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Pioneer Venus Orbiter Magnetic Field and Plasma Observations in the Venus Magnetotail

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This study uses Pioneer Venus orbiter (PVO) magnetometer and plasma analyzer measurements to investigate the draped-field tail of Venus with an emphasis on determining the magnetic field and plasma conditions within the various tail regions and their dependence upon interplanetary magnetic field (IMF) orientation. For this purpose PVO orbits during which the spacecraft's high inclination trajectory took it through the central magnetotail were identified. The criteria used to select these orbits were the existence of relatively complete magnetic field and plasma data during crossings of the magnetotail which lasted more than 3 hours. Examination of observations from four PVO tail seasons in 1981–1983 produced 12 orbits meeting these requirements. Analysis of the observations taken during those orbits indicates that the distribution of plasma within the magnetotail is highly asymmetric and controlled by the orientation of the IMF. In the plasma sheet and adjacent lobe regions downstream of the Venus hemisphere over which the solar wind motional electric field, $E_{sw} = -V_{sw} \times B_{sw}$, is directed away from the planet, PVO observed increasing fluxes of H^+ and O^+ as the spacecraft moves away from the tail axis toward the outer boundary of the tail. The greatest concentration of these O^+ ions was found in the vicinity of the cross-tail current layer downstream of this Venus hemisphere. No O^+ ions were observed outside of the magnetotail based upon the magnetic field data and the definitions adopted in this study. However, only slow, <310 km/s, antisolar directed O^+ is detectable by the PVO plasma analyzer and this factor may be the reason for the frequent observation of O^+ in the cross-tail current and the absence of measurable O^+ outside of the magnetotail where the bulk flow speeds are significantly slower than in the distant ionosheath. Downstream of the Venus hemisphere over which the solar wind motional electric field is directed in toward the planet, PVO does not usually observe significant fluxes of $E/Q = 0$–8 kV ions, except sometimes directly adjacent to the outer boundary of the tail. The outer boundary of the Venus magnetotail downstream of this hemisphere is typically a well-defined magnetopauselike current layer. The magnetotail-ionosheath interface downstream of Venus hemisphere over which the solar wind motional electric field is outward, however, is very broad and resembles a slow mode expansion fan with field strength slowly decreasing and plasma density gradually increasing as PVO moves outward and enters the ionosheath. These results are interpreted as being due to the more efficient pick-up of newly ionized atmospheric neutrals over the Venus hemisphere where the initial gyromotion takes the newly created ions away from the dense, lower atmosphere where they might be lost due to scattering (Cloutier et al., 1974). The implications of these findings for the formation and maintenance of the Venus magnetotail are discussed.

INTRODUCTION

In situ observations at Venus [*Dolginov et al.*, 1978; *Verigin et al.*, 1978, 1984; *Eroshenko*, 1979; *Gringauz*, 1981; *Russell et al.*, 1981; *Intriligator and Scarf*, 1984; *Slavin et al.*, 1984; *Marubashi et al.*, 1985; *Saunders and Russell*, 1986; *McComas et al.*, 1986; *Phillips et al.*, 1986, 1987] and Comet Giacobini-Zinner [*Smith et al.*, 1986; *Bame et al.*, 1986; *Meyer-Vernet et al.*, 1986*a*, *b*; *Slavin et al.*, 1986*a*, *b*, *c*; *Siscoe et al.*, 1986; *McComas et al.*, 1987] have demonstrated that magnetic tails form as a natural consequence of the solar wind interaction with unmagnetized bodies possessing extensive atmospheres. The basic mechanism was first proposed by *Alfvén* [1957] and is illustrated in the top panel of Figure 1. The portions of interplanetary flux tubes passing near the body are slowed due to the interaction with newly ionized atmospheric neutrals while the two ends continue to be pulled downstream at the solar wind speed. If the flux tubes are "tied" to the body for a period much greater than the free-stream flow time past the body, e.g., L/V_{sw}, where L is the radius of the obstacle, then the field lines will be bent back or "drape" about the body to some degree. The greater the time the interplanetary flux tubes take to slip about the body, the longer and more tightly draped the resultant magnetic tail. While the processes responsible for the "tying" can be quite complex, observations have shown that if the interaction is sub-Alfvénic, for example Io with respect to the corotating Jovian inner magnetosphere, then the flux tubes encountering the body are only slightly bent back [*Acuna et al.*, 1981] and best described as "Alfvén-wings" [*Drell et al.*, 1965; *Southwood et al.*, 1980; *Neubauer*, 1980]. However, even weakly super-Alfvénic interactions, such as in the case for Titan with respect to Saturn's middle magnetosphere, produce a well-defined magnetic tail [*Ness et al.*, 1982; *Neubauer et al.*, 1984].

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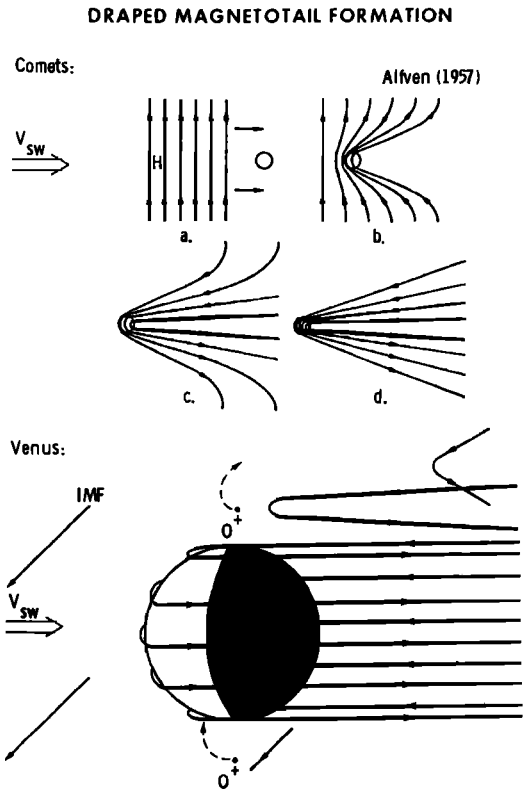

Fig. 1. Draped field magnetotails are formed when the solar wind is slowed locally due to a strong interaction with an obstacle. The top panel depicts such a situation for a comet as first envisioned by *Alfvén* [1957]. The bottom panel presents the corresponding case for Venus with the asymmetric O^+ mass loading predicted by *Cloutier et al.* [1974] causing more extensive field line draping over the hemisphere where the ionosheath motional electric field has an outward component.

