



PLASMA OBSERVATIONS NEAR VENUS ONBOARD THE
VENERA 9 AND 10 SATELLITES BY MEANS OF
WIDE-ANGLE PLASMA DETECTORS

K. I. Gringauz, V. V. Bezrukikh, T. K. Breus, T. Gombosi*
A. P. Remizov, M. I. Verigin and G. I. Volkov
Space Research Institute of the USSR Academy of Sciences
Moscow, Profsoyuznaya 88, USSR

Preliminary results of the measurements of the electron and ion components of plasma obtained by means of wide-angle detectors onboard the Venera-9 and Venera-10 satellites are presented. Stable electron and fluctuating ion fluxes were detected in the optical and corpuscular umbra. As a result of the plasma characteristics observed at a few hundred kilometers above the optical umbra, we refer to this region as corpuscular penumbra. By means of a number of bow shock crossings, we analyzed its structure which turned out to be variable with time. The relatively small fluctuations of the bow shock crossing positions and grouping of corresponding shocks near the planet suggest the nonmagnetic nature of the Venus obstacle.

INTRODUCTION

Low-energy plasma measurements were conducted by means of wide-angle detectors installed on the Venera-9, -10 space vehicles launched into the Venus satellite orbits on October 1975. The orbital period of both satellites was ~ 2 days, the orbit altitude at pericenter ~ 1500 km, at apocenter $\sim 110,000$ km, inclination $\sim 30^\circ$. The ionic component of plasma was measured in 16 energy intervals from Venera-9 (in energy range 0 to 4400 eV) using a modulated Faraday cup oriented to the Sun with an angular opening of $\pm 45^\circ$; measurements of the electron component of plasma were carried out using an integral trap oriented in the anti-solar direction (with an angular opening of $\pm 40^\circ$). Sixteen values of retarding voltage were supplied to the analyzing grids in the range 0 to 300 V. Only the electron plasma component was measured from Venera 10 as the ionic Faraday cup current amplifier went out of operation during the flight to Venus. The equipment used differed slightly from the instruments operated earlier in plasma experiments in the Mars region (detectors are identical) on satellites Mars-2, Mars-3 and Mars-5 and described in detail by Gringauz et al, (1974).

Before the flight of Venera-9, -10 the experimental results relating to the region of solar wind interaction with Venus were not systematic. For the first time the simultaneous disturbances of ionic component of the interplanetary plasma and magnetic field connected with the near-planetary shock wave

* On leave from the Central Research Institute for Physics,
Budapest, Hungary.

were discovered on October 18, 1967 when the Venera-4 station approached Venus (Gringauz et al, 1968; Dolginov et al, 1968). Later, near-planetary shock wave front crossings were registered on October 19, 1967 from Mariner-5 (Bridge et al, 1967); on May 17, 1969 from Venera-6 (Gringauz et al, 1970) and on February 7, 1974 from Mariner-10 (Bridge et al, 1974; Ness et al, 1974). Measurements of the low-energy plasma ion component were taken from Venera-4 and Venera-6 by means of the wide-angle traps with two values of retarding potential 0 V and +50 V (Gringauz et al, 1970); from Mariner-5 the ion component of plasma was also measured using a modulated trap in the energy range 40 to 9400 eV (Bridge, et al (1967), and from Mariner-10 measurements of only the electron component of plasma which were carried out in the energy range 13 to 715 eV using an electrostatic analyzer oriented mainly in the anti-solar direction (Bridge et al, 1974). Thus, before the flight of Venera-9, simultaneous measurements of the plasma electron and ion components in the region of the solar wind interaction with Venus were not conducted. It is worthwhile to mention the full absence of experimental data on the plasma characteristics in the optical umbra of the planet.

The shock wave front position was defined in the previous experiments from Venera-4, Mariner-5, Venera-6 (Gringauz et al, 1967) only with large angles Sun-Venus-vehicle, ϕ (112° , 138° , 129° , respectively) where the relative uncertainty of the front position was sufficiently small: $\Delta\tau/\tau \ll 1$ where τ - is the distance from the Venus center to the front, and $\Delta\tau$ is the front position uncertainty associated with both motion characteristics and the front thickness as well as with frequency of plasma or magnetic measurements in each specific experiment. As was mentioned by Bridge et al. (1975) according to the Mariner-5 and Mariner-10 data, front crossings traveling from the magnetosheath with lower τ and ϕ , $\Delta\tau$ was ~ 3000 km and was comparable with the dimensions of the obstacle creating the front ($\Delta\tau/\tau \approx 0.2$ to 0.3).

Earlier a paper was published (Gringauz et al, 1976a) with the first preliminary data obtained on October 26, 1975 while Venera-9 was flying from the optical umbra of Venus into the solar wind. At present, the results of measurements conducted in the near-planetary parts of the orbits are partially processed (the first month's operation, 12 passes of Venera-9 and 4 passes of Venera-10). Some results of measurements conducted during these flights are considered and discussed below.

