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ION POPULATIONS IN THE TAIL OF VENUS

O. Vaisberg,* A. Fedorov,* F. Dunjushkin,* A. Kozhukhovsky,* V. Smirnov,* L. Avanov,* C. T. Russell** and J. G. Luhmann**

* *Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, Moscow 117810, Russia*
** *Institute of Geophysics and Planetary Physics, University of California at Los Angeles, Los Angeles, CA 90024-1567, U.S.A.*

ABSTRACT

Plasma measurements in the tails of Venus showed the existence of several ion populations. Measurements performed on Venera and Pioneer Venus spacecraft at different planetocentric distances showed the evolution of the plasma parameters along the tail. Low-energy ion fluxes measured in the tail at close downstream distances, are also observed farther downstream, and show low acceleration from 0.5 R_V to 12 R_V. High energy ions (energetic O^+ ions) reported from PVO observations in the tail at 10-12 R_V seem to be the same ion component that was observed as energetic ions at the tail boundary close to the planet have on Venera spacecraft. We give evidences that these ions are accelerated in the narrow shear layer near the tail boundary.

INTRODUCTION

Venus is the most extensively studied case of the solar wind interaction with a non-magnetized planet. The solar wind-Venus interaction was mainly studied on Venera 9 and 10 in 1975-1976 /1-3 / and on Pioneer Venus Orbiter (PVO) in 1978-1992 [see /4 - 7/ for reviews]. We summarize existing plasma observations within the Venusian tail and discuss the origin of the tail plasma.

PLASMA WITHIN THE TAIL

Plasma instruments flown. The Venera 9 and 10 satellites had two plasma spectrometers: a 2-D ion spectrometer consisting of 6 narrow-angle cylindrical electrostatic analyzers with channel electron multipliers (CEMs) RIEP /8/ and a combination sunward-looking differential ion Faraday cup and antisunward oriented integral electron Faraday cup D-127 /9/. The energy ranges were: 50 eV/Q to 20 keV/Q (RIEP) and 0-4 keV/Q for ions and 0-400 eV for electrons (D-127). The temporal resolution of both spectrometers was 160 sec. Measurements of plasma and magnetic field on Venera 9 and 10 within the tail from approximately 0.5 Rv behind the terminator to about 5 Rv downstream were performed on selected orbits in October 1975- March 1976 . The 3-D PVO plasma analyzer /10/ was of the quadrispheric electrostatic type with five collectors. The energy per unit charge (E/Q) range from 50 to 8000 eV/Q was scanned in 9 minutes. PVO operated in orbit around Venus from December 1978 until October 1992.The orbit of PVO crossed the tail in two regions: near periapsis, just behind the planet, and near apoapsis at 8-12 R_V downstream.

Plasma Regions in Close Downstream Region. Figure 1 shows the plasma regions and boundaries behind the terminator as observed on Venera 9,10 with the RIEP /1/ . (1) The boundary layer within the ionosheath of shocked solar wind that is characterized by increased fluctuations, addition of pick-up ions at the lower end of energy spectrum, depletion of high-energy tail of ion velocity distribution, and seen as deceleration and rarefaction region in hydrodynamic parameters. (2) The flow of lower energy ions separated by relatively thin boundary (a tail boundary) from the hotter ionosheath flow. The converging to the tail axis direction of the tail flow, observed at these distances behind the planet, suggests that the source region of the tail plasma flow is located near the terminator. Evidence that the tail plasma consists of planetary ions were givenin / 11, 12/. (3) The innermost region, a cavity behind the planet, where no measurable fluxes of ions above the lower energy threshold of the RIEP ion spectrometer of 50 eV have been observed. Sporadic ion fluxes in a wide energy range were observed in this region / 2/.