The major difference between Venus and the cometary interaction considered by Alfvén is that the strong gravitation force exerted by a planet, as contrasted with a comet, confines most of the neutral atmosphere to low altitudes where irradiation by solar EUV produces a cool, dense ionosphere. Consequently, it is this electrically conducting ionosphere which forms the primary obstacle to the solar wind at Venus [*Elphic et al.*, 1980; *Slavin et al.*, 1980]. Whereas this relatively impenetrable obstacle at Venus causes strong deflection of the flow away from the stagnation point [e.g., *Spreiter and Stahara*, 1980], the cometary interaction is characterized by extreme slowing and heating of the flow, but little deflection of the stream lines [e.g., *Schmidt and Wegmann*, 1982]. The Venus ionosphere is usually only weakly magnetized and the source of the magnetic fields populating the tail region must be predominantly field lines that drape about the dayside ionopause or close through the cross-tail current layer [*Russell et al.*, 1981; *Slavin et al.*, 1984; *Saunders and Russell*, 1986]. The residence time for field lines in the Venus magnetotail, which determines the length of the tail, is poorly known, but it is estimated to be 10–30 min [*Eroshenko*, 1979; *Saunders and Russell*, 1986]. These residence times imply magnetotail lengths of 50–150 R_V. By comparison, the time required for inviscid gasdynamic flow about a tangential discontinuity ionopause is only a few minutes [*Spreiter and Stahara*, 1980] and would not produce the greater than 12 R_V long tail observed by Venera and PVO. The reason that the innermost interplanetary flux tubes draped about the ionopause take so long to slip about Venus is generally thought to be mass loading by atmospheric O^+ [e.g., *Vaisberg and Zeleny*, 1984; *Russell et al.*, 1985; *McComas et al.*, 1986] in a manner qualitatively similar to that at comets, albeit confined to much lower altitudes. In these theoretical models the mass loaded field lines fill the downstream region to produce the well-developed magnetotail observed in the magnetometer measurements.

A related theoretical prediction (*Cloutier et al.* [1974]; see also *Manka and Michel* [1973]) is that the mass loading process at Venus should be asymmetric, as shown in the bottom panel of Figure 1. Cloutier et al. suggested that a more efficient pickup of newly created ions should take place over the hemisphere, where the $-V_{sw} \times B_{sw}$ motional electric field of the solar wind causes them to initially gyrate outward from the planet and avoid scattering within the atmosphere. Studies of the magnetic field in the near-Venus ionosheath by *Luhmann et al.* [1985] and *Phillips et al.* [1986, 1987] have supported this hypothesis with PVO observations showing stronger draping signatures over the preferred hemisphere for ion pickup. In particular, those studies have detected both an overall increase in magnetic field intensity and a significant curl to the field over the hemisphere where E_{sw} is outward presumably due to a braking/compression of the ionosheath flow and a net outward electric current associated with the pickup of new O^+ ions.

Previous studies utilizing the PVO plasma analyzer measurements have demonstrated the presence of O^+ in the downstream wake region [*Intriligator*, 1982; *Mihalov and Barnes*, 1982]. However, despite the crucial role mass loading by O^+ pickup ions is thought to play in tail formation, no extensive investigations of the combined plasma and magnetic field data within the different regions of the magnetotail have been conducted [see *Intriligator and Scarf*, 1984; *Slavin et al.*, 1984]. Accordingly, this study addresses the nature and implications of the PVO magnetic field and plasma measurements taken inside the Venus magnetotail. It will be shown that significant fluxes of H^+ and O^+ ions are observed in the outer portions of the tail lobes downstream of the Venus hemisphere over which E_{sw} is outward, a correlation is shown to exist between O^+ events and crossings of the cross-tail current sheet suggesting a concentration of pickup ions in this region, and a strong dependence of tail boundary structure upon IMF direction is demonstrated which may indicate that the tail is resupplied with new flux tubes in an asymmetric manner. These results are compared with the 1975–1976 Venera 9 and 10 observations and discussed in terms of their implications for the global interaction of the solar wind with Venus.

CASE STUDIES

The PVO orbit is highly inclined, 105°, and eccentric with an apoapsis of 12 R_V and a periapsis in or just above the ionosphere. In this study, the position of the spacecraft and the orientation of the magnetic field are referenced to the Venus solar orbital (VSO) coordinate system. In this frame of reference the X and Y axes lie in the Venus orbital plane, X is positive toward the Sun, Y is positive in the direction opposite to that of planetary orbital motion, and Z completes the right-handed system. As noted in previous studies, this orbit is ideal for the investigation of many aspects of the Venus magnetotail. When apoapsis is on the nightside, PVO moves northward through the Venus tail at distances of $X = -12$ to -8 R_V. The result is a trajectory nearly parallel to the plasma sheet separating the two tail lobes [*Slavin et al.*, 1984; *Saun-*

TABLE 1. PVO Central Tail Crossings

Date	Duration, hours	$\langle B_y \rangle_{TAIL}$, nT	$\langle B_z \rangle_{TAIL}$, nT	O^+	IMF B_y
Nov. 27, 1981	5.5	−0.32	−0.59	$Z_{VSO}<0$	negative
Nov. 29, 1981	8.5	0.54	−0.49	$Z>0$	positive
Jul. 9, 1982	4.5	−1.18	−0.23	$Z<0$	negative
Jul. 10, 1982	5.5	−1.82	−0.67	$Z<0$	negative
Jul. 11, 1982	6.0	−0.58	−1.10	$Z<0$	mixed
Feb. 21, 1983	4.5	0.10	1.17	$Z>0$	mixed
Feb. 22, 1983	3.5	−4.07	0.38	$Z<0$	negative
Sep. 24, 1983	5.0	1.32	1.17	mixed	mixed
Oct. 1, 1983	8.0	−2.25	−0.07	$Z<0$	negative
Oct. 2, 1983	6.0	−0.90	0.58	$Z<0$	negative
Oct. 3, 1983	5.0	2.72	−1.74	mixed	positive
Oct. 6, 1983	3.5	4.09	−2.27	$Z>0$	positive

ders and Russell, 1986]. Hence when PVO passes directly downstream of where field lines are slipping around the ionopause (see Figure 1), it will spend significant time in the plasma sheet and frequently encounter the embedded cross-tail current sheet.