CORPUSCULAR AND OPTICAL UMBRA, CORPUSCULAR PENUMBRA

Plasma measurements in a mode with increased sampling were begun, as a rule, in the optical umbra of the planet at altitudes 1500 to 2000 km at a distance 3000 to 4000 km from the Sun-Venus line. In this mode one value of the electron and ion trap current was measured once per second. Since the measurements of the plasma ion component were made in 16 energy intervals and the electron component measurements were conducted with 16 values of retarding voltage, and in each energy interval and with each value of retarding voltage the current was measured 10 times, the full differential energy spectrum of ions and integral energy spectrum were obtained in 160 sec. During this time the satellites with the velocity ~ 7 km/sec traveled ~ 1100 km;

this should be taken into account in regions with large gradients of the surrounding plasma characteristics.

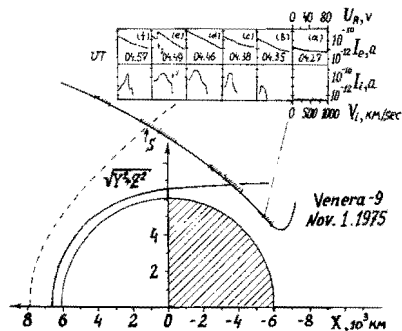
Fig. 1 in $X, \sqrt{Y^2 + Z^2}$ coordinates (X axis passes through the planet center and is directed to the Sun) gives the portion of the Venera-9 trajectory during the passage from the optical umbra into the solar wind on Nov. 1, 1975. The energy spectra of ions obtained during this flight are given in the upper part of the figure. In the optical umbra of the planet the energy spectra of electrons consistent with a density $n_e \sim 1 \text{ cm}^{-3}$ and a temperature $T_e \sim (2-5) \cdot 10^5 \text{ K}$ were regularly measured. In the same region in $\sim 70\%$ of the telemetry samplings the measured ion fluxes turned out to be lower than the instrument sensitivity threshold, and in $\sim 30\%$ of the samples, fluctuating ion fluxes were irregularly distributed in all energy intervals up to 4.4 keV. The plasma peculiarities characteristic of the optical umbra of the planet were recorded at several hundred kilometers higher than the optical umbra boundary. This region, which is wider than the optical planetary umbra and which is characterized by the absence of distinct directed ion fluxes, we refer to as the corpuscular umbra region.

Fig. 1 shows the spectra (a) of electrons and ions in the corpuscular (and optical) umbra region. The bulk of the readings in the ion spectrum lie lower than the instrument sensitivity; the points show individual readings of recorded ion currents.

Between the corpuscular umbra and the magnetosheath, which exists behind the near-planetary shock wave front, a zone called by us as the corpuscular penumbra, was observed (spectra (b) in Fig. 1). Within this zone the plasma ion component is characterized by lower transport velocities as compared to that in the magnetosheath (spectra (c) in Fig. 1); the directional character of ion motion in the corpuscular penumbra is shown clearly.

Let us consider the crossing of the corpuscular penumbra in more detail. Fig. 2 gives five successive ion spectra recorded on October 30, 1975 from satellite Venera-9 during its passage through the corpuscular umbra (spectra a, b, c) into the magnetosheath (spectrum e). As mentioned above,

FIGURE 1. A PART OF VENERA-9 TRAJECTORY NEAR VENUS AND THE ENERGY SPECTRA OF ELECTRONS AND IONS OBTAINED DURING THIS FLIGHT. "S" WAS THE SATELLITE POSITION WHEN IT CROSSED THE BOW SHOCK (DASHED LINE). THE SOLID LINE IS THE OBSTACLE POSITION ACCORDING TO THIS SHOCK.



in each energy interval the current was recorded 10 times (with absence of "failures"). However, because of the transient while changing the modulating high voltage on the ion trap grid, even in the quiet surrounding plasma, the first reading of current, as a rule, differed from the rest. Therefore, Fig. 2 gives 9 readings of ion current in each energy interval (in the first energy interval, 0 to 40 eV the last 5 readings of current are given). As it is seen from Fig. 2, the directional character of ion fluxes became noticeable on spectrum (d), Fig. 2, when the satellite went out into the penumbra (according to our terminology).

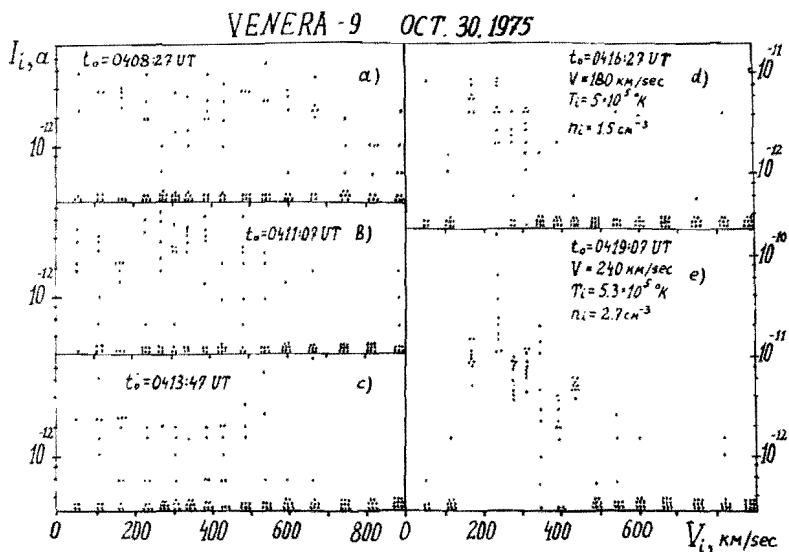


FIGURE 2. THE ION SPECTRA RECORDED DURING THE FLIGHT OF VENERA-9 FROM CORPUSCULAR UMBRA (a, b, c) ACROSS THE CORPUSCULAR PENUMBRA (d) INTO THE MAGNETOSHEATH (e).

