Plasma Near Venus From the Venera 9 and 10 Wide-Angle Analyzer Data

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Preliminary results of ion and electron plasma measurements near Venus are presented and discussed. The data were obtained with wide-angle plasma analyzers carried on the Venera 9 and 10 spacecraft. On the basis of 33 bow shock crossings the position of the shock is quite stable and agrees well with theoretical predictions of Spreiter et al. with $H/r_0 = 0.01$ and a stagnation point altitude of ~500 km. This observation lends strong support to the assumption that the solar wind interacts with the upper ionosphere of Venus and not with a planetary magnetic field. These spacecraft are the first to explore the optical umbra of Venus. Close to the planet a stable population of electrons and an ill-defined population of positive ions were found; this region is called the corpuscular umbra. The corpuscular umbra and the transition region are separated by a zone which contains both positive ions and electrons and is characterized by a flow velocity reduced in comparison with that of the transition region. This zone is called the corpuscular penumbra. The distribution of plasma density behind the bow shock (including the optical umbra of the planet) is given, and the existence of a Venusian plasma magnetic tail is revealed.

INTRODUCTION

The Venera 9 and 10 spacecraft were injected into orbits about Venus on October 22 and October 25, 1975, respectively. The periods of the satellites were ~48 hours, their orbits were ~1500 km in pericenter and ~110,000 km in apocenter, and their inclination was ~30°.

The experiments with wide-angle plasma analyzers described below made the first simultaneous measurements of both the electron and the ion plasma component near Venus. Plasma experiments on Venera 4 [*Gringauz et al.*, 1968], Mariner 5 [*Bridge et al.*, 1967], and Venera 6 [*Gringauz et al.*, 1970] measured only the ion component, while Mariner 10 [*Bridge et al.*, 1974] measured only the electron component of the plasma. Until the Venera 9 and 10 flights, no experimental data were available on plasma characteristics in the optical shadow of the planet. The ion plasma component was measured on board the Venera 9 and 10 spacecraft in 16 energy intervals within the energy range 0–4400 eV (for protons) with a modulated Faraday cup detector. This sensor had an angular acceptance angle of ±45° and was sunward oriented. The electron plasma component was measured with a wide-angle ±40° antisunward oriented analyzer. The electron energy distribution was analyzed by the retarding potential method. Sixteen values of retarding potential U_R were used in the range $0 \lesssim U_R \lesssim 300$ V. The equipment used differed slightly (the sensors were the same) from that used in the plasma experiments near Mars made on board Mars 2, 3, and 5 and is described in more detail elsewhere [*Gringauz et al.*, 1974*a*].

In all the near-planet measurements reported in this paper (except for the measurement on April 19, 1976), electron and ion analyzer currents were recorded once per second. Ten current measurements were made in each energy interval and for each value of U_R, so that the complete differential ion and integrated electron energy spectra were measured in 160 s. On April 19, 1976, currents were measured once every 4 s; one measurement was made in each energy interval and for each value of U_R. Measurements of successive spectra were made every 2 min. The Venera 9 satellite measured simultaneously both electron and ion plasma components. The satellite Venera 10 measured only the electron plasma component because of some malfunction, as was mentioned by *Gringauz et al.* [1976*b*, *c*]. However, on April 19, 1976, ion plasma component measurements resumed; their data are used below.

The research team engaged in the experimental program for the Pioneer-Venus 1978 satellite [*Bauer et al.*, 1977] formulated a series of questions about the properties of near-Venus space which should be answered. The results of the Venera 9 and 10 plasma measurements yield answers to some of these questions.

The amount of experimental data obtained by both satellites is large; not all of it has been processed up to June 1977 (i.e., before the IAGA Assembly in Seattle). Hence this publication is not a final one.

TYPICAL FEATURES OF THE BOW SHOCK NEAR VENUS

The time resolution of the Venera 9 and 10 instruments allows a detailed study of electron and ion plasma components when the satellites were traversing the bow shock near the planet. Considerably different structures were observed along different orbits of the satellites when they traversed the bow shock. Figure 1 gives the results of measurements of the ion and electron plasma components and the magnetic field, carried out on the Venera 9 satellite in 50 s during traversals of the bow shock on December 17, November 1, and October 26, 1975. Magnetic data given both here and below have been kindly supplied to us by Sh. Dolginov and E. Yeroshenko. The same figure shows mean ion energy values E_i in the energy intervals where measurements were made near the bow shock as well as retarding potentials U_R of the electron analyzer. As Figure 1 demonstrates, the transit of the bow shock (indicated in Figure 1 by the letter S) is, within the telemetry time resolution, simultaneously recorded in measurements of the ion and electron plasma components and in magnetic field measurements. The transit time through the shock observed on December 17 was <1 s and on November 1 about 15–20 s, and the bow shock was crossed at least three times during observations on October 26. If it is assumed that the bow shock did not move on December 17 and October 26, then with a satellite velocity v of about 7 km s^{-1} taken into account the shock thicknesses corresponding to these transit times are ≤10 km and about 100–150 km, respectively. The first and third crossings of the bow shock on October 26, 1975, took τ

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Paper number 8A0270.
0148-0227/78/088A-0270$01.00

