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COMPARISON OF INDUCED MAGNETOSPHERES AT VENUS AND TITAN

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Abstract. Considerable evidence exists from data obtained by artificial satellites of Venus describing the detached bow shock wave which develops at Venus due to the interaction of the super-Alfvenic, supersonic solar wind. However, there is no such direct evidence for any bow shock wave at Titan due to the interaction with the corotating Saturnian magnetosphere. This is because the fast mode MHD Mach number was less than unity at the time of Voyager 1 close flyby. In spite of this difference in plasma regimes, there is a certain striking similarity in these two interactions. (1) Both obstacles to plasma flow have appreciable ionospheres and are globally nonmagnetic, (2) Downstream from both obstacles, an induced bipolar magnetic tail is formed with a central field reversal region which is analogous to the earth's neutral sheet-plasma sheet region. This paper will discuss plasma and magnetic field data from the Venera 9 and 10 spacecraft at Venus and from Voyager 1 at Titan which lead to new conclusions regarding the magnetic tail structure of their induced magnetospheres: (3) There appears to be evidence for magnetic merging in these induced tails so that magnetic reconnection between the oppositely directed tail lobes occurs. The single tail crossing at Titan shows evidence of merging while the repeated tail crossings at Venus indicate that similarly observed merging there is not a permanent feature.

1. Introduction

Magnetospherelike structures are often found in the universe. They can originate both near bodies and systems that have intrinsic magnetic fields and near objects without such a field. However, until recently, only those magnetospheres that are generated in a supersonic plasma flow were studied in situ by experiments on various spacecraft. In the course of plasma and magnetic measurements carried out on board the spacecraft Voyager 1 in 1980 in the vicinity of Titan, a satellite of Saturn, a bipolar magnetic tail was observed to have been developed [Ness et al., 1981] behind Titan. This magnetospheric tail is generated in the subsonic plasma flow of Saturn's magnetosphere corotating past Titan [Bridge et al., 1981].

Thus, the opportunity to compare phenomena occurring during supersonic and subsonic plasma flow past obstacles presented itself for the first time. Titan does not appear to possess an intrinsic global magnetic field [Ness et al., 1982; Smith et al., 1982; Strobel and Shemansky, 1982]. Hence, it is convenient for such a comparison to choose Venus, which does not possess an intrinsic magnetic field either, but also has a well-developed atmosphere and ionosphere [Dolginov et al., 1968; Mariner Stanford Group, 1967]. Some of the phenomena occurring during plasma flow past Venus and Titan have already been compared [Ness et al., 1982; Gurnett et al., 1982; Neubauer et al., 1984; Kivelson and Russell, 1983]. In the present work, a more systematic analysis of the similarities and differences of the magnetic tails of Venus and Titan is attempted. At first, we briefly discuss some of the proposed models of the configuration of the magnetic field and the induced currents in the tails of induced magnetospheres.

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2. On Special Features of the Magnetic Field in Induced Magnetic Tails

The ideas developed by Alfven [1957] and Gold [1966], for plasma tails of comets or the moon, are used most often for the description of processes leading to the formation of a magnetic tail behind planets which do not have their own magnetic field. As the plasma of the solar wind enters the atmosphere of a comet, ions, which are generated as a result of the ionization of its neutral atmospheric components, are added to the plasma flow. Consequently, the speed of the plasma near an obstacle decelerates, as compared to the speed of the solar wind at larger distances from it. That deceleration causes the lines of force of the interplanetary magnetic field, "frozen" into the plasma because of the high magnetic Reynolds number, to be stretched in the direction of the velocity of the plasma flowing past the obstacle, draping the field lines and forming a magnetic tail (Figure 1a). The configuration of the magnetic field in the vicinity of the nonmagnetic obstacle which is shown in Figure 1a has two characteristic features: (1) all magnetic lines of force start and terminate in the plasma flowing past the obstacle, so that closed lines of force are absent; and (2) everywhere in the vicinity of the obstacle, the projection of the magnetic field $\vec{B}$ onto the direction defined by the component of the distant magnetic field, which is perpendicular to the plasma flow ($B_{\perp\infty}$), is positive; in other words, the scalar product $(\vec{B} \cdot \vec{B}_{\perp\infty}) > 0$.

The model of the configuration of the magnetic field in the vicinity of Venus, developed by Yeroshenko [1979] on the basis of results of measurements of the magnetic field behind Venus on board the spacecraft Venera 9 and 10, is represented in Figure 1b and has a different characteristic. The magnetic field, which is

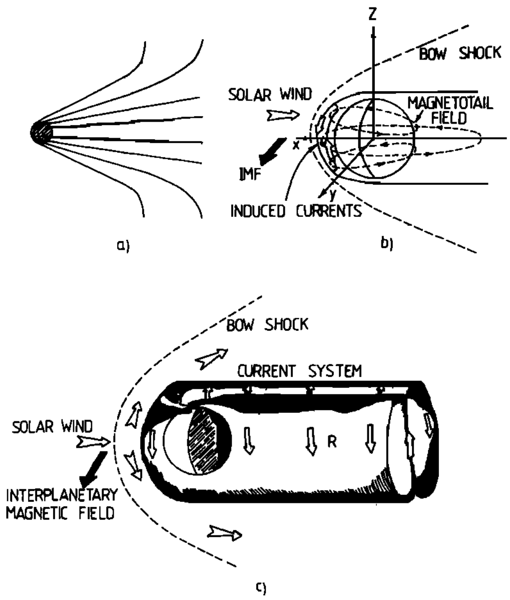

Fig. 1. Sketches of magnetic line of force and current systems associated with solar wind interaction with (a) comets [Alfven, 1957], (b) Venus [Yeroshenko, 1979], and (c) Venus [Gringauz, 1981].

generated by the induced currents flowing above the dayside of the planet, is elongated by the flow of plasma and generates a bipolar magnetic tail, which consists of two lobes. The lines of force of the magnetic field from the tail lobes connect in such a way that the magnetic field in the neutral layer that separates the two lobes is directed opposite to $\vec{B}_{\perp\infty}$. The characteristic features of the Yeroshenko [1979] model of the configuration of the magnetic field in the case of flow past a nonmagnetic obstacle are (1) the presence in its vicinity of closed magnetic force lines and (2) a negative sign of $(\vec{B}\cdot\vec{B}_{\perp\infty})$ in the magnetic tail.