This study examines the measurements taken with the UCLA magnetometer [*Russell et al.*, 1980] and the NASA/Ames plasma analyzer [*Intriligator et al.*, 1980] for the fifth through the eighth PVO tail "seasons" (i.e., 1981–1983). These seasons occur every 225 days when the plane of the PVO orbit sweeps through the region downstream of Venus. During each season the spacecraft enters the tail, at least briefly, during approximately 10–15 orbits as the variations in the solar wind velocity vector cause large amplitude tail motion transverse to the X axis [e.g., *Slavin et al.*, 1984]. For the purpose of this study, the small number of orbits where the spacecraft spent long intervals in the central region of the tail were identified. The availability of relatively continuous magnetometer and plasma measurements was the first of the event selection criteria. Next, it was desired to select orbits for which PVO passed close to the cross-tail current layer, sometimes termed the "neutral sheet" by analogy to the earth's magnetotail, where the effects of mass loading should be most prominent. The quasi-circular cross section of the magnetotail [*Saunders and Russell*, 1986] implies that PVO trajectories passing near the midplane generally spent the longest periods of time within the tail. For this reason, the second criterion was that PVO have spent 3 hours or more continuously in the tail. Examination of the 1981–1983 PVO magnetotail observations has confirmed that these longer crossings of the tail correspond to orbits during which the cross-tail current layer is often encountered as the tail moves and undulates under the influence of the solar wind. Application of these two criteria to our data set produced the 12 Venus central tail traversals listed in Table 1. As indicated, the number of well-observed central tail passages per season varied between two and five. In the sections to follow, case studies taken from these Venus magnetotail traversals will be presented for both IMF $B_y > 0$ and IMF $B_y < 0$ conditions. The results derived from the individual cases will then be further examined using data from all 12 central tail traversals.

November 29, 1981

One such IMF $B_y > 0$ pass on November 29, 1981, during which PVO spent more than 8 hours in the tail, is presented in Figures 2*a*–2*f*. Figure 2*a* plots the projection Pioneer Venus orbit in the Z-X plane for this day. For comparison, the average magnetotail boundary from *Saunders and Russell* [1986] is displayed as a dashed curve. The boxed-in portion of the PVO trajectory corresponds to the interval when the magnetic field and plasma observations indicate that the spacecraft was in the tail. Note that essentially complete magnetic field and plasma coverage is available for this pass. Crosses, stippling, and an absence of stippling correspond to the presence of O^+ and H^+ together, H^+ alone, and a lack of measurable ions, respectively.

The top portions of the data figures show E/Q ion spectra, 0–8 kV, with the starting times of the individual energy scans aligned with the time scale on the magnetic field plots. However, it should also be noted that the width of each E/Q step varies logarithmically so that a later feature in an individual spectrum will not be exactly coincident with the time scale for the magnetic field. The several minute timing drift over the duration of a spectrum is not significant given the limited time resolution of the analyses presented here. The magnetic field data displayed are 12-s averages in VSO Cartesian coordinates which have been converted to simple spherical coordinates [see *Slavin et al.*, 1984]. A magnetic field vector in the Venus orbital plane corresponds to theta = 90° with $+B_z$ and $-B_z$ fields being indicated by theta = 0° and 180°, respectively. The azimuth, or phi angle is measured counterclockwise, as viewed from the north celestial pole, with phi = 0° directed toward the Sun. The location of the PVO spacecraft is given in Cartesian VSO coordinates at the bottom of the figure.

Figure 2*b* begins at 1245 UT with the spacecraft in the ionosheath and below the magnetotail at $Z = -2.6\ R_V$. The plasma analyzer observations show the shocked H^+ and He^{++} ion spectra typical of this region. Based upon the direction of the preponderance of the ionosheath magnetic field observations, Venus was in a positive IMF B_y sector (i.e., 0° < phi < 180°) and the IMF had a moderate southward component. In good agreement with the average tail surface in Figure 2*a*, the magnetic field began to increase in strength around 1310 UT and rotate into a "toward" lobe orientation with theta approaching 90° and phi near 0°. The next plasma analyzer scan showed no detectable ion fluxes consistent with the passage of PVO through a magnetospauselike current layer into a low beta (i.e., $\beta = (nkT_i + nkT_e)/(B^2/8\pi)$) lobe or boundary layer region of the tail. The regions of the tail, i.e.,

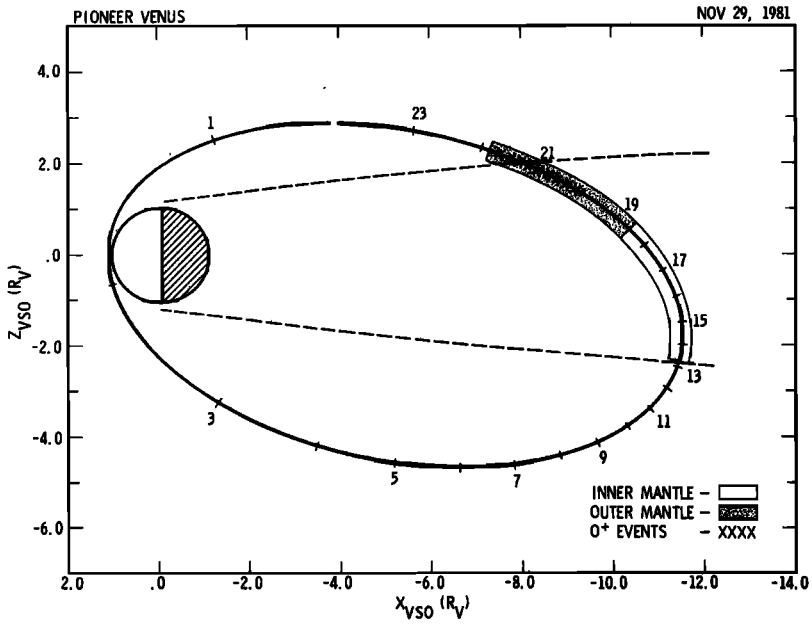

Fig. 2*a*. The projection of the PVO orbit into the *Z-X* plane (solid line) for November 29, 1981, is plotted along with the average tail boundaries (dashed lines) from *Saunders and Russell* [1986]. The interval during which the spacecraft was in the magnetotail is boxed with stippling marking the region with detectable levels of plasma ions (i.e., the outer mantle) and crosses indicating where O^+ ions were also observed.