To get an estimate of the plasma parameters in the penumbra, magnetosheath, and solar wind, the averaged values of currents in each energy interval were used (9 readings). The computed current values in our energy intervals are shown in Fig. 2 (d), (e) by solid lines with the parameters of the surrounding plasma (chosen in such a way that the weighted root-mean-square deviation of the computed current from the averaged measured currents should be minimum). In the penumbra the ion density is $n_i \sim 1.5 \text{ cm}^{-3}$; bulk velocity $V \sim 180 \text{ km/sec}$, temperature $T_i \sim 5 \cdot 10^5 \text{ K}$; in magnetosheath $n_i \sim 2.7 \text{ cm}^{-3}$, $V \sim 240 \text{ km/sec}$, $T_i \sim 5.3 \cdot 10^5 \text{ K}$, i.e., during the flight into the magnetosheath from penumbra on October 30, 1975 an increase of bulk velocity and ion density occurred and the temperature practically did not change. The non-monotonic change of the computed currents (Fig. 1) can be

explained by the chosen values of the relative widths of energy steps. The ion bulk velocity vector deviation from the normal to the trap aperture was not taken into account in the calculation. The analogous estimates of the plasma parameters on November 1, 1975 in the penumbra (spectrum b in Fig. 1) yield $n_i \sim 2.9 \text{ cm}^{-3}$, $V \sim 110 \text{ km/sec}$, $T_i \sim 3 \cdot 10^{50} \text{ K}$; in the magnetosheath (spectrum c in Fig. 1) $n_i \sim 13 \text{ cm}^{-3}$, $V \sim 230 \text{ km/sec}$, $T_i \sim 0.9 \cdot 10^5 \text{ K}$.

The bulk velocity and ion density in the magnetosheath also increase during this pass, but the ion temperature is decreased. The lower values of ion temperature estimated from spectrum (c), Fig. 1, as compared to (b) in penumbra can be caused by time variations of currents recorded by trap while taking this spectrum. Indeed, for the subsequent spectra in the magnetosheath on November 1, 1975 the estimated T_i values lay within $2.6\text{-}3.4 (10)^5 \text{ K}$, i.e. during this flight from the penumbra into the magnetosheath the ion temperature probably did not significantly change.

Note that the corpuscular penumbra was not recorded during all satellite flights. This can be associated with the fact that the characteristic size of the penumbra is of the order of the distance over which the whole energy spectrum of ions is taken in the given experiment, and during the satellite pass through the corpuscular penumbra, measurement can be made only in those energy intervals where the ion fluxes are absent in penumbra.

MAGNETOSHEATH AND NEAR-PLANETARY SHOCK WAVE

Let us return to Fig. 1. After exiting the corpuscular penumbra the satellite at $\sim 5000 \text{ km}$ traveled in the magnetosheath. This transition is accompanied by a monotonic growth of electron fluxes for all retarding potentials (compare spectra (c) and (d) in Fig. 1); the bulk velocity of ions increases from 230 km/sec to 270 km/sec ; the plasma density (defined from the ion trap recordings) increases from 13 cm^{-3} to 105 cm^{-3} . During spectrum (e) of Fig. 1, the satellite crossed the shock wave front S and went out into the solar wind (spectrum (f) in Fig. 1). It is clearly seen from Fig. 1 that in the given session of measurements the S front intersection is distinctly observed as a sharp decrease of the electron fluxes recorded (the ion component measurements at this time were made in energy intervals where the ion fluxes both in the magnetosheath and in the solar wind were absent). In the solar wind in this session of measurements the density was $n \sim 35 \text{ cm}^{-3}$; $T_i \sim 6.5 \cdot 10^4 \text{ K}$, $T_e \sim 150 \cdot 10^3 \text{ K}$, $V \sim 310 \text{ km/sec}$. Note that as the retarding voltage increases, the electron fluxes fall faster in the magnetosheath as compared to the solar wind (compare electron spectra (c) and (d) in Fig. 1). This can probably be explained not by "cooling" of electrons behind the shock wave front, but because of the satellite motion during taking the whole energy spectrum of electrons (from the large decelerating potentials to the small ones). This leads to an underestimation of electron temperature in the magnetosheath region formally defined from "energy" spectrum, and overestimation of their "density" as compared to the ion density.