The current system, which describes the configuration of the magnetic field in an induced magnetosphere, was proposed in the work of Gringauz [1981] and is shown in Figure 1c. As a matter of simplicity, it is possible to consider an induced magnetosphere's magnetic field as being generated by currents which flow along surfaces of a deformed solenoid which envelops the obstacle. The current system given in Figure 1c describes both the formation of a magnetic barrier on the dayside of the planet and the structure of currents which form the two lobes of the magnetic tail, divided by a neutral sheet. The plane of the neutral sheet is perpendicular to the $\vec{B}_{\perp\infty}$ component of the interplanetary magnetic field in a similar manner, as in the models given in Figures. 1a and 1b, and may rotate as that vector rotates.

Assume that at some distance from the planet, at point R (Figure 1c), reconnection of magnetic fields of both lobes of the tail occurs. Then, in that part of the magnetic tail which is closer to the obstacle, at planetocentric distances $r < R$, the formation of closed lines of force would be expected and the topology of the magnetic field will then look like that given in Figure 1b. At distances $r > R$, the topology of the magnetic field will correspond to that given in Figure 1a. Reconnection of the magnetic field of the lobes of the tail should lead to an acceleration of charged particles which are present in the vicinity of the neutral layer and the formation of a plasma sheet which consists, as in the magnetic tail of the earth, of energetic charged particles. The formation of closed lines of force in the induced magnetic tail (Figure 1b) should strongly influence the characteristics of the low-energy plasma in that region. In fact, in that case, the plasma in the magnetic tail becomes "isolated" from the flow of plasma in the transition region. This should result in more significant differences in parameters of the plasma in these regions and in a sharper boundary between them, the magnetopause, as compared to the models of an open magnetic tail (Figure 1a). It is understood that outside the magnetic tail, in the transition region in any case, the topology of the magnetic field will look like that given in Figure 1a. This is because, in the formation of magnetic field draping around an obstacle, the nature of the forces which cause a deceleration of the flow in the front of the obstacle is not important.

3. Magnetic Field in Tails of Titan and Venus

The magnetic field in the induced magnetic tail of Titan has been measured only once, that during the November 12, 1980 fly by of the spacecraft Voyager 1 [Ness et al., 1981, 1982]. At that time, Titan was within the magnetosphere of Saturn, at a distance of 2-3 R_s from its boundary at a local Saturnian solar time 1330. Hence, the plasma in the Saturnian magnetosphere, corotating with Saturn, interacted with Titan. The properties of that plasma have been studied in a number of papers and were summarized in recent reviews [Hartle et al., 1982; Neubauer et al., 1984]. According to the latter, the obstacle was nonmagnetic and asymmetric and the plasma flow, although subsonic ($M_s = 0.57$), was super-Alfvenic ($M_A = 1.9$) with a high β (= 11.1). As a result, a fast mode bow shock wave in the vicinity of Titan was absent since the corresponding Mach number was less than unity and behind the planet a two-lobe asymmetric magnetic tail was formed.

The results of measurements of the magnetic field on board the spacecraft Voyager 1 during its flyby in the vicinity of Titan are shown in Figure 2 in projections onto X-Y and Y-Z planes [Ness et al., 1982]. The undisturbed magnetic field in Saturn's magnetosphere, $\vec{B}_{\perp\infty}$, was approximately oriented southward along -Z, and was about 5 nT. The region of induced magnetic field, which consisted of two lobes with oppositely directed magnetic field, was crossed by Voyager 1 approximately from 0539:29 to 0545:51. The characteristic feature of that region is a large positive or negative X component of the magnetic field. The reversal of sign of the X component was recorded at about 0542:39 and has been interpreted as the spacecraft crossing the neutral sheet, which is assumed to be oriented approximately perpendicular to the Z axis.

An important feature of the magnetic data in the interval following the crossing of the neutral sheet (also, to a smaller degree, the interval prior to crossing of the neutral sheet) is the presence, in the magnetic tail, of a northward or