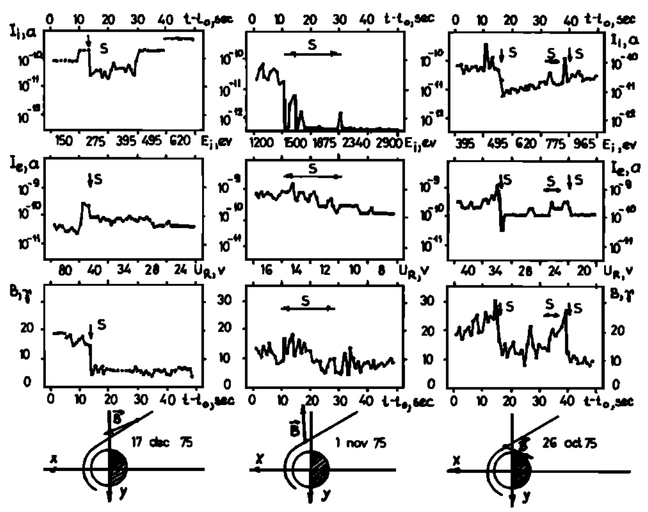

Fig. 1. Detailed plasma and magnetic field measurements for three bow shock crossings observed on Venera 9. Each panel shows a 50-s measurement interval in the vicinity of the shock. The top set of panels shows differential measurements of positive ion currents recorded as a function of time (top abcissa) and mean ion energy (bottom abcissa). The second data field from the top gives similar data for the electron component of the plasma. In this case the measurements are integral currents above a retarding potential U_R, rather than differential. The third data field from the top gives the magnitude of the magnetic field in gammas, and the bottom field shows the location of the bow shock crossing and the orientation of the magnetic field projected onto the ecliptic plane. The time or time interval when the shock crossing was observed is indicated in the figure by the arrows marked S.

$\sim$ 2 s, while for the second, T was about 4 s. Under the assumption that in the first case the velocities of the bow shock motion, V_s, and of the satellite, v, were oppositely directed while in the second case they were in the same direction, the bow shock velocity and its thickness δ can be assessed for October 26, as $V_s = v(T + \tau)(T - \tau)^{-1} = 20$ km s^{-1} and $\delta = (V_s + v)\tau = 60$ km, respectively.

It should also be pointed out that for some traversals of the bow shock the transition from the electron and ion spectra typical of the solar wind to those typical of the transition region occurred along orbit sections δ about 1000–3000 km long. (The term transition region was used in early papers which described the interaction of the solar wind with the earth. For obvious reasons this region in the case of the earth is now usually referred to as the magnetosheath. For Venus the intrinsic magnetic field is obviously insufficient to create an obstacle for the solar wind, and it seems appropriate to refer to the region of transitional flow by its original name.) Figure 2 illustrates projections of the orbits for which bow shock crossings were observed. The figure uses the customary X, $(Y^2 + Z^2)^{1/2}$ coordinates (the X axis is through the center of the planet and directed toward the sun) and includes data for 33 orbits of the Venera 9 and 10 satellites. According to the figure it can be seen that a fairly broad bow shock was recorded in about 30% of the cases.

The values of bow shock thickness δ observed near Venus can be so different (from $\delta \lesssim 10$ to $\delta \approx 3000$ km) because the nature of the shock depends on many variables, e.g., on Mach numbers, ratios of thermal to magnetic field energies, and the angle θ between the magnetic vector and the direction of the normal to the bow shock. For large Mach numbers typical of the bow shock near Venus, δ is most sensitive to θ. As is well known, in the case of the earth the transition from the plasma state before the shock front to that behind it for $50° \lesssim \theta \lesssim 90°$ occurs at distances $c/\omega_{pe} \lesssim \delta \lesssim 10c/\omega_{pi}$ (greater δ corresponds to smaller θ); then if the ion concentration in the solar wind is $0.5 \lesssim n_i \lesssim 20$ cm^{-3}, one finds $1 \lesssim \delta \lesssim 3000$ km. For smaller θ the thickness of a pulsating front can reach about 12,000 km [*Greenstadt*, 1976].

Since the orbits of the Venera 9 and 10 satellites intersect the near-planet bow shock not far from the ecliptic and since, as a rule, the interplanetary magnetic field component perpendicular to the ecliptic is small, the value of θ for any particular bow shock intersection can be evaluated by the angle between the projections of the **B** vector on the ecliptic (as shown at the bottom of Figure 1) and the normal to the bow shock.

As is seen from Figure 1, θ is close to 90° on December 17 but differs considerably from this value on November 1 and October 26. The expected bow shock thicknesses during these two orbits are $\delta \approx c/\omega_{pe} \approx 2$ km and $\delta \approx c/\omega_{pi} \approx 30$ and 60 km, respectively (n_i measurements were used after the satellite entered the solar wind); these estimates are in reasonable agreement with those given above of bow shock thickness based on transit times observed during these passes. The examples given and the totality of all bow shock crossings near Venus allow a conclusion to be made about the dependence of bow shock structure on the angle between the **B** vector and the normal to the shock front which is similar to that for a near-earth bow shock (see, for example, *Greenstadt* [1976]): the thickness of the bow shock grows with diminishing θ; it sometimes reaches up to about 3000 km for small θ. Previously, the dependence of the near-Venus shock front structure on θ was mentioned according to the data of the two bow shock crossings by Mariner 5, when it entered and when it left the transition region [*Greenstadt*, 1970].

Figure 2 compares the positions of 33 bow shock crossings observed by Venera 9 and 10 with the theoretical model of *Spreiter et al.* [1970]. The dashed curve in Figure 2 (and in similar figures which follow) indicates the position of the bow shock calculated for an ionospheric obstacle with $H/r_0 = 0.01$ and for an altitude of the stagnation point $\sim$500 km. It is evident that the experimental points lie close to the predicted location of the shock. In only six crossings out of the 33 examples which were studied did the observed position differ from that predicted by more than 1000 km.