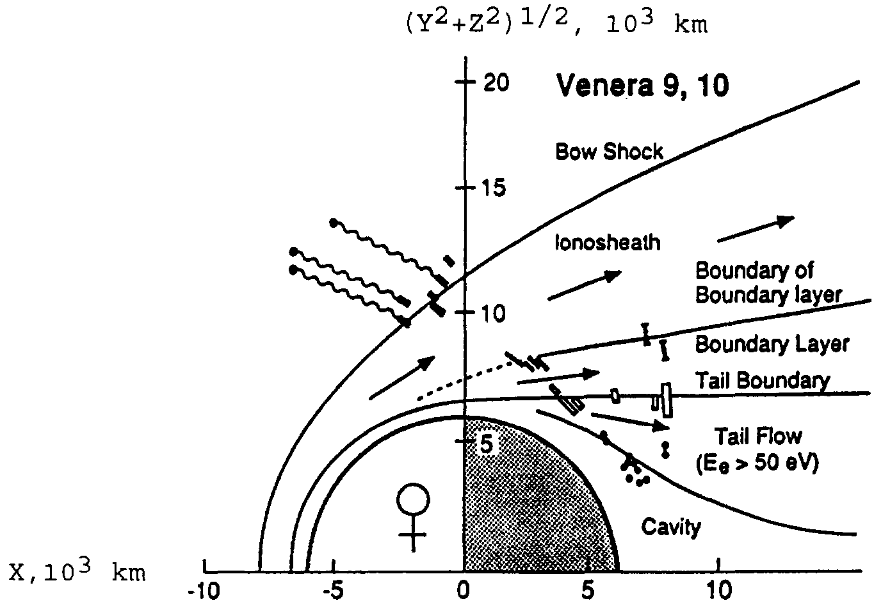

Fig. 1. The plasma boundaries behind the terminator in Venus-centered cylindric coordinate system with X-axis directed to the Sun, as observed on Venera 9 and 10 /1/.

Measurements made with the PVO retarding potential analyzer /13/ showed the existence of a distinct plasma region (the Venus mantle) between the ionosheath and the ionosphere where the electron energy spectrum is intermediate between the energy spectrum of the ionosheath and that of the ionosphere. The plasma mantle coincides with the region of low energy tail flow. It was shown in /11/ that the inflow of low-energy plasma in the tail is controlled by the IMF orientation. At high magnetic latitude, i.e. far from the VxB plane, the layer of the tail plasma flow is thick, while at low magnetic latitude, close to the VxB plane, the layer of low energy plasma in the tail is thin.

Figure 2 shows the structure of the tail boundary at close distances at high magnetic latitude in the VxB coordinate system /14/. Transition from the tail flow to ionosheath flow occurs within 20 sec of the RIEP measurements at given energy step. The change of frequency of magnetic field fluctuations confirmes this fast transition. Flow direction also changes. If the tail boundary is stationary its thickness is about 100 km. Most of observed tail crossings with Veneras showed rather distinct boundary between ionosheath and the tail flow. Another feature are 2.1 keV ions seen by RIEP analyzer at the tail boundary. Energetic ions were observed at every tail boundary crossing, but with different energies, from 2.1 to 12 keV/Q, within a time scale much shorter than the full RIEP energy scan. Plasma measurements and their comparison with magnetic field measurements give no evidence of measurable solar wind plasma flux penetrating into the tail at close downstream distances.

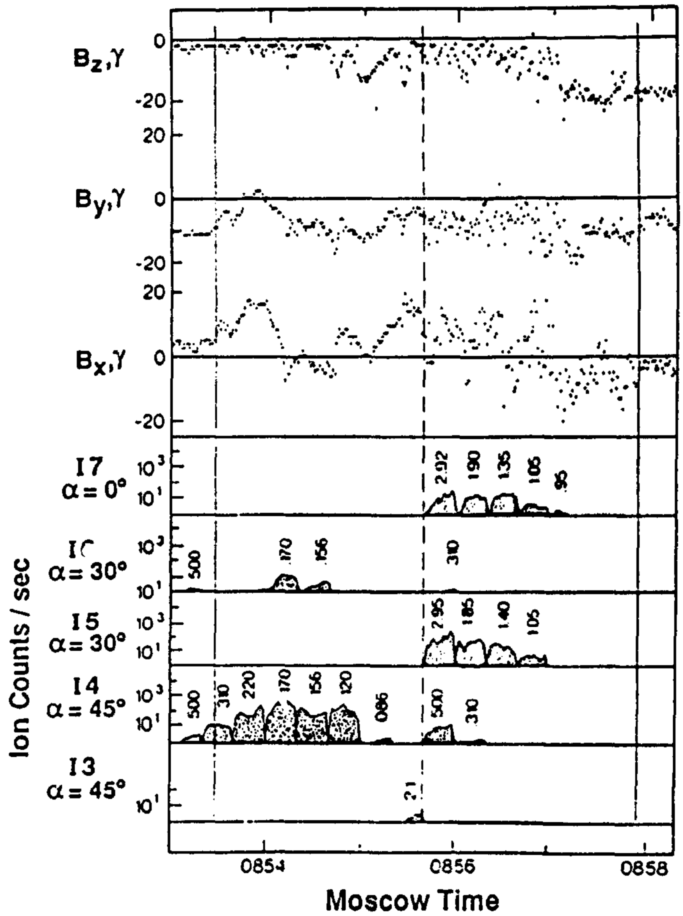

Fig.2. Structure of the tail boundary in the magnetic field (three upper panels) and according to the ion analyzers of RIEP (five lower panels). Electrostatic analyzers I4 and I6 cover the energy (E/Q) range 0.048-0.500 keV, analyzers I5 and I7 cover the energy range 0.32-2.9 keV, analyzer I3 covers the energy range 2.1-19.8 keV. Their orientation relative to the solar direction is indicated on the left of each panel. The tail is on the left side of diagram, the ionosheath is on the right side of it (satellite crosses the tail boundary from the side of the tail). The sharp tail boundary is seen in the change of ion energy, in the frequency of magnetic field fluctuations, and in the appearance of accelerated ions in the I3 data /14/.