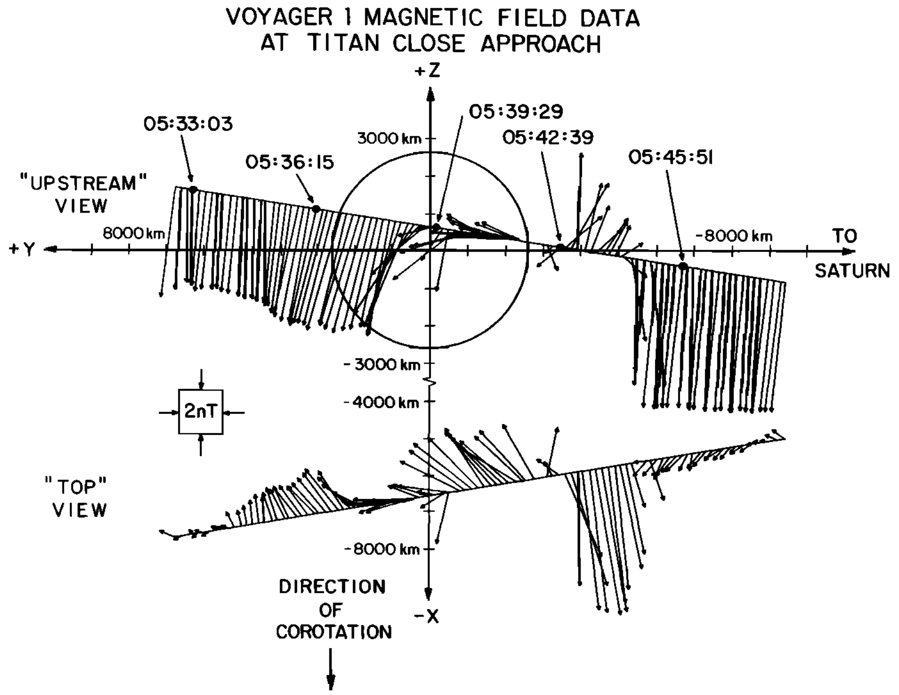

Fig. 2. Plots of B_{XY} (bottom) and B_{YZ} (top) vector components of the 1.92-s averaged magnetic field data (reduced by a factor of 5) superposed along the trajectory of Voyager 1 [from Ness et al., 1982].

positive Z component of the magnetic field. Saturn's magnetic field has a negative Z component, however. As can be seen in Figure 2, in that time interval in the magnetic tail, $\vec{B}\cdot\vec{B}_{\perp\infty} < 0$, which is not characteristic of simple draping around an obstacle of magnetic lines of force (see Figure 1a and the discussion in section 2 of this work). We can interpret the presence of a positive Z component of the magnetic field in the tail of the induced magnetosphere of Titan as evidence in favor of possible reconnection of oppositely directed magnetic fields of the two lobes of the tail and of the development, in the induced tail, of closed magnetic force lines in the X-Z plane. For illustration, see Figure 1b, where closed magnetic lines of force due to the different orientation of $\vec{B}_{\perp\infty}$ lie approximately in the X-Y plane.

Previously, Kivelson and Russell [1983] have suggested that these Voyager 1 data provide evidence for a reconnection type geometry of the magnetic field behind Titan. Unfortunately, conclusive evidence of the reconnection process in the magnetic tail of Titan, such as the measurement of heated electrons and accelerated ions [Neubauer et al., 1984] is absent. However, the rapid passage through the region of the induced tail by Voyager 1 and the prolonged cycle of operation of the plasma experiment (1 min, 36 s) does not permit us to make convincing positive conclusions as to the absence of such plasma indications for reconnection. An alternate possibility is that a northward component of plasma flow has led to a positive Z component of the magnetic field. But this results in $(\vec{B}\cdot\vec{B}_{\perp\infty}) < 0$ in only one lobe of the tail and this fact contradicts the results of measurements in Titan's magnetic tail (Figure 2).

For a comparison of the results of the measurements of the magnetic field in the induced tail of Titan with measurements of the magnetic field behind Venus, it is convenient to use measurements of that parameter on board the spacecraft Venera 9 and 10. This is because the spacecraft Pioneer Venus Orbiter could carry out measurements of the magnetic field in the tail of Venus only either very close to or at very large distances (7-12 R_V) from the planet [Russell et al., 1981].

As an example, consider the results of measurements of the magnetic field [Dolginov et al., 1978] on board the spacecraft Venera 10 on April 19, 1976, and on board the spacecraft Venera-9 on December 17, 1975. In the magnetic tail of Venus, these measurements were carried out at distances 3-5.5 R_V and 1.3-2 R_V from the center of the planet, respectively, i.e., at distances comparable (in units of radius of the planet) with distances 2.5-3 R_T at which measurements in the magnetic tail of Titan were carried out.

The results of measurements of the magnetic field behind Venus on April 19 and December 17 are shown in Figures 3 and 4 in the same projections as in Figure 2 but in the solar ecliptic coordinate system centered at Venus. Each vector in Figures 3 and 4 was obtained by averaging measurements of the magnetic field over $\sim$ 1 min, but during that time, the three components of the magnetic field were measured 8 times on April 19 and 60 times on December 17. In addition, the orientation of the Y and Z axes of the magnetometer during the measurements on April 19, 1976, was not known accurately, since during that measurement period, Venera 10 rotated slowly around the X axis with a velocity $\omega < 0.05$ deg/s [Dolginov et al., 1978]. Hence, it is not excluded that all vectors in the upper part of Figure 3 can actually be rotated by some angle.

During passage through the induced magnetic

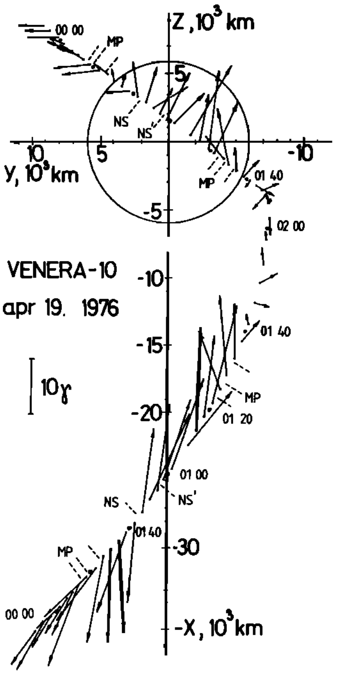

Fig. 3. Plots of B_{XY} (bottom) and B_{YZ} (top) vector components of the magnetic field data on April 19, 1976, superposed along the trajectory of Venera 10.

tail by Venera 10, the tail boundary moved and the spacecraft was within the tail approximately from 0020 to 0130 UT (see Figure 3). Shifting of the boundaries during that time interval will be discussed in more detail in section 4 while discussing the plasma measurements. At approximately 0043 UT, the dominant X component of the magnetic tail field changed sign, a fact that, as in the magnetic tail of Titan, indicates that the spacecraft crossed the region of the neutral sheet NS [Dolginov et al., 1978], while passing from one lobe to the other. In order to evaluate the sign of the scalar product ($\vec{B} \cdot \vec{B}_{\perp\infty}$) in the magnetic tail of Venus on April 19, 1976, for $\vec{B}_{\perp\infty}$ one can use the measurements of the magnetic field in the region prior to crossing the magnetopause. These measurements are chronologically closest to those measurements in the magnetic tail, and at distances of > 6 R_V from the center of the planet and of > 2 R_V from the axis of the tail in the transition region. Thus, one should not expect a considerable difference of direction of the magnetic field from its direction in the solar wind. After exit of Venera 10 from the magnetic tail, the direction of the magnetic field underwent considerable variations due to the quasi-parallel nature of the bow shock wave on the dawnside of the planet on April 19, 1976.