Fig. 3 gives the ion spectra obtained during the session on November 9, 1975 from Venera-9 in the magnetosheath (Fig. 3a) and in the solar wind (Fig. 3b); the calculated current values (see above) are shown in this picture by solid lines. As it is seen from Figure 3, the plasma ion component in the

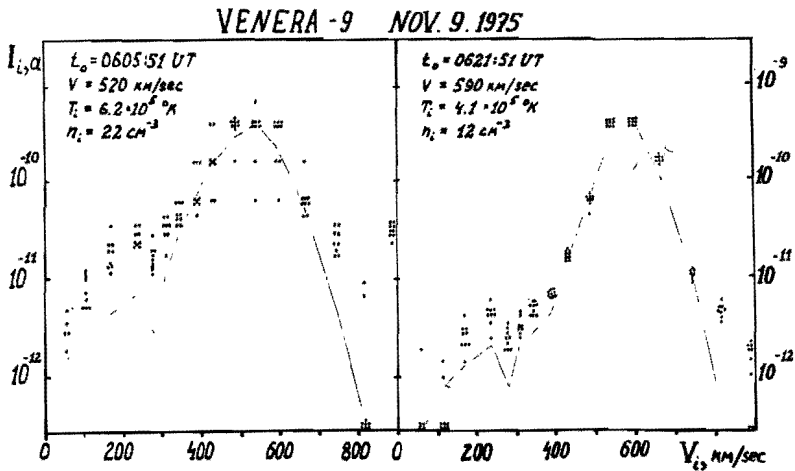
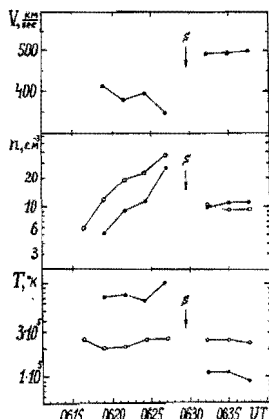


FIGURE 3. ION SPECTRA IN THE MAGNETOSHEATH (a) AND IN THE SOLAR WIND (b). SOLID LINES ARE THE CALCULATED CURRENTS WHILE t_0 IS THE BEGINNING OF THE GIVEN SPECTRUM.

magnetosheath behind the shock wave front not only decelerates and heats up as compared to that of the solar wind, but also it is characterized by significantly large fluctuations of ion fluxes in the energy intervals with the most fluxes recorded. Under conditions of strongly fluctuating fluxes of charged particles the fluctuation level should be taken into account for adequate description of the plasma state. The method described above that was used in determining the plasma parameters probably does not allow reliable numerical results to be obtained.

The behavior of the obtained parameters of ion and electron components of plasma in the near-planetary shock wave front intersection by Venera-9 on November 11, 1975 is given in Fig. 4. As one can see the density n decreases and bulk velocity V increases. The ion temperature decreases in crossing the shock wave front S going into the solar wind. Note that the estimates of electron temperature and density given in Fig. 4 are made without consideration of plasma density changes in the magnetosheath during a single energy spectrum measurement (see above). This probably causes the excess in the electron density in the magnetosheath over ion density, and the absence of significant variations of electron temperature at the shock wave front. Consideration of the plasma density gradient in the magnetosheath will result in a better agreement between the estimates of the electron and ion densities in the magnetosheath, as well as affecting the conclusion concerning the slight decreases of electron temperature

FIGURE 4. THE BEHAVIOR OF THE CALCULATED ION AND ELECTRON PARAMETERS NEAR THE INTERSECTION OF THE "S" BOW SHOCK. IN THE CALCULATIONS WE NEGLECTED THE DENSITY VARIATION DURING THE RECORDING OF THE SPECTRA.



while intersecting the shock wave front and going into the solar wind on November 11, 1975.

The sufficiently high time resolution of the instruments installed on Venera-9, -10 allows the behavior of the plasma electron and ion components in crossing the near-planetary shock wave front to be studied in detail. Essentially different front structures were observed on different satellite orbits at crossings of the shock wave front. Results of the measurements of electron and ion plasma components in the shock wave front intersection by Venera-9 on October 26, 1975 were given earlier (Gringauz et al., 1976). In this session of measurements the front crossing was recorded by electron and ion detectors simultaneously as a current decrease over 1 to 2 sec. Using the satellite velocity and assuming that the front did not move, a thickness of 10-15 km can be estimated (Gringauz et al., 1976). Of course it should not be excluded that in this session of measurement (similar to that considered below) the front could be moving with a velocity exceeding that of the satellite's (~ 7 km/sec); in this case the front thickness estimate must be increased.

Fig. 5 gives three successive electron integral energy spectra recorded from Venera-10 on November 2, 1975 passing from the magnetosheath (spectrum a) into the solar wind (spectrum c). In spectrum b the time interval ~ 20 sec is marked by S to show the intersection of the shock wave front by the satellite. As it is seen from Figure 5, the electron flux in the time interval S continuously decreased and the shock wave front thickness in this case can be estimated as ~ 150 km assuming again that the shock wave front did not move.

It should be noted that in some sessions of measurements shock wave front motions were possibly observed. For example, in Fig. 6 are shown the

FIGURE 5. THE ENERGY SPECTRA OF ELECTRONS REGISTERED BY VENERA-10 FROM THE MAGNETOSHEATH (a) INTO THE SOLAR WIND (c) INTERSECTING THE "S" BOW SHOCK. U_R IS THE RETARDING POTENTIAL OF THE ANALYZING GRID OF THE DETECTOR.