As has been pointed out previously on the basis of a more limited data sample [*Gringauz et al.*, 1976*b*, *c*], the small scatter

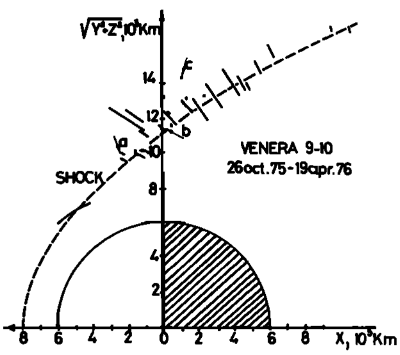

Fig. 2. Bow shock crossings observed near Venus by Venera 9 and 10 during the period October 26, 1975, to April 19, 1976. The location and duration of 33 crossings of the bow shock are plotted with reference to a theoretical shock position indicated by the dashed curve. The shock crossings have been rotated into a common plane, and the model is that of *Spreiter et al.* [1970], characterized by $H/r_0 = 0.01$, a stagnation point altitude of approximately 500 km, and Mach 8.

in the observations noted above is evidence that the size of the obstacle at Venus is quite stable with time. Moreover, the size of the obstacle does not seem to change with changes in the dynamic pressure of the solar wind; i.e., the position of the bow shock does not change appreciably for large changes in ρV^2. In fact, for the three bow shock intersections, marked by arrows in Figure 2, the solar wind ρV^2 was equal to 1.4×10^{-8} dyn cm^{-2} for intersection *a*, 4.2×10^{-8} dyn cm^{-2} for intersection *b*, and 8.4×10^{-8} dyn cm^{-2} for intersection *c*, while the distance of the bow shock from the planet remained practically the same for intersections *a* and *b* and grew (with growing ρV^2) for intersection *c*. By way of comparison, the location of the shock front near the earth and Mars is ρV^2 dependent, and its distance from the planet decreases with growing ρV^2 [*Binsack and Vasyliunas*, 1968; *Gringauz et al.*, 1976*a*].

It seems that a bow shock is always present near Venus, and its accurately determined spatial location makes it possible to give up some of the hypotheses proposed earlier about the interaction of the solar wind with Venus. These are the model [*Wallis*, 1972] according to which a bow shock cannot exist near Venus and the assumption [*Russell*, 1977] about the possibility of an attached bow shock near Venus.

THE ELECTRON COMPONENT IN THE TRANSITION REGION, PENUMBRA, AND OPTICAL UMBRA OF THE PLANET

Figure 3 illustrates electron spectra obtained on board Venera 9 on November 11, 1975, in the solar wind, in the transition region, and in the corpuscular umbra region (characterized by the absence of clearly defined ion fluxes directed from the sun [*Gringauz et al.*, 1976*b*, *c*]. In Figure 3 the vertical lines show the limits within which currents I_e recorded by an electron analyzer with a fixed value of U_R varied during the 10-s measurement interval. As this figure shows, during the motion from the solar wind to the transition region the electron flux densities (proportional to I_e) increase at all values U_R; fluctuations of the recorded currents also increase considerably. The smallest electron flux densities are recorded in the region of the corpuscular umbra of Venus. In this zone, fluctuations of the

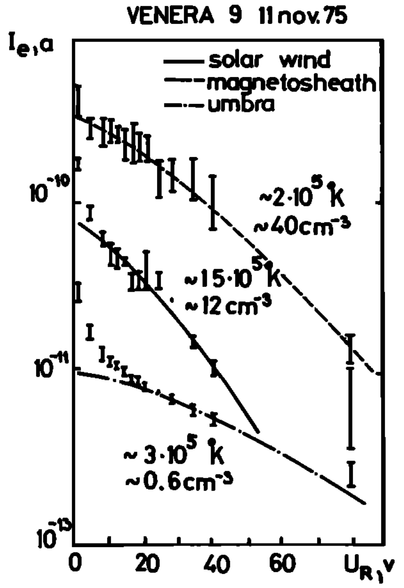

Fig. 3. Electron spectra obtained on Venera 9 in the solar wind, the transition region (magnetosheath), and the corpuscular umbra (see the discussion in the text for a detailed explanation of the figure).

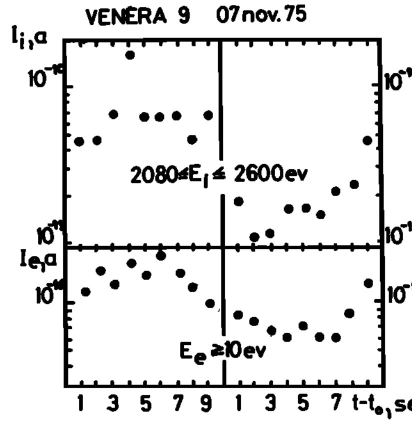

Fig. 4. Fluctuations in ion and electron currents recorded in the transition region by Venera 9 during a 20-s measurement.

electron flux densities are considerably less than corresponding fluctuations in the transition region.

One can judge the magnitude of the fluctuations observed in the transition region by ion flux densities given in Figure 4. This figure shows measurements of ion flux densities ($\sim I_i$) in the energy interval $2080 \leq E_i \lesssim 2600$ eV and electron flux densities ($\sim I_e$) with energy $E_e \gtrsim 10$ eV. As Figure 4 illustrates, in the transition region, $\Delta I_i/I_i \approx \Delta I_e/I_e \approx 1$; therefore under the conditions of strongly fluctuating charged particle fluxes the fluctuation level should be taken into account for an adequate description of the plasma state. To determine the parameters of the charged particle distribution function, we minimized the average square deviation of calculated values of currents of I_i and I_e from the measured values. Such a method makes it possible to obtain reliable numerical results only for plasma states with a low fluctuation level and a distribution function close to a Maxwellian one.