Over an interval of approximately half an hour, up to 0000 UT, the Y component of the magnetic field in the transition region was positive, even when the Z component was close to zero, i.e., the vector $\vec{B}_{\perp\infty}$ was approximately in the direction of the Y axis. The occurrence of negative values of B_Y in the magnetic tail of Venus may indicate possible reconnection of magnetic lines of force of both lobes of the tail during that measurement period. Note that the ambiguity of orientation of the Y and Z components of the magnetic field in that measurement period does not affect significantly the sign of the scalar product ($\vec{B} \cdot \vec{B}_{\perp\infty}$). But for a more reliable conclusion on the sign of that quantity in the magnetic tail on April 19, 1976, one needs a considerably lower upper limit of rotation speed of the spacecraft, compared to that value given in the work of Dolginov et al. [1978], say ω < 0.005 deg/s.

Measurements in the vicinity of Venus on December 17, 1975, on board Venera-9, were performed while in an attitude stabilized orientation. The bow shock wave, on the dawnside of Venus in the measurement period, was quasi-perpendicular [Verigin et al., 1978]. As can be seen in Figure 4, the magnetic field in the transition region had a regular character. The Z component of the magnetic field on December 17, both in the transition region and in the solar wind (after 1247 UT), was close to zero and $\vec{B}_{\perp\infty}$ was approximately in the direction of the positive Y axis. As can be seen from the data given in the top part of Figure 4, for an appreciable number of measurements of the magnetic field in the magnetic tail of Venus in that case, also ($\vec{B} \cdot \vec{B}_{\perp\infty}$) < 0. This fact does not conform to the idea that draping of the magnetic field around Venus is the sole process of formation of its magnetic tail.

Also, in the period of measurements in the induced magnetic tail, which is given in Figure 4, two lobes with oppositely directed dominant components of the magnetic field are clearly traced. Analysis of more detailed plots of the magnetic field, with averaging over 10 s, indicates the possibility for multiple crossing of

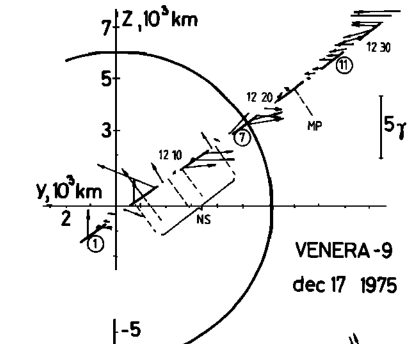

Fig. 4. Plots of B_{XY} (middle) and B_{YZ} (top) vector components of the magnetic field data on December 17, 1975, superposed along the trajectory of Venera 9. At bottom are the corresponding potential modulated Faraday cup spectra recorded on the same spacecraft.

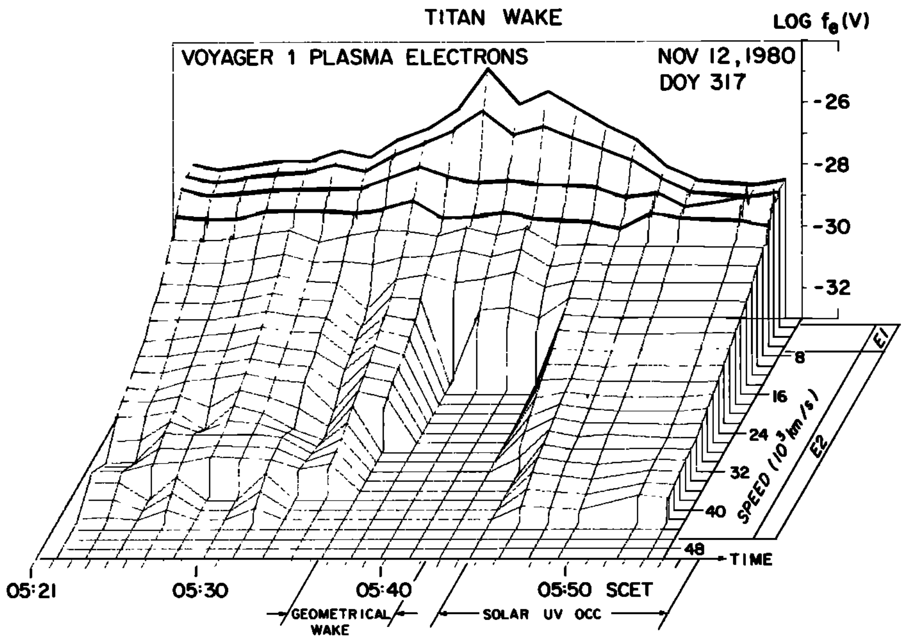

Fig. 5a. Three-dimensional representation of electron distribution function measured by Voyager 1 during flyby of Titan. The biteout feature occurs near 0540 in the higher-speed channels [from Hartle et al., 1982].

the neutral sheet NS during that traversal. Times at which the spacecraft Venera 9 crossed the NS or approached it closely ($B_x \simeq 0$) are indicated by light dashed lines in Figure 4.