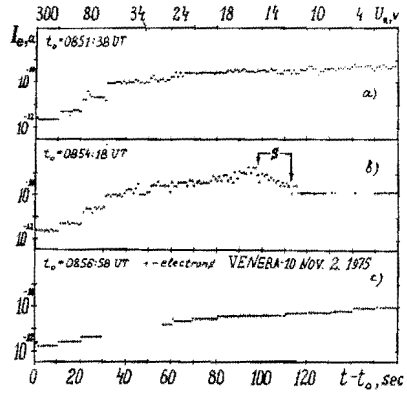
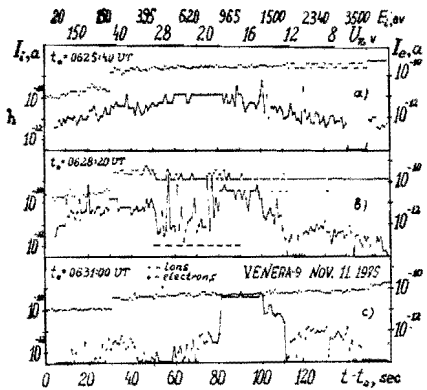


FIGURE 6. ENERGY SPECTRA OF IONS AND ELECTRONS RECORDED AS VENERA-9 PASSED FROM THE MAGNETOSHEATH (a) TO THE SOLAR WIND (c). IN THE TIME INTERVAL MARKED BY THE DASHED LINE ON SPECTRUM (b) CONSIDERABLE AND FAST OSCILLATIONS OF ION AND ELECTRON FLUXES WERE OBSERVED. U_R IS THE RETARDING POTENTIAL OF THE ANALYZING GRID OF THE DETECTOR WHILE E_i IS THE MEAN ENERGY OF THE GIVEN ENERGETIC INTERVAL OF THE FARADAY CUP.



electron and ion spectra obtained as Venera-9 on November 11, 1975 passes (spectra b) from the magnetosheath (spectra a) into the solar wind (spectra c). In the time interval marked by the dashed line in spectra b, considerable and fast oscillations of ion and electron fluxes were observed in which can be interpreted as oscillatory motions of the shock wave front towards the satellite with a velocity that exceeds the satellite velocity by 10 to 20 times, or as a pulsating front of width 200 to 300 km. Front motion at a more considerable distance was observed on November 9, 1975 when Venera-9 intersected the near-planetary shock wave front with a point spread in space of ~ 1000 km. It also should be noted that during one flight (Venera-9 on November 7, 1975) a very wide front was observed on which the transition from the charged particles spectra typical for the solar wind to the typical spectra of the magnetosheath occurs over a ~ 3000 km portion of the orbit.

Fig. 7 shows the analyzed cases of the intersections of the near Venus shock wave front by Venera-9 (circles) and Venera-10 (points). The solid line with a circle marks shock wave front intersections on November 7, 1975 and on November 9, 1975 when the uncertainty of the front position was ~ 3000 km and 1000 km, respectively. The dashed line in Fig. 7 shows the shock wave front position computed by Spreiter et al. (1970) for an obstacle characterized by the parameter $H/\tau_0 = 0.01$ and by a sub-solar point altitude above Venus' surface of ~ 500 km (solid line). The short solid lines show the Venera-9 orbit parts where such ion spectra were observed as are characteristic of the corpuscular penumbra. As it is seen from Fig. 7, with the chosen obstacle size and shape, the observed positions of the corpuscular penumbra and the near-Venus shock wave front are in good agreement with the computed ones.

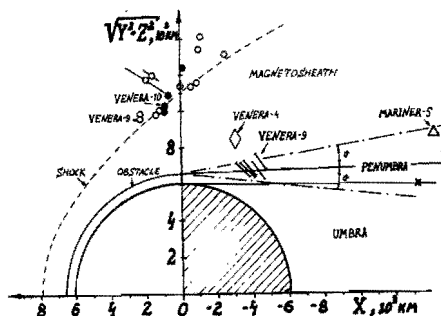
DISCUSSION

A. The Corpuscular Umbra and Penumbra Regions

The discovery of ion fluxes in the energy range ~ 1 to 4.4 keV in the deep optical and corpuscular umbra of the planet is one of the unexpected, incomprehensible, and therefore, the most interesting, result of the measurements described. As is noted above and as is seen from Fig. 2, such fluxes are recorded in approximately 30% of cases during some flights (in $\sim 70\%$ of the total number of measurements these fluxes are lower than the instrument sensitivity level). However, the ion fluxes in the mentioned energy interval were not recorded in portions of the trajectory in the corpuscular umbra located closer to the magnetosheath, in the corpuscular penumbra and in the deepest part of the magnetosheath (compare a and c, d, e spectra in Fig. 2).

The characteristic size of the corpuscular penumbra is ~ 1000 km (see Fig. 1, 7) in qualitative agreement with the assumption that it can be formed as a result of erosion of an initially rather sharp boundary of the obstacle (the scale height of the ionized or neutral part of the Venus atmosphere is the natural thickness of the obstacle boundary near the terminator) because of the thermal motion of the plasma particles, or an

FIGURE 7. BOW SHOCK CROSSINGS OF VENERA-9 AND VENERA-10. THE SOLID LINE WITH CROSS REPRESENTS THE POSITION OF THE OPTICAL UMBRA.



instability of the Kelvin-Helmholtz type on the obstacle boundary. However, while these mechanisms can explain the plasma penetration deep into the optical umbra behind Venus, they do not explain the existence of ion fluxes with such energies which were not observed in the corpuscular penumbra region, and it is necessary to assume the presence of ion accelerating processes deep inside the corpuscular umbra of the planet. The presence of large fluctuations of ion fluxes deep in the corpuscular umbra of the planet can be indirect evidence in favor of the fact that at least some accelerating mechanisms are stochastic.