Tail Plasma at Distances 4 - 5 R_V. The plasma and magnetic field measurements were made only on two passes of Venera 10 through the intermediate (2.5 to 5 R_V downstream) tail of Venus. On the Venera 10 pass on March 26, 1976 the measurements were made only within the tail, no boundary crossing was observed. Figure 3 shows the RIEP dynamic spectrum of ions, along with the B_X magnetic field component. In this case the ions were nearly permanently observed within Venusian tail. Ions with significantly higher energy and lower temperature are observed in one-to-one correspondence with currents seen in variations in the B_X component. No hot ions were observed at the B_X reversal at the current sheet separating the two tail lobes, although two small bursts of 2 keV/Q ions occurred at the edges of the current sheet. After the central current sheet crossing, the mean ion energy started to increase, probably due to the approach to the tail boundary. The mean ion energy in this pass is larger than average energy at closer distances to Venus.

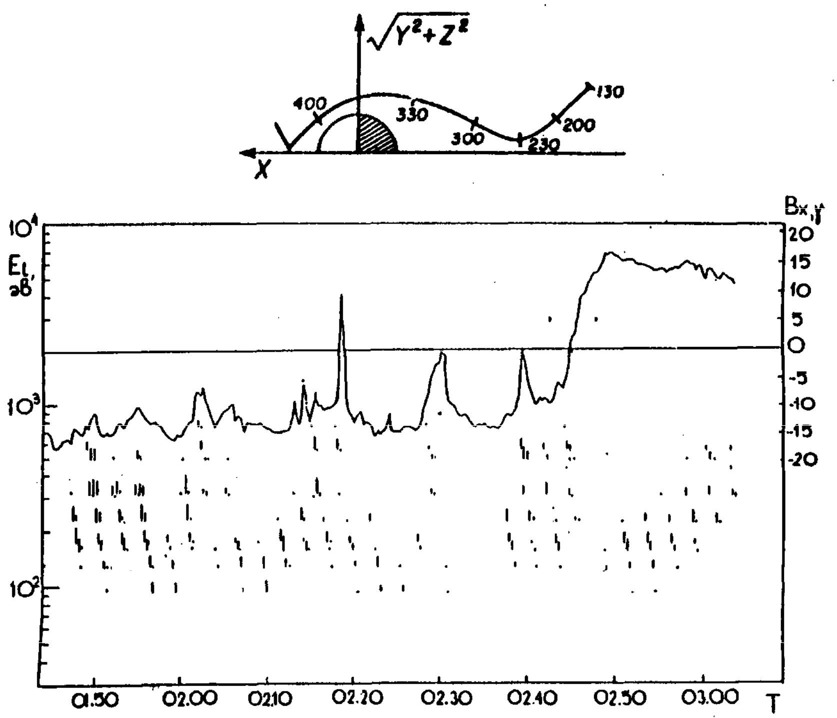

Fig. 3. (a) Bx magnetic field component and dynamic spectrum of ions as measured by the RIEP spectrometer on a Venera 10 pass within the tail on March 26, 1976. The Venera 10 orbit is shown above in the cylindrical coordinate system. The length of the bar shows the logarithm of the ion counting rate at specific energy E/Q (scale is on the left). Note that whenever a Bx variation is observed, the energy of ions is increasing. The Bx reversal that seems to be the main current sheet is indicated by an arrow.

The only reported tail boundary crossing of Venus at intermediate distances was on April 19, 1976. The sharp tail boundary was easily seen by the sudden change of ion temperature. No traces of solar wind in the tail are observed. The energy of convective motion does not show a jump at the tail boundary. This effect of continuous change of the flow energy that develops through the mass-loading region was also observed near Mars at comparable downstream distances /1, 15/, and was explained in /15/ in terms of momentum balance in the mass-loading region.

Observations of the high energy ions (with calculated an ion temperature of about 1000 eV) at the magnetic field reversal within the tail were reported in /16/, and were interpreted in terms of isotropic plasma layer of the Venus tail.

Plasma at Large Downstream Distances (8 - 12 R_V). According to PVO measurements /4, 5/ ion fluxes in the tail are not regularly recorded at these distances, the tail is considered to be devoid of plasma. However, there are significant numbers of what are called O^+ events, the high-energy ions that are usually, but not always, located at about a factor of 16 in E/Q value above any low-energy component. As a result the higher energy peak was identified as O^+ ions of planetary origin /4, 5/. The O^+ events normally occur within the magnetotail. The flux of these ions lies in the range of 10^6 - 10^7 ions/cm^2 sec for 1/3 of their cases, with 2/3 of the observations below this level. The estimated temperature is typically several tens of eV. It was suggested that the pick-up of exospheric photoions was the source of this plasma component in the tail /5/.