Another special feature of measurements of electron and ion plasma components in the neighborhood of Venus on Venera 9 and 10 is the fact that systematic variations of plasma concentration during the measurement time of one spectrum are observed because of spacecraft motion and must be taken into account. For most passes in the transition region, n_e varies by about a factor of 2 in 160 s. In the data analysis this caused an underestimate of the temperature and overestimate of n_e.

In Figure 3 the smooth curves show electron spectra corresponding to the experimental values of I_e. The values of n_e and T_e shown in the figure are calculated by assuming an electron transport velocity equal to the ion transport velocity V_i in the transition region and in the solar wind, with the transport velocity equal to zero (isotropic distribution) in the corpuscular umbra region. As Figure 3 shows, during the passage from the solar wind to the transition region the electron concentration and temperature increase. On passing from the transition region into the corpuscular umbra the electron concentration decreases markedly, and T_e increases slightly mainly owing to slower decay of higher-energy electron fluxes compared with lower-energy electron fluxes (see Figure 3).

One of the peculiarities revealed during the measurements of electrons on board Mariner 10 is the depletion of electrons with energies of several hundred electron volts [*Bridge et al.*, 1976]. This effect was observed in several parts of the transition region behind the bow shock. According to *Bridge et al.* [1976] this effect could have been caused by the interaction of electrons with energies of a few hundred electron volts and the atmosphere of the planet when a magnetic field line linked the point of observation and the Venus atmosphere. The analyses of measurements of electrons with energy $E_e \gtrsim 150$ eV on Venera 9 and 10 showed that in some cases, depletion of energetic electrons in the transition region was observed as on Mariner 10 [*Bridge et al.*, 1976]. However, in other cases with approximately the same orientation of the local magnetic field this depletion was not observed. As an example, Figure 5 shows the measurements of electrons with energies $E_e \gtrsim 150$ eV made on Venera 9 on October 30 and November 1, 1975. During these two passes through the transition region the electron flux density (for $E_e > 10$ eV) grows monotonically with the satellite orbital motion (see Figure 5). The magnetic field orientation in the solar wind and in the orbit section where the depletion by energetic electrons was observed on November 1 (marked by a thick line on the t-t_0 axis) is approximately the same. However, on October 30 the depletion was not observed. Therefore on the basis of Venera 9 and 10 data it is difficult to determine the origin of the effect or to judge the correctness of the explanation given by *Bridge et al.* [1976].

By using measurements of the electron plasma components on Venera 9 and 10 made in cases with approximately the same solar wind velocities ($310 \lesssim V_i \lesssim 360$ km/s) and with $E_e \gtrsim 10$ eV the distribution of electron flux densities and concentrations in the region of interaction of the solar wind with Venus can be plotted. In Figure 6 for four passes of Venera 9 and one pass of Venera 10 the positions of the satellites are shown by various symbols on their orbits when the recorded flux densities of electrons with energy $E_e \gtrsim 10$ eV differ from corresponding electron flux densities in the solar wind by factors of 2, 1, 0.5, 0.25, and 0.12. The heavy curves connecting the same symbols show the surfaces on which the ratio of electron flux densities (with energy of $\gtrsim 10$ eV) in the interaction region and in the solar wind is constant.

The electron temperature T_e in the passes considered always exceeds 10 eV. When Figure 6 was plotted, only electrons of $\gtrsim$10-eV energy were used; in this case the fraction of the electron flux density with energy of $\lesssim$10 eV (which was not taken into account) can be neglected in determining the total electron flux density, provided $T_e > 10$ eV. Also, the thermal speed of the electrons is much greater than the bulk speed, and in this case the measured flux density is proportional to the omnidirectional electron flux density. Figure 7 illustrates the distribution of electron concentration n_e for the same passes through the interaction region as shown in Figure 6 (in relative units $n_e/n_{e\infty}$); the values referring to the solar wind are marked by ∞, as was done in Spreiter's original papers [*Spreiter et al.*, 1970; *Spreiter*, 1976]. In passing from data on $j_e/j_{e\infty}$ (Figure 6) to data on $n_e/n_{e\infty}$ (Figure 7) it was assumed in the calculations that the electron distribution function is Maxwellian, although the actual distribution function is non-Maxwellian. During further processing we can better approximate the actual distribution. Therefore the data given in Figure 7 should be considered as preliminary.

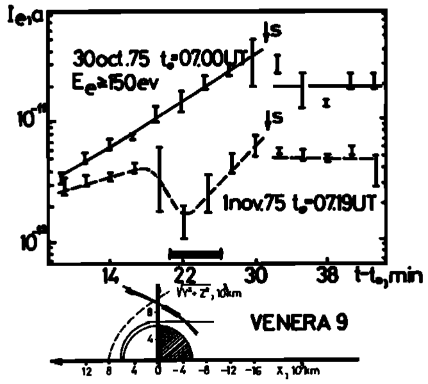

Fig. 5. Electron flux densities for energies above 150 eV observed in the transition region during two passes by Venera 9. The location of the spacecraft is shown in the bottom panel.