While ion fluxes in the optical and corpuscular umbra of Venus were at the limit of the instrument sensitivity, electron fluxes in these regions were always reliably measured with all retarding potentials (0 to 300 V), and for the characteristic parameters of the plasma electron component in the energy range 10 to 80 eV, we obtained $n_e \sim 1 \text{ cm}^{-3}$, $T_e \sim (2 \text{ to } 5) \cdot 10^{50} \text{ K}$. The preliminary estimates show that an influence of these electron fluxes on the neutral atmosphere can provide the existence of the Venus night-side ionosphere. The authors will analyze this problem in a separate paper.

It should be noted that in the previous plasma experiments in the Venus region there have already been observed the phenomenon which we can interpret now as entry into the corpuscular penumbra. While Venera-4 was approaching the planet surface, the ion flux recorded by the integral trap at altitude $\sim 3000 \text{ km}$ dropped to values less than those in the solar wind (Gringauz et al., 1968). While Mariner-5 was approaching the optical umbra, the ion fluxes recorded by this vehicle also decreased (Bridge et al., 1967) and due to the reconsidered data analysis in the region of nearest approach of the vehicle to the optical umbra, at $\sim 2500 \text{ km}$ from it the flux dropped to values lower than the instrument sensitivity limit (Bridge et al., 1975). The position of Venera-4 (rhombus) and Mariner-5 (triangle) at the appropriate times is shown in Fig. 7. The dashed lines in Fig. 7 show the Mach "cone" with opening angle $\theta = \arcsin 1/M$, $M = 8$. It is seen from Fig. 7 that both the Venera-9 orbit portions where the ion spectra characteristic for the penumbra were observed and the region with the minimum ion fluxes (Mariner-5 data) lies inside the Mach cone with $M \lesssim 8$. The phenomena observed from Mariner-5, by their character and location, can be interpreted as an entry of this vehicle into corpuscular penumbra (and as noted in Bridge et al., 1975, the disappearance of fluxes is possibly associated with Mariner-5 being at this moment in the corpuscular umbra of the planet). Venera-4 was beyond the Mach "cone" (Fig. 7) when the recorded ion fluxes dropped to the values lower than in the solar wind. However, with its further approach to the planet the ion fluxes recorded continued to decrease (dropping to the instrument sensitivity level at an altitude of $\sim 2500 \text{ km}$) consistent with the behavior of the plasma ion component observed while Venera-9 entered the corpuscular penumbra.

We can make some conclusions on the obstacle height over the sunlit part of the planet when interpreting the corpuscular penumbra as the smeared boundary of the obstacle that stops the solar wind near Venus. Therefore, we assume that the obstacle height corresponds to the middle of the penumbra. As it is seen from Fig. 7, the typical distance from Venus' optical umbra up to the middle of orbital sections where ion spectra

were observed (we associated them with the corpuscular penumbra) amounts to about 800 km. The obstacle height over the planetary surface (and beyond the terminator the obstacle height over the geometrical umbra) is naturally assumed to be a monotonically increasing function of ϕ -angle. Hence, over the sunlit Venus the height of the obstacle that stops the solar wind is less than about 800 km. It is the experimental evidence in favor of this fact that the steep fall observed in the electron density profiles at about 500 km in the Venus ionosphere (Fjeldbo and Eshleman, 1969) is a consequence of the interaction between the ionosphere and the solar wind.

B. Magnetosheath and Near-Planetary Shock Wave

As has been mentioned above and seen from Fig. 4, the plasma density n increases while the satellites move in the magnetosheath from the corpuscular penumbra to the shock wave front S , and then suddenly decreases at the shock wave front. This density increase is sometimes rather significant (by 20 to 50 times); plasma density decreases of more than four times were also observed at the shock wave front. Such large jumps of the plasma density at the shock wave front and the growth of n between the corpuscular umbra zone and the front is possibly associated with the presence of the additional degrees of freedom in the plasma at the magnetosheath region (oscillatory) and with the appropriate decreases of the adiabatic exponent as compared to the frequently used value $5/3$. It is not excluded that the increased gradients of the plasma density in the direction from the shock wave front to the corpuscular umbra boundary as compared to the analogous case in the Earth are associated with different nature of the obstacle: the magnetopause near the Earth and the diffusive atmospheric boundary near Venus. However, both of these conclusions need further theoretical and experimental confirmations. It should be taken into account that the plasma parameter estimates under the conditions of strongly fluctuating particle fluxes are not very reliable (see above). The comparison of the plasma parameter jumps at the shock wave front with the jumps calculated by the Rankine-Hugoniot relation assumes the absence of strong fluctuations of the plasma parameters behind the front at distances much less than the radius of the shock wave front curvature. Such a plasma state can be absent behind the near-Venus shock wave. Indeed, the linear dimension of the strong fluctuation region behind the collisionless shock wave near Venus and the Earth is defined by the solar wind plasma parameters and must be approximately the same. However, the characteristic size of the obstacle for the solar wind near Venus is ~ 10 times smaller than that near the Earth ($\sim 6 \cdot 10^3$ km and $\sim 6 \cdot 10^4$ km, respectively). According to the measurements taken from the Vela-4 satellite, strong fluctuations were observed by Montgomery et al. (1970) [at a distance of ~ 1500 to 3000 km (sometimes its distance amounted to $\sim 3 \cdot 10^4$ km)] behind the near-terrestrial shock wave front, and the plasma parameters in both sides of this region were compared with the Rankine-Hugoniot relations (Montgomery et al., 1970). For Venus ~ 1500 to 3000 km are comparable to the magnetosheath dimension and in this case the plasma current characteristics in the magnetosheath beyond the zone of strongly fluctuating fluxes will be not determined by local Rankine-Hugoniot relations but the total picture of the flow around the planet.