Statistical study of O^+ events in the distant tail /16/ showed their asymmetric location in the magnetic coordinate system. The vast majority of the O^+ detections are located in the hemisphere where the solar wind induced electric field points outward from the planet. Asymmetric pick up of ionospheric ions was initially proposed in /17/. The signatures of this asymmetry were noticed in several ways including the magnetic field strengths in the ionosheath near the terminator and in the downstream tail, and in the asymmetry of the ionopause altitude near the terminator /18, 19/. Subsequent detailed analysis of PVO plasma observations within the distant magnetotail showed that increased fluxes of two plasma components identified as H^+ and O^+ are observed in the plasma sheet and adjacent tail lobes /20/ , and confirmed their asymmetry in VxB frame. Another statistical study /21/ showed a solar cycle dependence in the observed O^+ flux.

Figure 4 shows PVO plasma and magnetic field observations in the distant tail on the orbit 190. This is a typical example of observations of higher energy component identified in /4, 5/. The tail at 10-12 R_V becomes very irregular, and the determination of its boundary location is difficult. We use B_X/B ratio being close to + 1 or - 1, as an indicator of the tail (where B_X is magnetic field component along Sun-Venus line, and B is the magnetic field magnitude). The B value is also increased within the magnetic tail, except within the current sheets, where B magnitude drops significantly (still the value of B_X/B ratio remains close to 1). There are multiple crossings of the tail boundary at the entry to the tail starting at about 11:50 UT. The energetic O^+ ions are seen in association with B_X/B ratio changes between 1 or -1 and lower values at tail boundary crossings, as well at the multiple tail boundary crossings at the tail exit (time interval 16:40 - 17:10 UT). The energetic O^+ ions are usually observed where energy of lower energy component changes. This orbit and some other PVO tail crossings show that there is a plasma flow inside the magnetic tail with measurable flux, with the energy significantly smaller than the energy of the solar wind flow. This plasma flow, that is observed within the layer, adjacent to the tail boundary, is quite similar to what was observed on the Venera spacecraft at closer distances.

The flow direction of energetic O^+ ions is quite close to the antisunward direction of the ionosheath and tail flows. The temperature of energetic O^+ ions as several tens eV /5/. So the thermal energy spread is much smaller than transport energy. There is nothing similar to classic pick-up process when pick-up ions form the ring in the velocity space.

We selected 8 PVO tail crossings at large distances with significant flux energetic O^+ ions for comparative analysis of three ion components: external solar wind flow, energetic O^+ ions, and low energy plasma flow in the tail. The energy spectra all three ion components were approximated by convected Maxwellian distributions in supposition that ions are protons. The parameters of the tail plasma are quite similar to what was observed on Venera spacecraft at closer distances, the average convective energy being slightly larger (see Table 1). The number density of the energetic O^+ ions jbserved at the tail boundary is by factor of 10 smaller than the number density of the low energy tail flow, and the number flux of the energetic O^+ ions is by factor of 2-3 smaller than the number flux of the low energy tail flow. The average calculated temperature of energetic O^+ ions is close to what was reported in /5/.