the lobes, boundary layers, and plasma sheet, have been identified and marked in the same manner as used by *Slavin et al.* [1984]. Briefly, the regions of strong, low variance fields oriented approximately toward or away from the planet correspond to the lobes of the tail and are marked with a cross-hatch bar code such as the regions around 1358 and 1422 UT. The higher variance, low field strength intervals with an absence of shocked solar wind–type ion spectra (e.g., after 1425 UT) are identified as encounters with the plasma sheet separating the two lobes and indicated with a horizontal bar code. Note that despite the anticipated high beta nature of this region, there is often a lack of measurable E/Q = 0–8 kV ions in the PVO plasma sheet observations [*Slavin et al.*, 1984] as will be addressed later in this paper. Finally, the regions of slightly decreased magnetic field magnitude relative to the lobes (e.g., ~1330–1349 UT) and intermediate variance levels correspond to the "boundary layers" adjacent to the plasma sheet and outer boundary of the tail where the plasma beta is presumably between that of the low beta lobes and high beta plasma sheet and ionosheath. These boundary layer regions are marked with a slant-line pattern. As shown in Figures 2*b*–2*f*, the Pioneer Venus spacecraft spent most of this pass in the plasma sheet with numerous cross-tail current layer crossings. The complete crossings of the current layer are associated with a reversal in the phi direction of the field by up to 180° such as the three clean events between 1645 and 1710

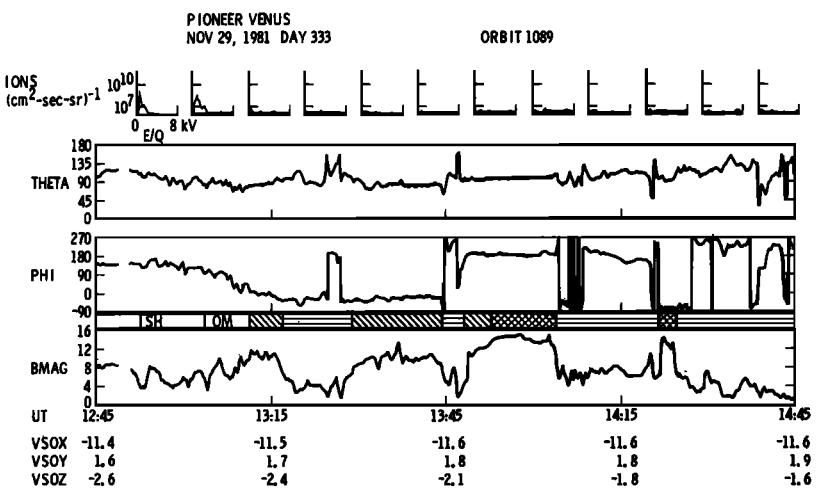

Fig. 2*b*. Ion flux versus energy/charge for individual spectra are shown at the top with the magnetic field in spherical coordinates plotted in the bottom panels. In these coordinates a magnetic field lying in the Venus orbital plane corresponds to theta = 90° with $+B_z$ and $-B_z$ fields corresponding to 0° and 180°. The phi angle is measured counterclockwise viewed from the north with phi = 0° directed toward the Sun. In the region identifier bar the ionosheath is marked by ISH, the outer mantle by OM, the lobes by cross-hatch, the boundary layer regions by slant line shading, and the central plasma sheet by horizontal lines.

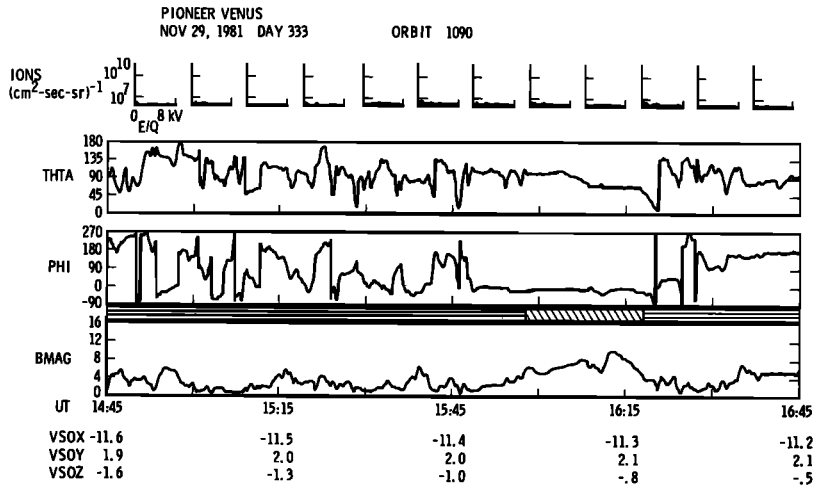

Fig. 2*c*. The same format as in the preceding figure, but for the interval 1445–1645 UT. Note the great amount of time spent in the plasma sheet as determined by the weakness of the magnetic field [*Slavin et al.*, 1984].

UT. These observations as well as the long span of time spent in the tail, i.e., over 8 hours, mark this orbit as one passing through the central part of the Venus magnetic tail as was the purpose of the selection criteria discussed earlier.

Shortly after 1830 UT in Figure 2*d* the lobe magnetic field begins to weaken slightly as very low ion fluxes appear in the lower E/Q channels. At that time PVO was around 0.5 R_V above the Venus orbital plane and just entering the northern half of the tail as shown in Figure 2*a*. The trend continues in Figures 2*e* and 2*f* with the field continuing to weaken and very slowly rotate toward the ionosheath orientation observed prior to entry into the magnetotail. While these smooth variations in the magnetic field were taking place, a gradual increase in the ion flux levels was occurring. In addition to an increase in the ion density, a gradient in plasma flow speed was also evident. Antisunward flow speeds based upon the lowest energy/charge peak, assumed to be H^+, are displayed for each spectrum. The flow speed started out quite slow, 234 km/s at 1900 UT, and increases as PVO moves northward through the tail until a speed of 330 km/s was reached around 2150 UT. The magnetic field also ceased its rotation near that time with the spacecraft clearly located in the ionosheath at $Z = 2.1$ R_V in good agreement with the average tail boundary model in Figure 2*a*.