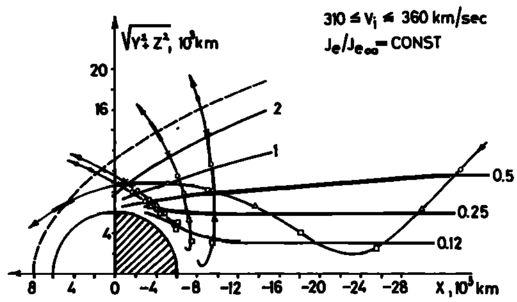

Fig. 6. Electron flux densities j_e in the interaction region at Venus compared with the corresponding flux density in the solar wind, $j_{e\infty}$. The data are for electrons with energies greater than 10 eV. Symbols on the trajectories indicate observed flux densities 2, 1, 0.5, 0.25, and 0.12 times those in the solar wind. The heavy solid curves show traces of surfaces of constant relative flux density.

The antisolar ($X < 0$) part of the solar wind region disturbed by Venus can be conditionally divided into three zones: external, where $D = (Y^2 + Z^2)^{1/2} > 6500$–$7000$ km; near internal, where $D < 6500$–7000 km, $X > -10{,}000$ km; and far internal, where $D < 6500$–7000 km, $X < -10{,}000$ km ($D \approx 6500$–7000 km approximately corresponds to the 'ionopause' of *Spreiter et al.* [1970]).

As Figures 6 and 7 demonstrate, in the external region the distribution of $j_e/j_{e\infty}$ and $n_e/n_{e\infty}$ qualitatively coincides with magnetohydrodynamic calculations of solar wind flow around an impenetrable obstacle [*Spreiter et al.*, 1970; *Spreiter*, 1976]. In the near internal region the distributions of $j_e/j_{e\infty}$ and $n_e/n_{e\infty}$ qualitatively correspond to theoretical calculations carried out under the assumption of the flow around an obstacle by a collisionless neutral plasma (without magnetic field and with a Debye radius much less than the obstacle dimensions) freely expanding into the corpuscular umbra (see, for example, *Gurevich et al.* [1969]). However, in the far internal region the lines of $j_e/j_{e\infty}$ = const, $n_e/n_{e\infty}$ = const are very stretched; this observation suggests that there should be a field, apparently a magnetic field which prevents plasma from filling the region behind the obstacle and causes the plasma disturbance at considerable distances (>5–6 R_V (Venus radii)) from the obstacle. This interpretation is in agreement with the observa-

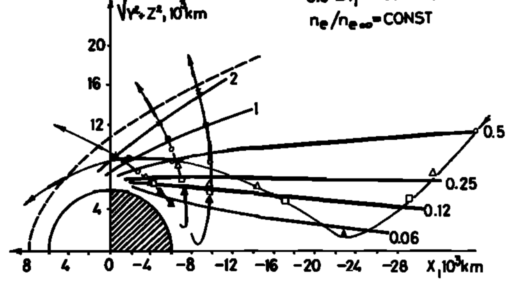

Fig. 7. Electron number densities in the interaction region at Venus relative to those in the solar wind. The representation is similar to that in Figure 6.

tions made by *Dolginov et al.* [1977], who recorded the magnetic field with $B_X > B_{Y,Z}$ at large values of X.

For values of D less than about 8000 km, extrapolated curves (Figures 6 and 7) of $j_e/j_{e\infty}$ = const and $n_e/n_{e\infty}$ = const converge at the planet terminator at a height of about 500–1000 km, i.e., close to the height of the obstacle which deflects the solar wind as estimated by *Gringauz et al.* [1976*b*, *c*] from the data of ion measurements (see also the next section).

The results of calculations carried out by Spreiter's group [*Spreiter et al.*, 1970; *Spreiter*, 1976] are the only results which give a 'global' picture of the solar wind flow field around the planet (the results include the plasma number densities, the flow velocities, and the magnetic field which are to be expected in the interaction region near Venus); they are a convenient 'frame of reference,' with which plasma characteristics in the solar wind zone disturbed by the planet can be compared.

THE ION COMPONENT IN THE TRANSITION REGION, PENUMBRA, AND OPTICAL UMBRA OF VENUS

The analysis of ion measurements shows that in addition to the transition region, regions of corpuscular umbra and penumbra [*Gringauz et al.*, 1976*b*, *c*] also exist near Venus. These regions were determined phenomenologically. The region was called a corpuscular umbra where there was no regular registration of ion flux densities by the Faraday cup and only separate ion current spikes distributed in all energy intervals in disorder were observed. The region was called a penumbra where lower (in comparison with the transition region) ion flux densities with lower antisolar velocity V_i were recorded. According to Spreiter's calculations [*Spreiter et al.*, 1970; *Spreiter*, 1976], $V_i/V_{i\infty}$ in the region $X < 0$ is everywhere >0.75; let us take the condition $V_i/V_{i\infty} < 0.75$ for the determination of the corpuscular penumbra.

Figure 8 illustrates ion spectra obtained from Venera 9 on November 1, 1975, and from Venera 10 on April 19, 1976. These 2 days are characterized by fairly low values of the solar wind velocity (310 and 350 km/s, respectively) and T_i (6.5×10^4 and 9×10^4 °K) and by high values of n_i (35 and 65 cm^{-3}). It should be mentioned that on April 19, 1976, ion spectra in the solar wind had an anomalous 'tail' in the region of high energies (2–4 keV). In the figure each ion energy spectrum corresponds to the orbit section with which it is connected by a straight line; calculated plasma parameters are shown for each spectrum. In both cases the solar wind characteristics were almost constant during motion of the satellite in the region disturbed by the planet.