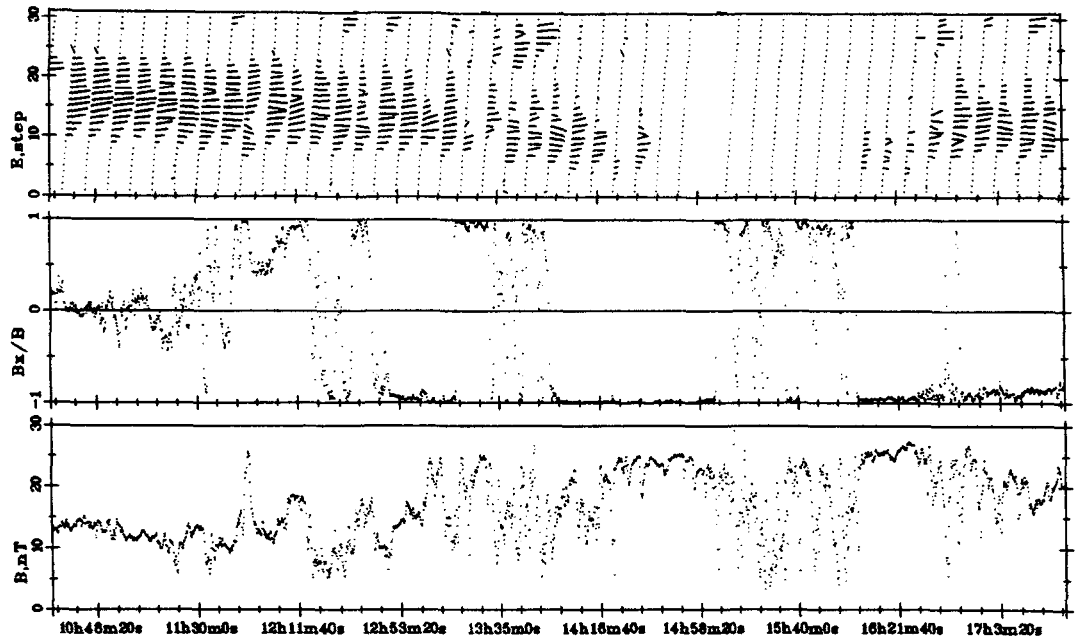

Fig. 4. Dynamic spectrum of ions and the magnetic field in the distant Venus tail on the PVO orbit 0190, June 13, 1979. Upper panel is a modification of conventional dynamic spectrum of ions, the energy range of 0 - 8 keV/Q devided logarithmically in 32 energy steps. All measurements are shown by bars at every E/Q step with the length of the bar proportional to the logarithm of the ion flux. The origin of each bar is located at the point in the energy-time spectrogram, where the specific measurement was made. The energy-time plane is simultaneously superimposed on Venus-centered XY- coordinate plane in order to indicate flow direction. The Sun-directed X axis is aligned (with opposite sign) with the time axis, and the Y axis (lying in the orbital plane and directed opposite to the direction of orbital motion of Venus) aligned with +Y values corresponding to decrease in energy. The Sun is to the left relative to the part of the plane shown. The direction of the bar corresponds to the azimuthal direction of the maximum flux (at the specific R/Q step) as measured by the PVO plasma spectrometer. The middle panel is Bx/B ratio that is used for magnetic tail identification. Magnetic field magnitude B is shown on the bottom panel.

Plasma Within the Current Sheets. There are a limited number of plasma observations within the cross-tail current sheets. The observation of a hot ($T_i \sim 1000$ eV) ion population in one case at downstream distances of 4-5 R_V, and two more cases at unspecified distances were reported in /22/. The narrow-angle analyzer measurements suggest that the ion distribution function in the tail current sheet may be quite complicated. At 10-12 R_V only the high-energy ion component (O^+) has been analyzed, and it was found in /20/ that the greatest concentration of these O^+ ions is observed in the vicinity of the cross-tail current sheet. There have also been indirect assessments of the plasma properties in the current sheet. In order to maintain the pressure balance with the observed tail lobe field, the plasma sheet must have an energy density 1 keV/cm^3 /23/. Electrodynamics and pressure balance for the average magnetic tail configuration were considered in /24/. Obtained in this way velocities, number densities and temperatures of ions within central current sheet are given in /24/ . We used these values to calculate the plasma acceleration, which gives $4x10^4$ cm/sec^2 for distances between 8 and 10 R_V and $1.6x10^5$ cm/sec2 for distances 10-12 R_V. Table 1 summarizes the average parameters of the ion flux obtained from different sources.

TABLE 1 Tail Plasma Parameters

Region	Downstream Distance, Ro	Velocity, km/sec	Temperature of ions. eV	Number Density, cm^{-3}	Number Flux, $cm^{-2} sec^{-1}$	Ref.
Lobe	1	150 (p) or 40 (O^+)	3 - 10	0.12 (p) 0.5 (O^+)	2×10^6	V&Z
	1	100 (p)		0.8 (p)	9×10^6	Vg
Lobe	4 - 5	200 (p) or 50 (O^+)	4 - 35	0.3 (p) 1.2 (O^+)	5×10^6	V&Z
Current sheet	4 - 5	300 (p) or 75 (O^+)	10 - 75	0.2 (p) or 0.8 (O^+)	6×10^6	Vs
	4 - 5	100-200 (p)	100 - 200	1-4 (p)	4×10^7	Vg
Lobe	8 - 12	~ 400	1000?	0.07 (p) 0.005 (O^+)	3×10^7	McC
	8 - 12	230	6.5	0.9 (p)	2×10^7	This study
Current sheet	8 - 12	~ 400	500 (p) or 8000 (O^+)	0.9 (p) 0.06 (O^+)	3.5×10^7 (p) 2.5×10^6 (O^+)	McC
	8 - 12		n x 10		10^6 - 10^7	M&B
	8 - 12				1.6×10^7	I

Note: No measurements of ion composition were made, so numbers indicated depend on assumed major ion.
References: V&Z - /12/
Vg - /22/
Vs - Calculated by author from ion spectra shown in Figure 4 of /14/
McC - Derived from self-consistent analysis of magnetic structure of the tail in /24/
M&B - Maximum flux of energetic O+ ions provided in /5/
I - Maximum flux of energetic O+ ions provided in /4/

SOURCES OF THE TAIL PLASMA

Plasma Mantle. The plasma mantle /1,13/ is one of the important sources of the tail plasma. The ion flux entering the tail from the terminator region is of order $5x10^6$ cm^{-2} sec^{-1} /12/. In the assumption that plasma mantle on the nightside is a continuation of the magnetic barrier on the dayside the model of the plasma mantle based on the expected acceleration of pick-up photoions within the depleted convecting magnetic flux tubes of the magnetic barrier was proposed in /12/. The loaded field lines are accelerated from the subsolar region to the terminator by the magnetic pressure gradient within the magnetic barrier. The model gives reasonable values of the temperature of ions and the total ion influx to the tail ($5x10^{24}sec^{-1}$), but higher transport energies than observed.