The PVO observations of gradually increasing H^+ ion fluxes as the spacecraft moved outward from the tail axis is consistent with a transit of the "corpuscular penumbra" or "mantle" region reported by Venera 9 and 10 [e.g., *Verigin et al.*, 1978; *Vaisberg and Zeleny*, 1984]. The Venera orbiters found that within the distant "wake" of Venus, corresponding to the magnetic tail in the magnetometer observations [*Dolginov et al.*, 1978], a gradual decrease in ion flux and antisolar bulk speed occurred as the spacecraft passed from the ionosheath in toward the Sun-planet line (see Figure 8). Possibly because these spacecraft encountered the tail at distances only half those of PVO, the Venera 9 and 10 plasma analyzers were apparently able to detect plasma ions and electrons throughout the tail. The PVO plasma analyzer measured significant ion fluxes only in the outer layers of the lobes and in some portions of the plasma sheet, as will be discussed further in the cases to follow. For the purposes of this study, the region of the magnetic tail where PVO detects significant ion fluxes will be termed the "outer mantle," or OM, to distinguish it from the "inner mantle" where the fluxes are below the level for detectability.

Singly ionized oxygen in the PVO plasma measurements appears as ion fluxes displaced by a factor of 16 in E/Q from the H^+ peak [*Intriligator*, 1982; *Mihalov and Barnes*, 1982].

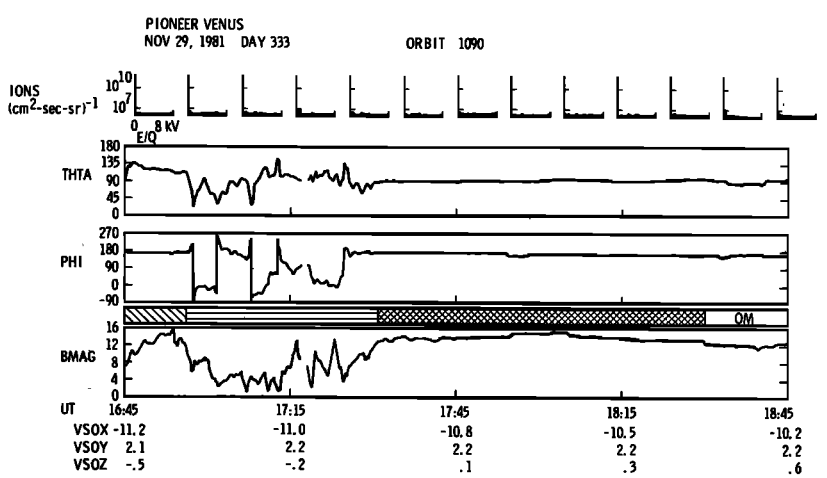

Fig. 2*d*. The same format as in the preceding figure, but for the interval 1645–1845 UT. Low-energy ion fluxes are beginning to appear in the last two spectra as the magnetic field starts to weaken and slowly rotate away from the antisunward direction.

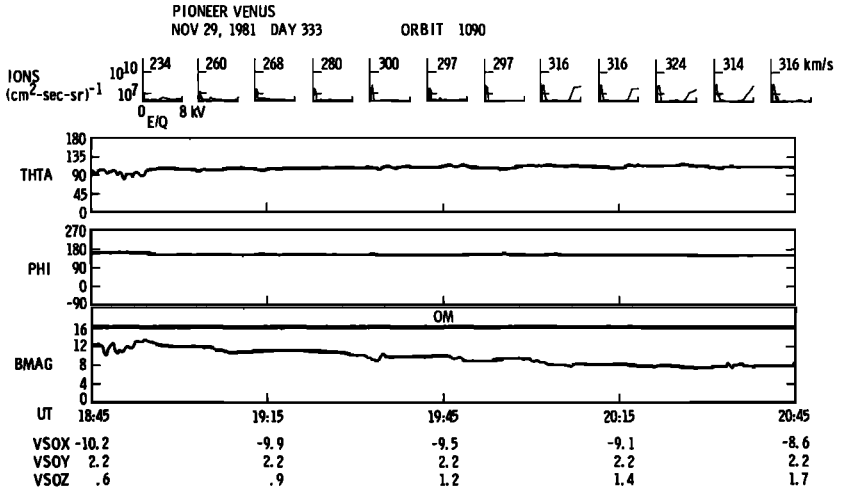

Fig. 2*e*. The same format as in the preceding figure, but for the interval 1845–2045 UT. Ions with E/Q 16 times that of the low-energy peak, corresponding to O^+ [*Intriligator*, 1982; *Mihalov and Barnes*, 1982], are apparent in the scans after 2000 UT. Antisolar plasma flow speeds for protons derived from fitting Maxwellians to the low-energy ion peaks are printed in each of the upper panels. Note the gradual increase in flow speed.

Oxygen ions possessing a bulk speed much in excess of 300 km/s possess an E/Q exceeding 8 kV and cannot be measured with the Pioneer Venus plasma analyzer. Returning to Figure 2*a*, the portion of the PVO orbit within the magnetotail, but lacking measurable plasma ion fluxes, is indicated with an empty curved rectangle while the part with measurable H^+, the outer mantle, is marked with stippling. The portions of the orbit where H^+ and O^+ were detected, i.e., after 2000 UT, are indicated with crosses. The highest O^+ fluxes measured during this orbit were observed at 2110 UT. Note the low bulk flow speeds, 270–280 km/s, which are required before the high end of the O^+ spectrum can be observed. No O^+ was detected outside of the tail, as defined by the magnetic field data, but this may be due to the >300 km/s flow speeds typical of the distant ionosheath. The irregular, perhaps time aliased shapes of the distributions make it difficult to determine an absolute density, but the O^+ number density was approximately 1% of that of the H^+ as found by previous studies [*Intriligator*, 1982; *Mihalov and Barnes*, 1982].