The data of Figure 8 show that on November 1, while the satellite passed from the solar wind into the interaction region at Venus, plasma parameters changed in the following way: at the bow shock the bulk velocity V_i decreased, and the ion temperature T_i and ion concentration n_i increased; with further penetration into the transition region, V_i was practically constant, and n_i decreased from 110 to 13 cm^{-3}. The spectrum recorded at 0435 UT is characterized by a considerable fall of V_i (to 110 km/s); we interpret this spectrum in terms of passage into the corpuscular penumbra zone. Further spectra (a sample is given for t = 0427 UT November 1, 1975) belong to the corpuscular umbra; they are characterized by the fact that only irregular signals (ion spikes) were recorded for ions, and currents which could be attributed to normal ion flux densities were not observed. Considering all data obtained in this region (i.e., all energy channels), irregular ion spikes were observed in 30% of the telemetry samples. The results obtained in the corpuscular umbra are given in more detail by *Gringauz et al.* [1976*b*, *c*]. There were no ions with energies of >2 keV in the session of November 1, 1975, either in the transition region or in the corpuscular penumbra, and their registration in the corpuscular umbra indicates that there are acceleration mechanisms in this region (see also data of *Gringauz et al.* [1976*b*, *c*]).

On that section of the orbit of Venera 10 which passed through the interaction region near Venus, ion flux densities were regularly recorded everywhere. Therefore this section, although it passed through the optical umbra of the planet, was only in the transition region and in the corpuscular penumbra. This is conclusive evidence that the 'length' of the umbra in the case under consideration is no more than 3–4 R_V from the planet and that the corpuscular penumbra of the planet is bounded by the hatched region in Figure 8. Inside this region the bulk velocity does not exceed $0.75V_i$ in the undisturbed solar wind, as has already been mentioned. When a satellite passes near the terminator of the planet, sometimes the penumbra is recorded only in one ion spectrum; this fact allows direct measurements of an obstacle height [*Gringauz et al.*, 1976*b*, *c*].

The ion spectra measured on April 19, 1976, have several maxima recorded in different energy intervals. However, all the spectra among these maxima have one largest 'major'

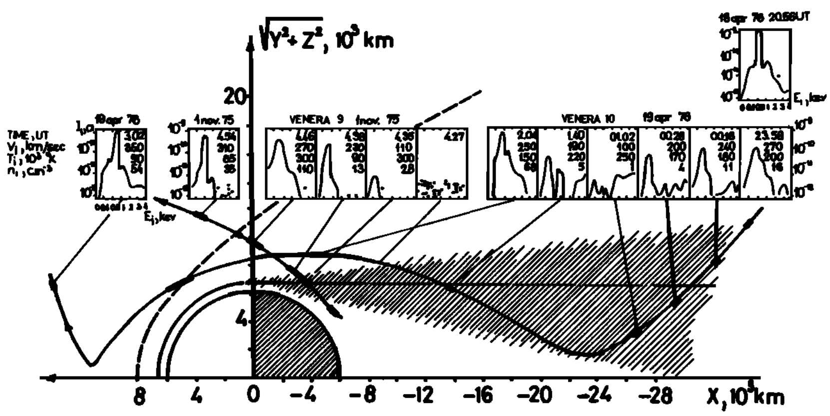

Fig. 8. Representative ion spectra observed in the interaction region at Venus. Each data panel is connected by a line to a region on the trajectory where the data were obtained. The ordinate of each panel gives the ion current, and the abcissa the mean ion energy per charge. Figures inside each panel list (from top to bottom) time in universal time, proton velocity in kilometers per second, proton temperature in multiples of 10^3 °K, and number density in units per cubic centimeter.

maximum which almost always occurs at the lowest energy, E_{min}, which characterizes the observed maxima. Both the magnitude of the ion signals and the value of E_{min} which corresponds to the major maximum systematically decreased as the satellite moved from the bow shock deeper into the transition and penumbra regions. Hence there is a good reason to believe that the major maximum mentioned is determined by solar wind protons. As Venera 10 moved from the outer boundary of the penumbra (2358 UT April 18, 1976) to the area deep within this region (0140 UT April 19, 1976), the value of n_i fell from 15 cm^{-3} down to <1 cm^{-3}, that of V_i from about 270 km s^{-1} down to $\lesssim$100 km s^{-1}, and T_i increased by about 1.5 times.

According to measurements of *Dolginov et al.* [1977] carried out on Venera 10 a change in sign of the magnetic field component B_X was recorded at 0042 UT on April 19, 1976 (antisunward **B** was replaced by sunward **B**). Figure 9 shows ion spectra measured in the vicinity of the Venera 10 orbit section within which **B** changed its sign. Intense high-energy ion fluxes were recorded at 0042 UT. Their temperature can be estimated at about 10^3 eV.

A zero value of B_X (the major **B** component; $B_X > B_{Y,Z}$ in this region) corresponds to the minimum magnetic energy, so the increase of plasma pressure in this region is quite natural. Ion spectra measured on both sides of the reversal of B_X show an increase of the energetic ions with energies $\gtrsim$2 keV. This observation seems to indicate a region similar to the plasma sheet in the magnetospheric tail of the earth (which is known to consist of charged particles with energies of the order of a few keV).

The occurrence of high-energy ions near the points where B_X changed sign was observed in the other cases at lower values of X, for example, on November 11 and November 25, 1975.