Despite the possible absence of a plasma state with small fluctuations in Venus' magnetosheath, the obstacle and the shock wave front positions detected near Venus agreed with gasdynamic calculations Spreiter et al. (1970) carried out under the assumption that the obstacle boundary is a tangential discontinuity and the Rankine-Hugoniot relations are performed locally at the shock wave front (very small part of the strong fluctuation region behind the shock wave front). However, for the flow around the Venus both these assumptions become less valid (as compared to the flow of solar wind around the Earth); nevertheless, the measurements and, in particular, the agreement of the mutual positions of the near-planetary shock wave front and the obstacle with the gasdynamic calculations allow the application (at least qualitative) of gasdynamic approximations in the case of the solar wind interaction with Venus.

It can be noted that the intersection points of the shock wave front by satellites (Fig. 7) with different revolutions around the planet are grouped near the front position indicated by the dashed line. Only in five cases of 16 were the deviations from the front (reckoned in the normal to the front) as high as ~ 2000 km. This fact probably indicates the nonmagnetic nature of the obstacle creating the near-Venus shock wave. Really, if the atmosphere or the ionosphere of the Venus is an obstacle, then due to the low scale heights in the atmosphere and ionosphere as compared to the planetary radius the obstacle dimension must be rather stable, even with great changes of the solar wind dynamic pressure, and according to Spreiter et al. (1970) for $M \approx 5$ and given obstacle dimension the front position only slightly depends on M . Near the Earth (Bezrukikh et al., 1976; Fairfield, 1971) and Mars (Gringauz, 1975; Gringauz et al., 1976b) the near-planetary shock wave positions are more changeable.

Let us discuss the near-Venus shock wave front peculiarities noted during separate passes. All front intersections given here are recorded by Venera-9 and Venera-10 over the dawn side of Venus* in rather narrow interval of planetocentric distances τ and angles ϕ (see Fig. 7). Near-planetary front intersections over the dawn side of Venus at approximately the same interval τ and ϕ were earlier observed from Mariner-5 and Mariner-10 (Bridge et al., 1967, 1974; Ness et al., 1974). According to the data obtained from these vehicles the uncertainty of the front position was, as noted above, ~ 3000 km and was interpreted in terms of "parallel" shock wave (Bridge et al., 1975). In reality, over the dawn side of Venus the expected directions of the interplanetary spiral magnetic field and the normal to the shock wave front are rather colinear than orthogonal. However, a very wide shock wave front with a characteristic dimension ~ 3000 km was observed once in 16 flights (on November 7, 1975) but is not considered to be typical.

*Here the side looking in the direction of the Venus orbital motion despite its own reverse rotation is regarded as the morning side (by analogy with the Earth).

The great difference of time intervals for which satellites crossed the shock wave front (from 1-2 sec to ~ 5 min or from 10-15 km to ~ 3000 km assuming a stationary front) can be associated with the different classes of shock wave structures depending on Mach number, heat energy density relation to the magnetic field energy density, the angle between the direction of interplanetary magnetic field force lines and the shock wave front σ , ion and electron temperature relations, etc. The character of structure and the shock wave front width are changed depending on these parameters and the front width can be determined by, e.g.

$$\sim c/\omega_0 \approx 2 \text{ km}, \omega_0 = \sqrt{\frac{4\pi ne^2}{m}} \quad - \text{Langmuir frequency}$$

$$\sim c/\Omega_0 \approx 70 \text{ km}, \Omega_0 = \sqrt{\frac{4\pi ne^2}{M}} \quad - \text{ionic Langmuir frequency} \quad (1)$$

$$\sim c\sigma/\Omega_0 \approx 2 \div 70 \text{ km}, \sqrt{\frac{m}{M}} < \sigma < 1; \sim \rho_i \approx 60 \text{ km} \quad - \text{ionic thermal Larmor radius}$$

etc. (Sagdeev, 1964). The estimates of the front width are made with $n \approx 10 \text{ cm}^{-3}$, $T \approx 2 \cdot 10^{50} \text{ K}$, $H \approx 10\gamma$. One can see that the estimates of width of the collisionless shock wave obtained from experiments on Venera-9, -10 are not inconsistent with the modern theoretical conceptions. Further detailed studies of the separate intersections of the shock wave near Venus will require simultaneous data on the plasma electron and ion components and three components of magnetic field.

CONCLUSIONS

1. Multiple measurements of electron and ion plasma components were carried out by means of wide-angle plasma detectors in the optical and corpuscular umbra of Venus, in the corpuscular penumbra, in the magnetosheath, during the front intersection by the near-planetary shock wave, and in the solar wind.

2. Electron fluxes appropriate to a density $\sim 1 \text{ cm}^{-3}$ and temperature $\sim (2-5) \cdot 10^{50} \text{ K}$ were detected in the optical and corpuscular umbra of the planet; in these regions the ion fluxes fluctuate and are distributed randomly over all energy intervals up to 4.4 keV. These electron fluxes can ionize the Venus neutral atmosphere and explain the existence of the Venus night-side ionosphere.