The O^+ events in Figures 2*e* and 2*f* were often accompanied by crossings of the cross-tail current layer and the broader plasma sheet region indicated by the strong decrease in field intensity. This is particularly true for O^+ events where the flow speed was well below 300 km/s and the full distributions where observed such as between 2045 and 2150 UT. These events are also remarkable in that they began with jumps across the current sheet of almost 180° in the phi angle of the magnetic field (i.e., prior to 1800 UT), but decreased with each succeeding crossing until the tail is exited shortly after 2145 UT. This general correlation between slow moving O^+ and crossings of the cross-tail current sheet, often with $\Delta phi < 180°$, is a common feature of the Venus magnetotail. However, as demonstrated in Figures 2*b* and 2*c* (e.g., 1430–1600 UT), it should also be noted that the PVO plasma analyzer sometimes does not detect any significant 0–8 kV ion fluxes within the boundaries of the current sheet or the plasma sheet as determined by magnetic field observations. One explanation offered by *Slavin et al.* [1984] was that these regions

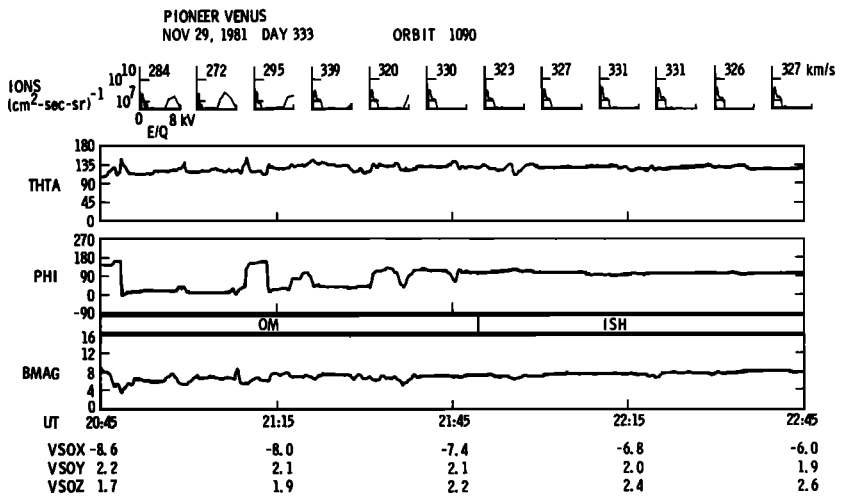

Fig. 2*f*. The same format as in the preceding figure, but for the interval 2045–2245 UT. Note the slower flow speeds obtained for the spectra containing the highest O^+ fluxes and their coincidence with a series of current sheet crossings. Finally, it is seen that as the current sheet intensity (i.e., the magnitude of the jumps in phi angle) decreases with each succeeding encounter the plasma spectra and field observations return to typical ionosheath values.

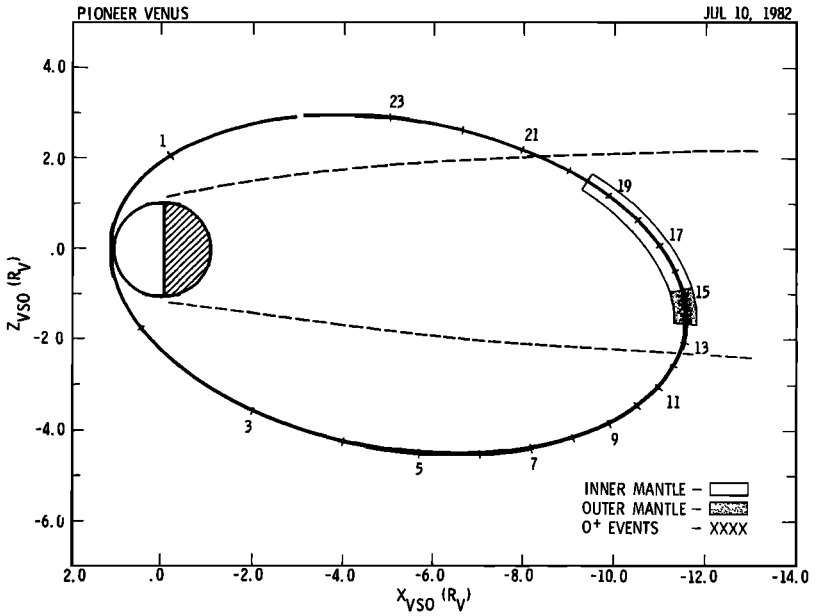

Fig. 3*a*. The Pioneer Venus orbit for July 10, 1982, is plotted with the tail regions indicated as in Figure 2*a*. Note that for this traversal the O^+ ions were observed only in the southern portions of the tail.

of the distant Venus plasma sheet where no ions are observed might be dominated by O^+ ions moving faster than 310 km/s and therefore not detectable by the PVO analyzer. While this hypothesis is quite speculative, particularly since O^+ is rarely observed to exceed 1% of the total ion density, it is of interest to note that at least one MHD model of the Venus tail has been published recently which does predict plasma sheet flow speeds of 300–500 km/s at distances of $X = -10$ to -12 R_V [*McComas et al.*, 1986].

July 10, 1982

A PVO orbit passing through the central magnetotail during an IMF $B_y < 0$ sector is considered in Figures 3*a*–3*e*. On July 10, 1982, the entry into the Venus magnetotail begins near 1400 UT in Figure 3*b*. Prior to that time typical shocked solar wind H^+ and He^{++} ion spectra were observed in conjunction with a slightly northward IMF in negative B_y sector (i.e., 180° < phi < 360°). The PVO entry into the tail on this occasion was marked by a gradual decrease in the solar wind ion flux as O^+ ions appear at high E/Q. The magnetic field signature is a very slow rotation into a more lobe-like configuration which is most evident in the phi angle. As in the preceding case, the O^+ fluxes tend to be accompanied by excursions into the diamagnetic cross-tail current layer, such as near 1500 UT. However, the converse need not be true with current sheet crossings later showing no significant ion fluxes. It was not until approximately 1515 UT that the magnetic field reaches its full lobe field strength, indicated by the cross-hatch lobe identifier. The ion flux fell to background levels between 1515 and 1700 UT as PVO moved from $Z = -0.8$ to $+1.5$ R_V. After 1700 UT the spacecraft observed no significant $E/Q = 0$–8 kV ion fluxes independent of the tail region identifications based upon the magnetic field data.