4. Plasma in Induced Tails of Venus and Titan

Although the magnetic field configurations in the induced tails of Venus and Titan have many common features, the plasma characteristics appear to differ greatly. In Figure 5, the electron components of the plasma in the induced tails of Titan and Venus are compared. Figure 5a is taken from the work of Hartle et al. [1982], and it shows values of the electron distribution function with respect to velocity in the energy range 10-5950 eV. These were determined from measurements of the electron component of the plasma on board Voyager 1 during its flyby in the vicinity of Titan (see the trajectory in Figure 2). Figure 5b is plotted on the basis of the results of measurement of the electron component of plasma on board Venera 10 on April 19, 1976, and it gives the value of currents recorded by a wide-angle plasma analyzer at seven values of decelerating voltages at the analyzing grid of the apparatus. These currents are approximately proportional to integral fluxes of electrons with energy $\gtrsim$ 0, 10, 20, 40, 80, 150, 300 eV. In order that relative spatial resolutions of data in Figures 5a and 5b be comparable, in Figure 5b only every fifth one out of those available integral electron spectra is shown.

Regardless of some differences in the properties of the spectra given in Figures 5a and 5b, from a comparison of the plots it is seen clearly that the fluxes of low-energy electrons in the magnetic tail of Titan increase, while fluxes of low-energy electrons in the magnetic tail of Venus decrease, relative to their values in the surrounding region. That comment applies to electrons with energy $\lesssim$ 100 eV, i.e., with velocities $\lesssim 6.10^3$ km/sec, and these portions of the electron spectra are indicated by heavier lines in Figure 5a. On the other hand, a bite-out of electrons with energy $\gtrsim$ 700 eV is distinctly observed in the data of Voyager 1 behind Titan (Figure 5a) [Hartle et al., 1982]. This effect does not have an analogue in the measurements of electron fluxes on board Venera 10 on April 19, 1976 (Figure 5b). Nevertheless, it should be noted that on that spacecraft, integral electron fluxes with energy $\gtrsim$ 300 eV were recorded, and a possible reduction of electron fluxes with $E_e \gtrsim$ 700 eV might be unnoticeable in the background of significantly larger electron fluxes with energy from 300 to 700 eV.

At smaller distances from Venus, in some cases there was observed a depletion of the fluxes of energetic electrons $E_e \gtrsim$ 150 eV, as compared to their values in the solar wind and in the transition region. The measurements indicating that

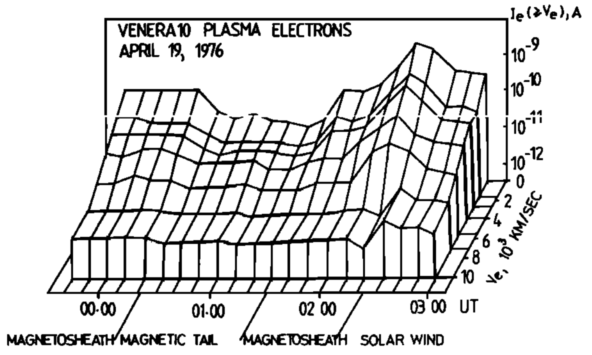

Fig. 5b. Three-dimensional representation of electron integral spectra measured by Venera 10 on April 19, 1976, during passage through solar wind Venusian wake and induced magnetic tail.

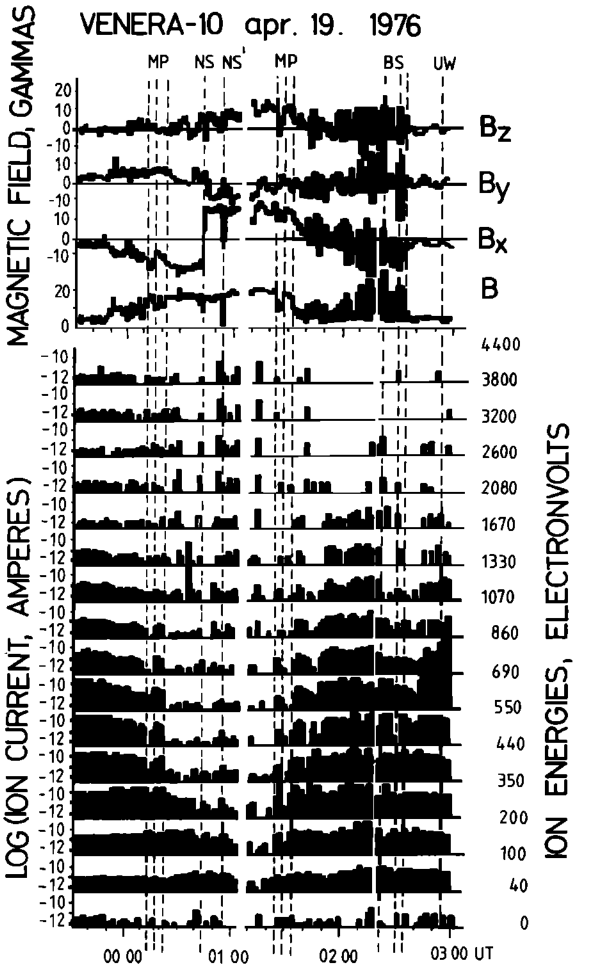

Fig. 6. Simultaneous magnetic field data, three orthogonal components and magnitude with indication of maximum and minimum during measurement intervals, and Faraday cup currents in 16 different energy channels from 0 to 4400 eV measured by Venera 10 on April 19, 1976, during passage through solar wind Venusian wake region. Note multiple crossings of magnetopause (MP), neutral sheet (NS and NS') and bow shock (BS).

fact can be found in the work of Verigin et al. [1978] in Figure 5. The phenomenon of the depletion of the fluxes of electrons with energy of several hundreds of electron volts behind Venus was also observed on the spacecraft Mariner 10 [Bridge et al., 1974]. These observations resemble the phenomenon of a bite-out of electron fluxes on Voyager 1.