DISCUSSION

The data obtained near Venus with the wide-angle plasma analyzers proves first of all that the position of the detached bow shock is described quite well by the magnetohydrodynamic calculations made by *Spreiter et al.* [1970] under the assumption of a one-fluid plasma model and a completely impenetrable obstacle (full pressure balance at the ionopause) with $M_\infty = 8$, $\gamma = \frac{5}{3}$, $H/r_0 = 0.01$, and a stagnation point altitude of ~500 km (Figure 2). The distribution (of plasma number density) in the transition region behind the bow shock for $D \geq 8000$ km is qualitatively consistent with the calculations made by *Spreiter et al.* [1970] and *Spreiter* [1976]. Despite the fact that for the bow shock crossings shown in Figure 2 the solar wind velocities varied over a wide range (300–800 km/s), the bow shock position near Venus was far more stable than that near the earth and Mars [*Binsack and Vasyliunas*, 1968; *Gringauz et al.*, 1976*a*]. From our viewpoint this proves that the obstacle which creates a bow shock at Venus has a different nature from that at the earth and Mars and its size is quite stable and depends only slightly on variations in solar wind plasma parameters. The agreement between the bow shock position and the calculations [*Spreiter et al.*, 1970] made under the assumption that there is no dissipation of the solar wind energy at the obstacle shows conclusively that this dissipation is low and the neglect of it in Spreiter's calculations was justified. At the same time the existence of such dissipative effects is beyond any doubt and can be directly observed. As was discussed previously [*Gringauz et al.*, 1977], the interaction between solar wind electrons which are found in the optical umbra of the planet with the nightside atmosphere makes an important contribution to the formation of the nightside ionosphere of Venus. Such an interaction should also take place in the dayside atmosphere of the planet. However, since the data of the Venera 9 and 10 radio occultation observations reveal that the electron density value in the dayside maximum of ionization depends strongly on the solar zenith angle [*Aleksandrov et al.*, 1976; *Yakovlev et al.*, 1976], a conclusion can be made that the solar wind contribution to ionization in this case is insignificant and that the ultraviolet solar radiation is the main source of ionization in the dayside ionosphere. Thus despite the fact that the solar wind energy dissipation in the Venus atmosphere probably is present, it cannot be essential.

In a recent paper by *Russell* [1976*a*] the magnetic measurements carried out on Venera 4 are revised, and a conclusion is made that the Venus surface magnetic field is ≈30 γ. This value is the highest of those suggested up to the present. However, even with such a high value for the intrinsic field the magnetic pressure is insufficient to deflect the solar wind flow at Venus; thus no investigator has seriously considered that a planetary magnetic field could constitute the obstacle at Venus.

Despite the fact that during the last 10 years a series of papers dealing with the characteristics of the obstacle near Venus has been published [*Dessler*, 1968; *Johnson and Midgley*, 1969; *Cloutier et al.*, 1969; *Spreiter et al.*, 1970; *Bauer et al.*, 1970, 1977; *Michel*, 1971; *Wallis*, 1972; *Cloutier and Daniell*, 1973; *Spreiter*, 1976; *Russell*, 1976*a*, 1977], insufficient experimental data are available for a final solution of this problem. The concept that the solar wind can decelerate near Venus only at ionospheric heights is common to all the papers. There have been various suggestions on the causes of deceleration (impenetrability of the ionosphere for solar wind plasma [*Dessler*, 1968; *Spreiter et al.*, 1970; *Bauer et al*, 1970], the magnetic field generated by currents induced in the ionosphere due to the electric field—$(1/C)[\mathbf{V}_i \times \mathbf{B}]$ [*Johnson and Midgley*, 1969; *Cloutier and Daniell*, 1973], or loading of the solar wind flow by ionospheric ions [*Cloutier et al.*, 1969]); however, there are no estimates of obstacle altitude which give a subsolar point above ~500 km in altitude.

Since Russell recently argued that there is no intrinsic magnetic field at Mars, a comparison of some data which have been obtained from the satellites of both Venus and Mars is of interest. As is well known, Vaisberg et al. paid great attention to the concept of the mean position of the bow shock at Mars and suggested that the distances from the planet which have been given by *Gringauz et al.* [1976*b*] are too large. Figure 10 compares (in units expressed in planet radii) the mean position of the bow shock near Mars as calculated by *Vaisberg* [1976] (the closest to the planet of all the estimates available at present) with the data on the bow shock intersections obtained near Venus by the satellites Venera 9 and 10 which have been

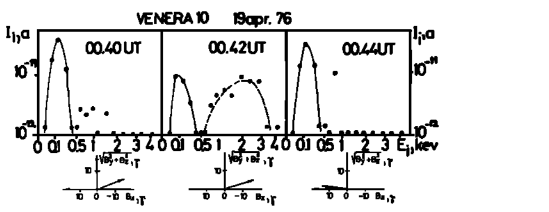

Fig. 9. Energetic ions observed by Venera 10 near a region where B_X changed sign.

already shown in Figure 2. It is evident that though the Venus ionosphere is fairly like that of Mars (see, for example, *Gringauz and Breus* [1976]), there is some reason owing to which the bow shock near Mars is substantially farther away from the planet than that near Venus. We believe that the intrinsic magnetic field of the planet at Mars is the cause and that there is no such magnetic obstacle at Venus.

Spreiter et al. [1970] and *Spreiter* [1976], who presented (as has been mentioned) the only global picture of solar wind flow around Venus, noted that actually the dissipation of solar wind energy near the obstacle should cause a deceleration of the plasma in some broad boundary layer. According to *Spreiter* [1976], this dissipation can be taken into account if an 'effective viscosity' is included in the magnetohydrodynamic equations. The specific mechanisms which can produce this viscosity are reviewed in a paper by *Hartle* [1976]. They are the following: charge exchange of protons with neutrals [*Wallis*, 1971], mass loading of the solar wind with atmospheric photoions, electodynamic effects due to the currents induced in the ionosphere, and plasma instabilities caused by the opposite directions of the density and temperature gradients at the solar wind–ionosphere boundary. In the work of *Hartle* [1976] as well as in the works of *Gringauz et al.* [1976*b*, *c*] the probability of Kelvin-Helmholtz instability is mentioned.