The outbound exit from the tail in Figure 3*e* was rapid with

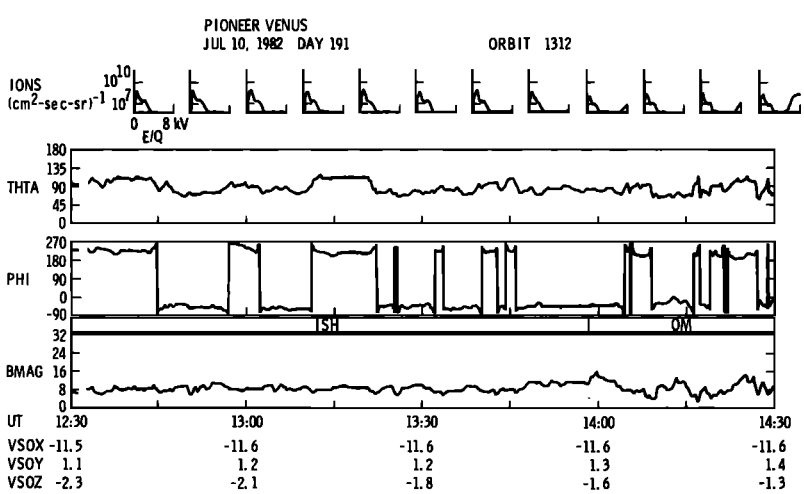

Fig. 3*b*. Plasma spectra and magnetic field observations for 1230–1430 UT are displayed. Typical shocked solar wind H^+ and He^+ spectra are observed until just before 1400 UT when the low-energy ion fluxes begin to decrease and the low E/Q shoulder of the O^+ distribution begins to appear.

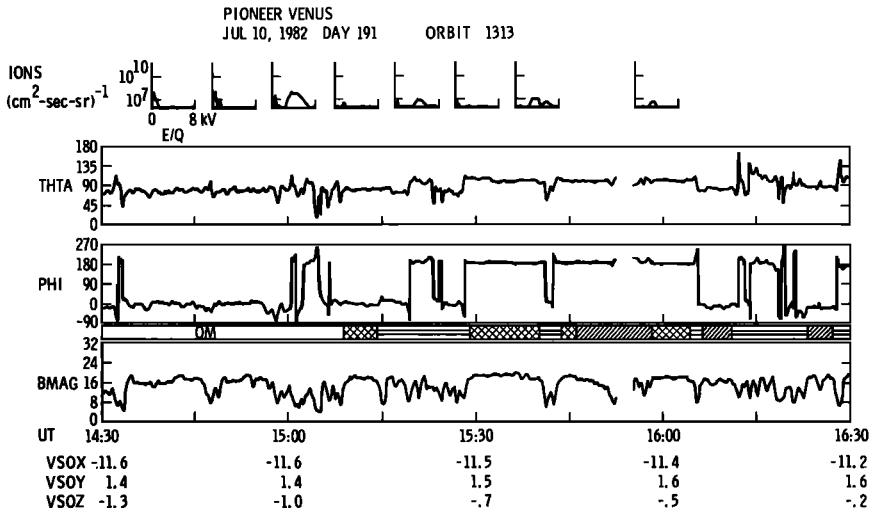

Fig. 3*c*. Plasma spectra and magnetic field for 1430–1630 UT are displayed. Note that no plasma ions are observed after approximately 1510 UT.

a sudden decrease in field strength and a change in field direction accompanying the reappearance of shocked solar wind ion spectra. Only a small ion flux increase was observed in the last full spectrum prior to exiting into the ionosheath. Hence it was observed that the boundary between the tail and ionosheath on the side with the more extensive outer mantle of H^+ and O^+ ions resembled a broad slow mode expansion fan with the plasma density slowly decreasing as the magnetic field increased in strength and rotated into a taillike configuration. The boundary on the opposite side of the tail, in contrast, was a relatively thin, magnetopauselike current layer. Finally, comparison with the November 29 observations also indicates that a reversal in IMF sector polarity from positive to negative results in the H^+ and O^+ fluxes shifting from the $Z > 0$ half of the tail to $Z < 0$.

October 1, 1983

A third example of a PVO central tail traversal is displayed in Figures 4*a*–4*d*. This case, October 1, 1983, is of particular interest because, along with November 29, it corresponds to one of the longest intervals of continuous tail observations by PVO identified in this study. In the interest of brevity, only the latter half of this traversal showing the transition from the $Z < 0$ region containing measurable H^+ and O^+ fluxes to the "empty" $Z > 0$ portion of the tail is displayed. As with the July 10 event, Venus was in a negative IMF B_y sector. A reduction in the ionosheath ion flux and the appearance of the low E/Q shoulder of the O^+ distribution (not shown) began around 1015 UT with the spacecraft 2.6 R_V beneath the Venus orbital plane. Consistent with the two previous cases, no O^+ ions were detected outside of the tail. With the exception of a short period of high, steady fields and abscent ion fluxes around 1120–0045 UT, variable H^+ and O^+ distributions were observed throughout the inbound half of the tail pass. The crossing into the $Z > 0$ region of the tail shown in Figure 4*b* took place around 1500 UT. Just prior to that time, 1415–1445 UT, slow-moving O^+ is present in conjunction with a series of cross-tail current sheet crossings. The outbound half of the magnetotail in Figure 4*c* was characterized by no measurable ion fluxes in either the magnetic lobes (cross-hatched) or plasma sheet (horizontal line) regions as was also the case for the July 10, 1982, negative IMF B_y tail passage

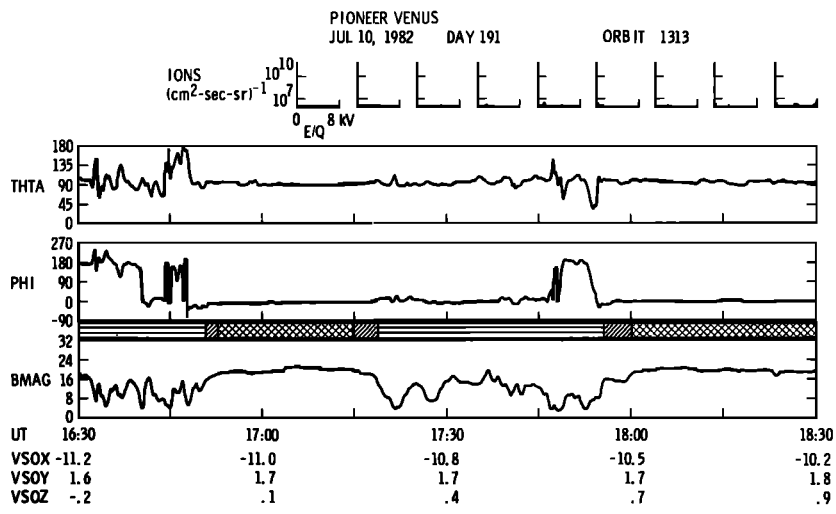

Fig. 3*d*. Plasma spectra and magnetic field observations for 1630–1830 UT are displayed. During this interval tail motion continues to produce encounters with the plasma sheet and both lobes.

