 10 and experimental data from the Pioneer Venus orbiter.

shadow (Fig. 5), with measurements of $n_{e(\max)}$ in the nightside ionosphere, revealed that these are correlated (Gringauz et al. 1979). The hypothesis was used that the electron fluxes directed at the planet, and measured at altitudes of > 1500 km (Fig. 5), reach altitudes of ~ 140 km and by means of impact ionization form the ionospheric layer corresponding to the principal nighttime maximum n_e in the ionosphere. (Note again that the data of Pioneer's electrostatic analyzer have confirmed the presence of electron fluxes with energies on the order of tens or hundreds of eV in the nightside ionosphere.) Estimates have shown that in order for these fluxes of ionizing electrons to reach the magnitude of $n_{e(\max)}$, corresponding to observations in the nightside ionosphere, the concentration of neutral substances at an altitude of ~ 140 km must be 10^9 cm^{-3}, two orders of magnitude lower than that assumed in 1977 for the models of Venus's neutral atmosphere. The temperature of the neutral particles T_n in this case should also be much lower than that in the 1977 models.

The results of the Pioneer Venus orbiter mass spectrometer measurements published by Niemann et al. (1979*a*) revealed that the 1977 models were incorrect; instead, estimates of nighttime n_n and T_n at an altitude of ~ 140 km based on the hypothesis of impact ionization as the source of $n_{e(\max)}$ and using data of the Venera 9 and 10 electron analyzers (cf. Fig. 11) were right. We regard this as convincing support for the theory that impact ionization by electrons from the magnetosphere wake is a mechanism, if not the main one, for formation of the principal ionization maximum in the nighttime magnetosphere of Venus.

IV. CONCLUSION

Several features of the Venus magnetosphere, as revealed by magnetic and plasma measurements on board Veneras 9 and 10, are similar to the well-known peculiarities of the Earth's magnetosphere:

1. A well-developed outgoing shock wave;
2. A current of plasma immediately behind the shock wave front, which satisfies the hydromagnetic theory;
3. A magnetosphere wake which extends slightly along the Sun-planet axis;
4. A plasma layer in the middle of the magnetic wake which separates the two strands of antiparallel lines of force (directed away from the Sun and toward the Sun).

These common features of magnetospheres, despite the substantially different nature of the obstacles to the solar wind, are one of the proofs that magnetosphere-like structures with long wakes may be formed in supersonic fluxes of magnetized plasma near widely differing obstacles, from comets to galaxies.