Vaisberg and Bogdanov [1974], as a continuation of their assumption that the obstacles decelerating the solar wind near Mars and Venus are of similar nature (which from our viewpoint is not correct), noted the presence of the broad boundary layer near Venus (which from our point of view is correct). However, *Vaisberg et al.* [1976*a*, *b*], interpreting the results of their own ion measurements from Venera 10 in 1976, have not used the concept of boundary layer but spoke about a rarefaction wave. We consider that the effective viscosity of the obstacle is the main cause of the penumbra region formation (see *Gringauz et al.* [1976*a*, *b*] and Figure 8), where $V_i/V_{i\infty} \lesssim 0.75$, i.e., lower than the lowest value permissible according to the calculations in which dissipation is not taken into account. Calculations of the properties of the boundary layer near the obstacle boundary have been made by *Pérez de Tejada and Dryer* [1976] for a two-dimensional model and are qualitatively consistent with our results.

Figure 8 shows that the corpuscular penumbra begins above the planet terminator and grows in transverse dimension with increasing distance downstream from the terminator. The essential feature of the interaction region near to and downstream from Venus is the existence inside it ($D \lesssim 7 \times 10^3$ km) of constant plasma density lines aligned along the sun-Venus direction (Figure 7). Simultaneously, *Dolginov et al.* [1977] observe in the same region that the magnetic field is aligned along the X axis. It seems reasonable to us to call this region the Venus plasma magnetic tail. A dot-dashed curve in Figure 8 shows the approximate position of the plasma magnetic tail. A part of the corpuscular penumbra is inside the plasma magnetic tail. The bulk velocity of plasma in this region continues to decrease with decreasing distance from the sun-planet line (i.e., while it is penetrating into the plasma magnetic tail). The variations of plasma parameters in this penumbra region remind one of the variation of plasma parameters observed in the plasma mantle of the earth's magnetospheric tail [*Akasofu et al.*, 1973; *Rosenbauer et al.*, 1975]. Hence it cannot be excluded that this part of the penumbra region at Venus is produced by processes close to those occurring in the earth's plasma mantle.

The umbra region (where ion fluxes are not recorded regularly by the Faraday cup) begins above the terminator of the planet and gradually narrows while the penumbra enlarges; it probably extends to a distance of $\lesssim$3–4 R_V. Obviously, this distance must depend on the ion bulk velocity and on the ion temperature in the transition region. The fact that the accelerated particles which are absent in the transition region can be observed in the umbra as spikes gives evidence that the acceleration processes vary strongly in time. Perhaps these energetic ions are associated with some wavelike phenomena in the plasma magnetic tail. The pickup of ionospheric ions should result in the generation of waves which can appear in the umbra [*Hartle*, 1976; *Wallis*, 1971]. Electron fluxes are recorded in the umbra quite regularly, and the electron density is ≈ 1 cm^{-3}. The possible effects of the interaction of these electrons with the planet nightside neutral atmosphere are considered by *Gringauz et al.* [1977]. The magnetic field in the umbra varies with the interplanetary field [*Dolginov et al.*, 1977].

Russell [1976*a*, *b*] considered the data which have been presented by the authors of the Venera 4, Mariner 5, and Venera 9 experiments. He concluded that a magnetosphere existed at Venus owing to an intrinsic magnetic field of the planet. The data of *Russell* [1976*a*, *b*] give evidence which supports the existence of the boundary layers and magnetic tail near Venus. Although according to our data the penumbra shape and spatial position differ appreciably from the 'boundary layer' according to *Russell* [1976*b*] and the plasma magnetic tail boundary is at much lower distances from the sun-Venus line than that in Figure 2 of *Russell* [1976*b*] (see our Figure 8), the data given in Figure 8 do not contradict in their general features the conclusions of *Russell* [1976*b*].

It is evident that the plasma measurements described in this paper do not allow us to determine the origin of the magnetic field in the plasma magnetic tail and leave open the question whether it is an intrinsic field of the planet or one which is induced by the ionospheric currents.

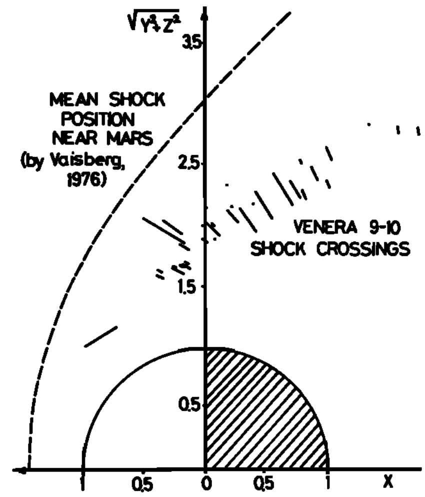

Fig. 10. A comparison of shock crossings observed near Venus by Venera 9 and 10 with the mean position of the Martian bow shock derived by Vaisberg.

Acknowledgments. The authors express their sincere thanks to A. V. Dyachkov and L. A. Shvachunova for their participation in the data processing, to T. V. Stukalova for technical assistance in preparing this paper, and to Sh. Sh. Dolginov and E. G. Yeroshenko for permission to use their magnetic field data from the Venera 9 and 10 satellites.

The Editor thanks H. Bridge and P. A. Cloutier for their assistance in evaluating this paper.

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(Received October 7, 1977;
revised February 22, 1978;
accepted March 2, 1978.)