Ionospheric Clouds. Detached ionospheric clouds are frequently observed above the ionosphere /25/. The calculated Maxwell stress exerted by the draped magnetic field at a clear example of one such cloud would lead to the acceleration of the plasma to 90 km/sec, and the supply $2x10^{25}$ ions/sec to the tail /26/.

Plasma in Nightside Ionosphere. The nightside ionosphere that is very structured, and consists of dense rays separated by holes /27-30/, appears to be an important source of tail plasma. The boundaries of the depletion regions are sometimes marked by a superthermal ion signature /29/.

The largest currents flow on the flanks of the rays /31/. Fast ions (> 40 eV) are a minor constituent and typically have a tailward component of velocity. The average electron density N_e over the entire umbra at altitudes 2000 km is 39 cm^{-3}. Adopting an average energy of 13 eV for the superthermal O^+, corresponding to a velocity of 12.5 km/s (about 4 km/sec greater than escape velocity), the resulting global mean flux is calculated as $1x10^7$ cm^{-2} sec^{-1}. The energetic ions (E > 40 eV), most frequently O^+ ions, that occur only on the nightside at solar zenith angles > 120^o. were studied in /32/. The maximum energetic ion flux observed between 1900 and 2500 km is < $4x10^6$ $ions/cm^2sec$. The average O^+ flux for ions with energy > 40 eV is about $4x10^4$ $ions/cm^2sec$. Tailward flow is typical, but sunward flows are also observed.

Gasdynamic Models with Mass Loading. Moore et al. [1991] developed a gasdynamic model of the Venus magnetotail assuming a tapered ionopause obstacle and mass addition by exospheric O^+. In the central magnetotail their model predicts oxygen ions number densities of about 0.2 cm^{-3} and temperatures of the order of 100 eV, flowing tailward at speeds of about 200 km/sec at 10 R_V. The ions picked up well above the ionopause are accelerated only in one hemisphere where the motional electric field is directed away from the planet. These particles form an asymmetric ion population with energies about 16 times the solar wind proton energy. The total escape rate of planetary O^+ ions calculated in this model is $2x10^{24}$ sec^{-1}. This model reproduces many observed features but does not develop the tail with a distinct boundary.

DISCUSSION

Properties of the tail plasma populations are not well understood due to the lack of mass separating measurements. Identification of ions observed at 10-12 R_V downstream with plasma populations observed at closer distances have not been made so far.

From Venera 9, 10 measurements we know that the outflowing low energy plasma populate the outer part of the tail at close downstream distances and significant part of the tail to at least 5 R_V downstream. Significantly lower number density, temperature and transport velocity of this plasma compared to the ionosheath plasma, as well as an existence of a distinct boundary between the tail flow and the external flow, observed in many cases at distances up to 4-5 R_V downstream, show that this plasma is of planetary origin.

Ion populations, observed in the current sheets at 4-5 R_V , have different plasma parameters from those typical of the lobe plasma at the same distance. Usually the plasma populations associated with the current sheets are more energetic, but not necessary hotter, than the lobe plasma. The origin of the two different plasma populations observed at different downstream distances is poorly known. There is a reasonable degree of confidence that at least two sources of tail plasmas are operative, namely the pick-up of planetary photoions within the magnetic barrier, that is the source of the lobe plasma /12/, and nightside ionosphere escape /27, 28, 31/. Another ionospheric source may be provided by detached plasma clouds /25, 26/. As ionospheric tail rays are usually associated with the current sheets at close distances to the planet /31, 33/, it is tempting to identify this plasma population as the result of acceleration of ionospheric plasma.

Other tail-associated plasma population(s) observed at different distances are accelerated ions at the tail boundary. Energetic ions have been observed with RIEP plasma analyzer on Venera 10 at the tail boundary /14/. Ions in the same energy range were observed with Pioneer Venus plasma analyzer /4, 5/ at 10 - 12 R_V, and were identified as pick-up oxygen ions. We gave some evidence that energetic O^+ ions are also associated with the tail boundary, that suggests that Venera and PVO observed the same phenomena at the tail boundary.

There could be several sources of energetic O^+ ions: (1) pick-up of ions in the external flow or from the topside ionosphere, the process, proposed in /17/, (2) acceleration of ions observed in the tail at closer distances, particularly ions in the current sheets, and (3) acceleration of ions at the tail boundary. We see difficulties in the explanation of the energetic O^+ ions in terms of pick-up process /17/, in spite of the agreement of observed flux asymmetry in VxB coordinate system with the theory. The direction of their propagation, coinciding with the direction of external flow, and their low temperature do not seem to be in agreement with /17/. Pick-up in the external flow leads to development of the ring distribution in the velocity space, maximum velocity reaching the twice of the velocity of the main flow, and the spatial extent of the pick-up process comparable to gyroradius of pick-up ions, the the features that are not observed.