3. The corpuscular penumbra is detected at hundreds of kilometers higher than the optical umbra; the plasma density and bulk velocity there are less than those in the magnetosheath.

4. Charged particle fluxes in the magnetosheath fluctuate strongly; plasma density estimates show a considerable increase during satellite flights from the corpuscular penumbra to the shock wave front.

5. The measurements carried out during a number of intersections of near-planetary shock wave front showed that the front structure varies

considerably in time (from a sharp front with the thickness on the order of 10 km to a diffusive and stretched over ~ 3000 km).

6. The observed points of intersection by satellites on different passes have a rather small spread and the appropriate front positions are grouped near the planet. This fact apparently indicates the non-magnetic nature of the obstacle near Venus.

REFERENCES

- Bezrukikh, V. V., T. K. Breus, M. I. Verigin, P. A. Maisuradze, A. P. Remizov, E. K. Solomatina (1976): Dependence of the Earth's magnetopause and bow-shock positions on the solar wind parameters and the magnetopause plasma structure observed by charged particle traps aboard the Prognoz and Prognoz-2 satellite. To be published in Space Research 16.
- Bridge, H. S., A. J. Lazarus, C. W. Snyder, E. J. Smith, L. Davis, P. J. Coleman, D. E. Jones (1967): Mariner-V: Plasma and magnetic fields observed near Venus. Science 158:1669.
- Bridge, H. S., A. J. Lazarus, J. D. Scudder, K. W. Ogilvie, R. E. Hartle, J. R. Asbridge, S. J. Bame, W. C. Feldmann, G. L. Siscoe (1974): Observations at Venus encounter by the plasma science experiment on Mariner-10. Science 183:1293.
- Bridge, H. S., R. E. Hartle, A. J. Lazarus, K. W. Ogilvie, J. D. Scudder, C. M. Yeates (1975): Interaction of the solar wind with Venus. Preprint of paper presented at the USA-USSR bilateral seminar, Moscow, November, 1975.
- Dolginov, Sh. Sh., E. G. Eroshenko, L. N. Zhuzgov (1968): Study of magnetic fields by means of the Venera-4 space probe. Kosmicheskie Issledovaniya 6:561.
- Fairfield, D. H. (1971): Average and unusual locations of the Earth's magnetopause and bow shock. J. Geophys. Res. 76:6700.
- Fjeldbo, G., V. R. Eshleman (1969): Atmosphere of Venus as studied with the Mariner-5 dual radio-frequency occultation experiment. Radio Sci. 4:879.
- Gringauz, K. I., V. V. Bezrukikh, L. S. Musatov, T. K. Breus (1968): Observation of plasma near Venus on Venera-4 space probe. Kosmicheskie Issledovaniya 6:411.
- Gringauz, K. I., V. V. Bezrukikh, G. I. Volkov, L. S. Musatov, T. K. Breus (1970): A study of interplanetary plasma disturbances near Venus using the data obtained by Venera-4 and Venera-6 space probes. Kosmicheskie Issledovaniya 8:431.
- Gringauz, K. I., V. V. Bezrukikh, G. I. Volkov, M. I. Verigin, L. N. Davitaev, V. F. Kopylov, L. S. Musatov, G. F. Sluchenkov (1974): Study of solar

- plasma near Mars and along the Earth to Mars path by means of charged particle traps aboard the Soviet spacecrafts launched in 1971-1973, Part I. Methods and devices. Kosmicheskie Issledovaniya 12:430.
- Gringauz, K. I. (1975): Review of data on interaction of solar wind with Mars obtained by means of charged particle traps from Mars-2, -3 and 5 satellites. Preprint IKI AN SSSR D-220, Moscow.
- Gringauz, K. I., V. V. Bezrukikh, T. K. Breus, M. I. Verigin, G. I. Volkov, A. P. Remizov, G. F. Sluchakov (1976a): Preliminary results of plasma measurements near Venus by the Venera-9 satellite. Pis'ma v Astron. Zh. 2:82.
- Gringauz, K. I., V. V. Bezrukikh, M. I. Verigin, L. I. Dentschikova, V. I. Karpov, V. F. Kopylov, Yu. D. Krisilov, A. P. Remizov (1976b): Measurements of electron and ion plasma components along the Mars-5 satellite orbit. To be published in Space Research 16.
- Montgomery, M. D., J. R. Asbridge, S. J. Bame (1970): Vela-4 plasma observations near the Earth's bow shock. J. Geophys. Res. 75:1217.
- Ness, N. F., K. W. Behannon, R. P. Lepping, Y. C. Whang, K. H. Schatten (1974): Magnetic field observations near Venus: Preliminary results from Mariner-10. Science 183:1302.
- Sagdeev, R. Z. (1964): Cooperative phenomena and shock waves in collisionless plasmas in Reviews of Plasma Physics Vol. IV. Ed. by M. A. Leontovich, Translated from the Russian by Consultants Bureau, New York, 1966.
- Spreiter, J. R., A. L. Summers, A. W. Rissi (1970): Solar wind flow past nonmagnetic planets-Venus and Mars. Planet. Space Sci. 18:1281.