Let us compare the behavior of the ion component of plasma in the induced magnetic tails of Venus and Titan. Measurements of the ion component of plasma both on Venera 9 and 10 and Voyager 1 were carried out using wide-angle modulated Faraday cups. The techniques of these measurements and some results from them are presented in more detail in the works by Gringauz et al. [1976], Gringauz [1981], Verigin et al. [1978], Bridge et al. [1981], and Hartle et al. [1982]. The results of measurements on April 19, 1976, of the ion component of plasma in all adjacent 16 energy channels in the range 0-4400 eV are given in Figure 6. In the top part of that figure, three components and the magnitude B of the magnetic field are given as well (see section 3). Measurements of the fluxes of ions in all 16 energy channels take $\approx$ 64 s, after which, in $\approx$ 56 s, the following energy spectrum was measured. During these $\approx$ 64 s all three components of the magnetic field were measured 8 times, and in Figure 6 the range between maximum and minimum values of the magnetic field, which characterizes the amplitude of its variation over $\approx$ 64 s, is indicated by shading.

As can be seen in Figure 6, the energy spectrum of the ions in the magnetic tail of Venus differs sharply from the energy spectrum of ions in the transition region. In the transition region, the largest fluxes of ions were recorded in the energy range 350-1000 eV, while in the magnetic tail, as a rule, maximum fluxes of ions were in the range 40-200 eV. Three crossings of the boundary of the magnetic tail (MP) occurred on entry and also occurred during exit from it. Within the limits permitted by time resolution of the instruments, five crossings of the magnetopause were sharp, i.e., occurred in the intervals between measurements of $\approx$ 1 min. Lastly, the sixth crossing of the magnetopause coincided with the time of recording and lasted $\approx$ 1 min. Simple modeling of the motion of the magnetopause in the form of a harmonic oscillation permits an estimate of the period of these oscillations as $\gtrsim$10-12 min, and an amplitude 400-500 km in the direction perpendicular to the axis of the magnetic tail. Thus, it can be shown that the thickness of the magnetopause in the same direction was less than 400-500 km. The first estimates of the above pairs for every parameter are associated with magnetotail outbound crossings while the second ones refer to the inbound crossings. It is appropriate to note here that, according to data on measurements of the magnetic field on Voyager 1, upon entrance of the magnetic tail the magnetopause was crossed in $\approx$ 59 s, and in $\approx$ 79 s while leaving [Ness et al., 1982]. That yields estimates of its thickness of $\approx$ 1000 km and $\approx$ 1350 km, respectively.

A systematic decrease of the bulk velocity of plasma started approximately 30 min prior to the first crossing of the magnetopause, i.e., $\approx$ 4000 km before the boundary of the tail of the induced magnetosphere, and continued as the spacecraft penetrated within the magnetic tail. In Figure 6, that decrease in bulk velocity can be seen from the systematic shift of the maximum of measured fluxes into energy intervals with lower energies. Such a behavior of the ion plasma component gives reason to assume that ions with energies 40-200 eV in the magnetic tail are protons and constitute the principal population in the magnetic tail [Verigin et al., 1978]. The interpretation of Mihalov and Barnes [1982] of the measurements of the ion plasma component in the distant magnetic tail of Venus, obtained by means of an electrostatic analyzer on board the spacecraft Pioner Venus Orbiter (PVO), corroborates this conclusion.

Bursts of fluxes of energetic ions with energies >4 keV in the distant magnetic tail recorded on PVO were interpreted by Mihalov and Barnes [1982] to be generated by O^+ ions of planetary origin, which move with the local bulk velocity of the protons. Although their interpretation is not based on data of mass-spectroscopic measurements, it is nevertheless sufficiently convincing. However, the question remains open whether all facts of the measurement of energetic ions in the distant (PVO) or closer (Venera 9 and 10) region of the magnetic tail were related to heavy ions of planetary origin.

Another possible cause of the presence of energetic ions in the magnetic tail of Venus may be the presence of processes of acceleration in that region [Gringauz et al., 1976; Gringauz, 1981; Verigin et al., 1978]. In that case, bursts of energetic ions (or at least a part of them) may be interpreted as measurements of the plasma sheet behind Venus, which, as is known in the magnetic tail of the earth, consists of charged particles with an energy of several keV. If that interpretation is correct, then the intensity of accelerated protons in the plasma sheet should be highest in the regions of the magnetic tail that are closest to the neutral sheet, where the sign of the B_x component of the magnetic field changes and where processes of reconnection are possible. Comparison of measurements of ion plasma component and magnetic field on spacecrafts Venera 9 and 10 supports that assumption.

Actually, as can be seen in Figure 6, in the vicinity of the change in sign of the X component of the magnetic field, NS, the occurrence of energetic ions with energies 2-4.4 keV was recorded. Significant fluxes of ions with the same energies were recorded also in the vicinity of the region which is marked by the symbol NS' in Figure 6. The measurement of energetic ions in the vicinity of NS' can be associated with the motion of the neutral sheet. The result of that motion was that in the region NS', Venera 10 again twice crossed the neutral sheet. As can be seen in Figure 6 in the region NS', the X component of the magnetic field became negative again for a short time. Simultaneously, the magnitude of the magnetic field B reached a deep minimum $\sim$ 3 nT, as compared to the typical values of $\sim$ 20 nT for the magnetic field in the lobes of the tail during that orbital pass. Some other observed bursts of energetic ion fluxes (e.g., near 0115 UT) may also be connected with movements of the neutral sheet. We cannot, however, be sure that at the time of measurement of these bursts the spacecraft approached the neutral sheet, because the results of magnetic measurements make it possible only to fix actual crossings of the neutral sheet but not close approaches.