The gas dynamic model /34/ provides reasonable parameters of the pick-up oxygen ions, but it does not include essential elements of Venusian environment: magnetic barrier and the tail filled with slowly convected plasma. This may significantly modify the structure of motional electric field responsible for pick-up process, and may change the results of a model.

Let us consider the other option, an acceleration of the tail plasma. Superthermal ions observed in the current sheet structures at the edges of nightside ionospheric tail rays have energies about 10-40 eV (see /31/). The mantle plasma flow observed slightly downstream of terminator region has average energy about 120 eV . At 4-5 R_V downstream the current sheets population has about 370 eV, and the lobe population has average energy of about 210 eV. So the plasma in the tail lobes that apparently originates in the mantle undergoes very weak acceleration in the downstream region. This is confirmed by PVO observations (see Figure 4), the average convective energy of the lobe flow being of about 250 eV at 10-12 R_V. Plasma in the current sheets is accelerated significantly faster, from 10-40 eV above nightside ionosphere to about 370 eV to 4-5 R_V downstream, but still it acquires less than 100 eV per Venusian radius. From the observations of comets we know that the acceleration does not change significantly along the mass-loaded tail /35/. So we may not expect that the tail plasma will be accelerated more than to 1 keV at the distances of PVO observations.

Acceleration of ions at the tail boundary, the third case, could be possibly accomplished by the wave acceleration processes, particularly due to very high level of turbulence that is observed at the tail boundary (Figure 2). However the energetic ions are sometimes confined to the layer that is significantly thinner than the region of strong magnetic turbulence. The broad frequency range of the wave turbulence should lead to the velocity spread of accelerated ions that is comparable to their average velocity, while observed velocity distribution of energetic O^+ ions much more resembles resonantly accelerated particles.

There is another possibility to explain the confinement of energetic ions at the tail boundary, their low velocity spread, and the streaming of ions along the main flow. This also allows one to avoid the contradiction in previous explanations of the energetic O^+ ions as the tail population, that originated as typical pick-up ions. Our suggestion is that these ions are accelerated in the narrow shear layer between the fast ionosheath flow and the slow tail plasma flow, the source of the high energy of these ions is the shear motion. To test this hypothesis we made a simple model, consisting of the shear velocity layer of proton plasma with a constant transverse magnetic field, in which the velocity changes linearly from zero to some value V_0, and then remains constant. The direction of the magnetic field is such that the motional electric field in the shear layer and in the flow is directed along the velocity gradient. The O^+ ions with wide range of velocity, transverse to the magnetic field and to flow velocity, are injected in this layer from below. The resulting trajectories of these ions are shown on Figure 5. Two classes of trajectories are seen. The ions with high initial velocities penetrate the shear layer, and return back along trajectories resembling cycloids. The ions of smaller velocities have their trajectories completely within shear layer, and they propagate within it to significantly longer distances than ions with higher velocities.

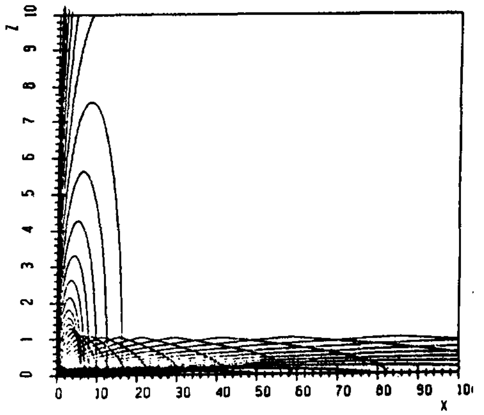

Fig. 5. Trajectories of the test heavy particles of different velocities entering velocity shear layer from below. X is along the velocity of the external proton flow, Z is transverse to the boundary (located at Z=0) between heavy ions at rest and the external flow. All distances are normalized to the thickness of the shear layer, so Z=1 is the upper boundary of the velocity shear layer. Magnetic field is directed outward of the plane. Motional electric field is directed along +Z. Note the different scales for X and Z axes, that distorts the ion trajectories.

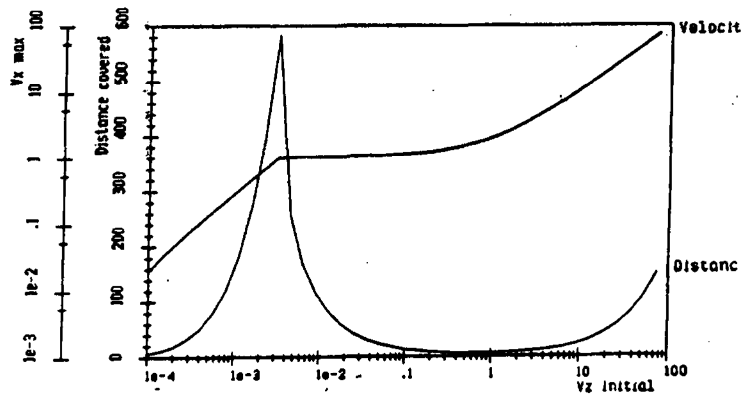

Fig. 6. The distance (ordinate, normalized to the layer thickness) covered by test particle along external flow direction before reentering back to the source region versus transversal velocity (abscissa, normalized to the velocity of external proton flow, in logarithmic scale) of the oxygen ion entering shear layer from below. Maximum velocity (second ordinate axis, normalized to the velocity of external flow, logarithmic scale) acquired by the ion while in the shear layer or in external flows also indicated.

Figure 6 shows this in more detail. There is a velocity range in which particles are captured within shear layer for so long, that they propagate within it up to several hundred times of the layer's thickness. The initial velocity of the ions that propagate to largest distance in the layer is about 3×10^{-3} of V_0 . The maximum velocity, attained by the trapped ions (for the full width at the half maximum) is in the range of 0.9 -1.0 of V_0. The model reproduces all main features of the energetic O^+ ions: confinement of the beam to the thin layer at the boundary, coalignement with external flow, average velocity value very close to the velocity of the external flow, low velocity spread compared to transport velocity. This simple model demonstrates that the proposed explanation is feasible, for the motional electric field direction that is compatible with observations of energetic O^+ ions. We are working on a more realistic model of the phenomena.

There is one more possibility that should be studied in detail. Very irregular flow at the tail boundary, observed at 10--12 R_V downstream suggest that tail rays may develop at Venus which is a specific feature of cometary interaction with the solar wind. That may provide an additional mechanism in addition to the magnetic barrier/mantle source and to the ionospheric tail rays/ plasma clouds source providing the tail plasma populations at Venus. The energetic O^+ ions may be associated in this case with the shear flows at the boundaries of the tail rays too.

CONCLUSION

1. The tail is frequently populated with outflowing plasma, from the terminator region to 10-12 R_V downstream. Significantly lower number density, temperature and transport velocity of this plasma compared to the ionosheath plasma, as well as an existence of a distinct boundary between the tail flow and the external flow, observed in many cases at distances up to 4--5 R_V downstream, show that this plasma is of planetary origin.

2. Ion populations observed in the current sheets are frequently confined to these current sheets and usually are more energetic, but not necessary hotter, than the lobe plasma.

3. There is a reasonable degree of confidence that at least two sources of tail plasmas are operative, namely the pick-up of planetary photoions in the magnetic barrier, that is the source of the lobe plasma /12/, and nightside ionosphere escape /17, 28, 31/ and detached plasma clouds /25, 26/. As ionospheric tail rays are usually associated with the current sheets at close distances to the planet /31, 33/, it appears that tail current sheet plasma may result from acceleration of ionospheric plasma.

4. The third tail-associated plasma population observed at close downstream distances are accelerated ions at the tail boundary. The possible source of the high energy of these ions is the shear motion between the external flow and the tail flow.

5. There are no firm indications of the solar wind plasma entry into the tail at close distances and to 4--5 R_V downstream.

6. Identification of energetic ions observed at 10--12 R_V downstream with pick-up ions in the external flow, the process, proposed in /17/, poses serious problems in spite of the agreement of observed flux asymmetry in VxB coordinate system with the theory. The direction of their propagation, coinciding with the direction of external flow, and their low temperature do not seem to be in agreement with proposed theory.

7. There is no appreciable acceleration of the lobe plasma from close dowmstream distance to 4-5 R_V downstream, the transport energy changes from about 120 eV for mantle flow at 0.5 R_V downstream to about 210 eV at 4-5 R_V downstream. Ion energies are about 10--40 eV for nightside ionospheric current sheets source /31/, while current sheets population has about 370 eV at 4-5 R_V downstream, giving average acceleration less than 100 eV per Venusian radius.

8. So we may not expect that the tail plasma will be accelerated more than to 1 keV at the distances of PVO observations. The natural conclusion seems to be that the energetic ions, up to 8 keV, observed at 10 - 12 R_V and identified as oxygen ions /4, 5/ are the same energetic ions that have been observed with RIEP plasma analyzer on Venera 10 at the tail boundary the /14/. This suggestion can explain at least some properties of the energetic O^+ ions, such as their confinement to the boundary of the tail and their registration at the sharp gradients of the main plasma flow.

9. The observed energetic ions are concentrated near the tail boundary, the ions have low temperature, and are streaming along the main flow. These ions do not seem to be the tail population either. We suggest that these ions are accelerated in the narrow shear layer between the fast ionosheath flow and the slow flow of the tail plasma. In this process they acquire the velocity of external flow, and their effective temperature is relatively low.

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