The appearance of energetic ions in the vicinity of the neutral sheet in the induced magnetic tail of Venus also can be seen from the spectra of the ion plasma component given in Figure 4. In that figure, the portions of the trajectory along which the spectra were measured are marked by dashed lines and circled numbers; spectra are given in the bottom part of the figure and are marked accordingly. It also can be seen from the data given in that figure that the largest fluxes of ions with energies 2-4 keV were recorded from 3 to 6 R_V, i.e., during the time when the spacecraft Venera 9 was in the vicinity of the neutral sheet NS, crossing it many times (see section 3 of this work). Other instances of the measurement of significant fluxes of energetic ions in the vicinity of the change in sign of the B_x component of the magnetic field in the magnetic tail of Venus on October 28 and November 25, 1978, are published in the works of Breus and Gringauz [1980] and Breus [1979], respectively.

The above described observations of an increased intensity of fluxes of energetic ions, with an energy of several keV in the vicinity of the neutral sheet in the magnetic tail of Venus, are plasma evidence of the presence of reconnection in that region. Unfortunately, they are not unique, since another possible explanation of these observations may be connected with the penetration of plasma of the transition region into the induced magnetosphere of Venus together with O^+ ions that are generated in it as a result of ionization of the planet's exosphere. Such penetration, as was suggested by de Tejada [1980], can be accomplished through the region of "magnetic poles" above which a current system which generates the induced magnetosphere separates (Figure 1c) and does not create a magnetic field, which would be an obstacle to the penetration into the magnetosphere of the plasma. As can be seen in Figure 1c, in that case, the plasma of the transition region with O^+ ions can directly penetrate into the neighborhood of the neutral sheet of the magnetic tail, where these ions will be recorded as added maxima at large energies in an energy spectrum. In the outer regions of the tail and in the transition region, that maximum will not be measured by plasma instruments on Venera 9 and 10, since the bulk velocity of the plasma increases there and the energy of O^+ ions exceeds the energy range of the plasma instruments. The final solution of the problem as to which of the two possibilities and in what degree each is realized in the induced tail of Venus will obviously be possible when energy-mass-spectrometric measurements of plasma are carried out in that region.

The prolonged cycle of operation of the plasma instrument on Voyager 1 severely limited the possibility for a reliable interpretation of the measured ion component of plasma on that spacecraft. Suffice it to say that in the magnetic tail of Titan, only two ion spectra were obtained. Careful analysis of simultaneous plasma measurements with information derived from plasma wave measurements was performed by Neubauer et al. [1984]. The authors of that work came to the following conclusions.

1. Plasma in the tail of Titan consists of ions N^+, N_2^+, or H_2CN^+,
2. Bulk velocity of plasma is 5-10 km/s,
3. Concentration of plasma is 6-10 cm^{-3},
4. Maximum concentration of plasma is 30-40 cm^{-3} and is reached in the vicinity of the magnetopause and neutral layer.
5. Charge neutrality should be provided by the presence of cold electrons (E_e < 10 eV).

Thus, in contrast to the magnetic tail of Venus, the concentration of plasma in the magnetic tail of Titan considerably exceeds its value in the plasma flow outside, where $n_i \sim 0.3$ cm^{-3} [Neubauer et al., 1984; Hartle et al., 1982]. The difference in plasma composition in the two magnetic tails, basically light ions (H^+) behind Venus, and heavy ions (N^+, N_2^+, or H_2CN^+) behind Titan, may be significant.

5. Discussion and Conclusions

It is convenient to start the discussion of the results of the comparison of induced magnetic

TABLE 1. Comparison of Features Observed in the Region of Interaction of Plasma and Venus and Titan Downstream.

Feature	Venus	Titan
Induced two-lobe magnetic tail	yes	yes
Reversal of magnetic field in magnetic tail	yes	yes
Transition processes due to $\partial B/dt \neq 0$	yes	?
Hot electrons in neutral sheet	?	no
Decrease of flows of energetic electrons	yes?	yes
Energetic ions in the vicinity of neutral sheet	yes	?
Supersonic flow of plasma near boundary of tail	yes	no

tails of Venus and Titan from Table 1 which sums up our results. Regardless of the fact that the plasma flowing around Venus was supersonic and around Titan subsonic, behind both planets a magnetic tail consisting of two lobes was formed. In the vicinity of the neutral sheet of that tail, a change in sign of the longitudinal component of the magnetic field took place. It is possible to draw the conclusion that the formation of the tail of the induced magnetosphere is to a considerable degree controlled by processes which originate in the forward portion of the obstacle, where the flow of plasma in both cases is subsonic due to the fact that at Venus the flow of plasma is decelerated after crossing the bow shock wave.

The configurations of the magnetic field in a single flight through the magnetic tail of Titan and two flights through the magnetic tail of Venus considered here do not confirm the idea that induced magnetic tails are formed as a result of simple draping around the obstacle of magnetic lines of force (Figure 1a). In the magnetic tail, the magnetic field vector in the plane perpendicular to the velocity vector of the inflowing plasma was often directed opposite to the direction of that vector in the plasma flow region undisturbed by the obstacle. Thus, in the cases considered, the topology of the magnetic field in the induced tails was more like that given in Figure 1b. From our viewpoint, that fact suggests the possible presence of processes of reconnection in the vicinity of the neutral sheet.

During laboratory modeling of the interaction of the solar wind with Venus in the stationary case ($\partial B/\partial t = 0$), the configuration of the magnetic field conforming to the model proposed by Yeroshenko [1979] was not observed [Dubinin et al., 1978]. Dolginov et al. [1981], while analyzing the configuration of the magnetic field behind Venus on the basis of data of the spacecraft Venera 9 and 10, came to the conclusion that in the majority of the 25 orbits they considered, the configuration of the magnetic field looked like that in Figure 1a, in complete agreement with the results of laboratory modeling. According to the analysis made in that work, such a configuration of magnetic field was observed in 18 different orbits. Out of the remaining seven orbits, in four cases, the configuration of the magnetic field was not explained, and in three cases, it conformed with the configuration of the magnetic field which is given in Figure 1b.

On the basis of data given in the work of Dolginov et al. [1981], it is difficult to judge the reliability of those conclusions. In Figure 2 of that work, which illustrates the similarity in the configuration of the magnetic fields behind Venus and in the model experiments, as projected onto a rotating plane including the X axis and the vector $\vec{B}_{\perp\infty}$, results are given of the measurements of the magnetic field during the 18 orbits already mentioned. It is readily seen in the data given in that figure that about half were obtained at distances from the X axis exceeding the radius of Venus, that is, clearly in the transition region, and not in the magnetic tail. Due to the effect of projection, the measurements even along these portions of the trajectory, which in the figure seemed close to the axis of the tail, in reality might have been performed rather far from it. Thus, the effect of draping of the magnetic field by Venus, which is clearly seen from the material analyzed by Dolginov et al. [1981] is, to a considerable degree, derived from measurements of the magnetic field in the transition region. There, such draping, of course, exists, as was already mentioned at the end of section 2 of this present work.

According to data in the work of Dolginov et al. [1981], the configuration of the magnetic field conforming to the model of Yeroshenko [1979] was observed only during three orbits. However, it is shown in our work in Figure 4, that also on December 17, 1975, the configuration of the magnetic field behind Venus conforms to the model of Yeroshenko [1979], while in the work of Dolginov et al. [1981], that case was included in the group of orbits which contradict the model mentioned. Note also that in the work of Yeroshenko [1979] it was reported that out of eight orbits of the spacecraft Venera 9 and 10, which the author analyzed, in six cases the configuration of the magnetic field behind Venus conformed to the model the author proposed. Additional examples of measurements when the magnetic field in the magnetic tail of Venus conformed to the model of Yeroshenko [1979] can be found as well in the publication of Vaisberg and Smirnov [1980]. Certainly, in many cases of observations of the magnetic field in the close (Venera 9 and 10) or distant (Pioneer Venus Orbiter) regions of the magnetic tail, the measured configuration of the magnetic field conformed to the model given in Figure 1a. Hence, it seems reasonable to conclude that a magnetic field which is described by the model of Yeroshenko [1979] is frequently present in the magnetotail of Venus.

We think that the occurrence of closed magnetic lines of force in induced magnetic tails (Figure 1b) may result from the reconnection of tail lobe lines of force. That process differs from the process of nonstationary induction ($\partial B/\partial t \not\approx 0$), which was called upon by Dolginov et al. [1981] as an explanation of the configuration of the magnetic field behind Venus in those cases which are not compatible with its configuration in the case of simple draping around the obstacle. We also note that a reconnection-type geometry magnetic field was observed by Kivelson and Russell [1983] during a specially selected PVO pass behind Venus, under steady solar wind conditions, which rather reliably excludes $\partial B/\partial t$ effects.

It is understood that one should not exclude the possibility that both processes may exert an influence on the configuration of the magnetic field in the tail of the induced magnetosphere. The existence of fluxes of ions with energy of several kev (Figures 4 and 6) in the region of the magnetic tail of Venus, which is adjacent to the neutral layer, is evidence in favor of the possible existence of the processes of reconnection.

We will briefly compare now the thickness of the boundary of the tail near Venus and Titan. As it has been shown above, during the period of measurements of April 19, 1976, at distances along the trajectory much smaller than the cross-sectional dimensions of the tail of Venus, three crossings of the magnetopause were observed while entering and again while exiting the tail. Such characteristics of the boundary of the tail unambiguously give evidence that its thickness is also much smaller than the cross-sectional dimension of the magnetic tail. For that orbit, the thickness of the magnetopause was estimated to be $\delta \lesssim 400-500$ km, that is $\delta/R_V < 0.08$. Estimates of the thickness of the magnetopause behind Titan give larger values $\delta \sim 1000 - 1350$ km [Ness et al., 1982], for which $\delta/R_T \sim 0.4 - 0.5$. Such a difference may be associated with the fact that in the magnetic tail of Titan and in its vicinity, the magnetic field was weaker than in the corresponding regions behind Venus (average 5-7 nT and 15-20 nT) and with the fact that in both the plasma flow around Titan and in the magnetic tail of Titan, a considerable quantity of heavy ions is present. We note at this point that the ion gyroradii measured as a fraction of a planetary radius are much greater at Titan than at Venus. However, quantitative comparison of thicknesses of both boundaries presents some problems.

Near both Titan and Venus, as the boundary of the magnetic tail is approached, the bulk velocity of the plasma decelerates and reaches its lowest values inside the tail. However, while the concentration of plasma falls as the induced magnetic tail of Venus is entered (such a conclusion is easily made on the basis of data given in Figures 5b and 6), the concentration of plasma increases by an order of magnitude (see section 4) as the induced magnetic tail of Titan is entered. Such a qualitative difference in the properties of plasma may be associated with the different "rigidity" of the atmospheric obstacle near the two planets: near Venus the ratio between scale heights of oxygen in the atmosphere and the radius of the planet is ~ 0.003, while near Titan the ratio of the scale height of the nitrogen atmosphere and the radius of Titan amounts to 0.03 [Ness et al., 1982]. That fact makes it possible that a larger relative volume of the atmosphere takes part in the formation of the magnetic tail. Note that in the case when the solar wind flows around a comet, it can be expected that the obstacle will be even "softer" than near Titan, and the ratio mentioned may be close to 0.5. In such a case one should expect an even larger participation of plasma in the formation of the magnetic tail of comets than in the case of the magnetic tail of Titan.

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