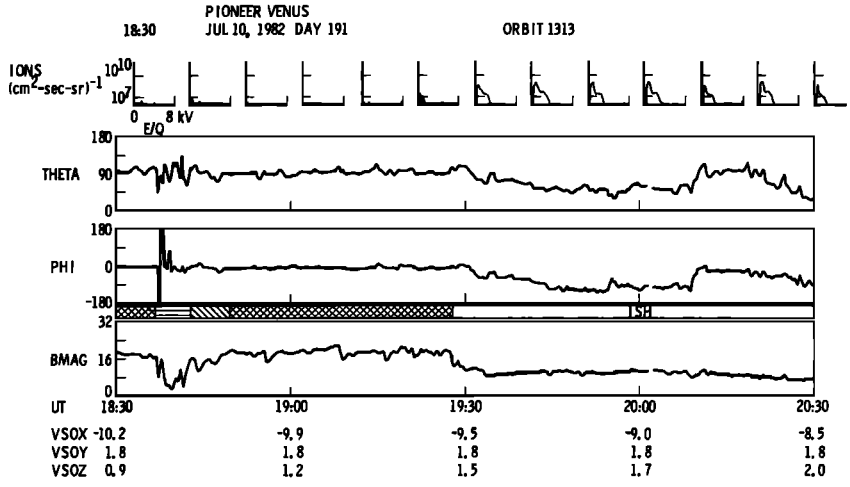

Fig. 3e. Plasma spectra and magnetic field observations for 1830–2030 UT are displayed. The exit from the tail just before 1930 UT is rapid and resembles the magnetopause at Earth.

considered earlier. Again, in the last spectra taken before the spacecraft exited the tail into the ionosheath there were only small fluxes of ions at low E/Q, presumably H^+, suggesting that little solar wind plasma enters from the ionosheath on this side of the tail. The outer boundary on the $Z > 0$ side of the magnetotail appeared to be a thin current layer across which the field decreased in magnitude and rotated to assume a negative IMF B_y ionosheath orientation as shocked solar wind H^+ and He^{++} reappeared.

To summarize, the three representative PVO traversals of the central magnetotail presented here have shown that the half of the tail containing measurable H^+ and O^+ in Figures 2, 3, and 4 corresponds to the region downstream of the Venus hemisphere over which the solar wind motional electric field, $E_{sw} = -V_{sw} \times B_{sw}$, is directed outward. The outer boundary of the tail on this side of the tail has also been shown to resemble a very broad slow mode expansion fan. In contrast, the tail boundary downstream of the Venus hemisphere over which E_{sw} is directed inward and the tail is relatively devoid of plasma appears to be a narrow current sheet much like the terrestrial magnetopause.

Additional Current Sheet–O^+ Events

The preceding examples were directed toward an examination of how magnetic field and plasma parameters in the Venus magnetotail vary along PVOs south to north trajectory in response to different IMF orientations. An additional result was the observation of a correlation between the appearance of O^+ ions and encounters with the cross-tail current sheet in the half of the tail containing measurable H^+ and O^+ ions. Figures 5 and 6 provide further examples of O^+ fluxes observed in or near the cross-tail current layer. They are significant in that they contain some of the most fully observed O^+ distributions found in this study and therefore may be considered as "best" examples of oxygen ions in the Venus magnetotail.

On October 3, 1983, Venus was in a positive IMF B_y sector and the PVO plasma analyzer observations of O^+ ions were primarily in the $Z > 0$ half of the tail consistent with the earlier case studies. For the interval displayed in Figure 5 the initial appearance of the O^+ ions was between 1615 and 1650 UT. Given the 10-min cycle time of the plasma analyzer, the correlation between the observation of O^+ and current sheet crossings is quite impressive with the O^+ ions appearing within minutes of the cross-tail current layer crossings. During the ~30-min interval between 1650 and 1715 UT there were no current sheet crossings and only H^+ was present in the ion spectra. The O^+ ions return with the reappearance of current sheet crossings after 1715 UT. As noted earlier, the current sheet during many of the O^+ events was weaker, $\Delta phi = 140°–160°$, than is generally the case in the half of the tail where no measurable ion fluxes are present.

The October 5, 1983, observations in Figure 6 are displayed in spite of this orbit not having satisfied all of the criteria required for the 12 cases listed in Table 1. The reason for its inclusion here is the presence of an exceptionally clear observation of O^+ ions in the cross-tail current layer near 1647 UT. Earlier in the pass (not shown) multiple correlated O^+–current sheet crossings were observed as is typical for the events examined in this study. The interval displayed in Figure 6 is unusual in that it contains single isolated current sheet crossing. The E/Q spectrum completed just as the cross-tail current sheet was crossed shows both H^+ and O^+ ions. The fact that the complete O^+ distribution falls within $E/Q < 8$ kV indicates that the flow speed was significantly less than 300 km/s. As PVO receded from the current sheet, the flow speed increased and only the low E/Q shoulder of the O^+ distribution was observable in the next plasma analyzer scan. After 1700 UT the magnetic field becomes less taillike, typical ionosheath H^+–He^{++}spectra return, and no further O^+ ions are observed. These current sheet–O^+ events serve to illustrate both the effects of flow speed on the detectability of O^+ by the PVO plasma analyzer and the clear presence of slow moving oxygen ions in the Venus cross-tail current layer.

DEPENDENCE OF O^+ EVENT LOCATION ON IMF DIRECTION

Table 1 summarizes each of the 12 Pioneer traversals of the central Venus magnetotail considered in this study. As indicated, the continuous intervals in the central Venus tail with good telemetry coverage varied in length from 3.5 to 8.5 hours, most probably reflecting the flapping and wind socking of the distant tail in response to changes in solar wind speed and flow direction as is also observed for the Earth's distant tail [e.g., *Slavin et al.*, 1984]. As mentioned earlier, two meth-

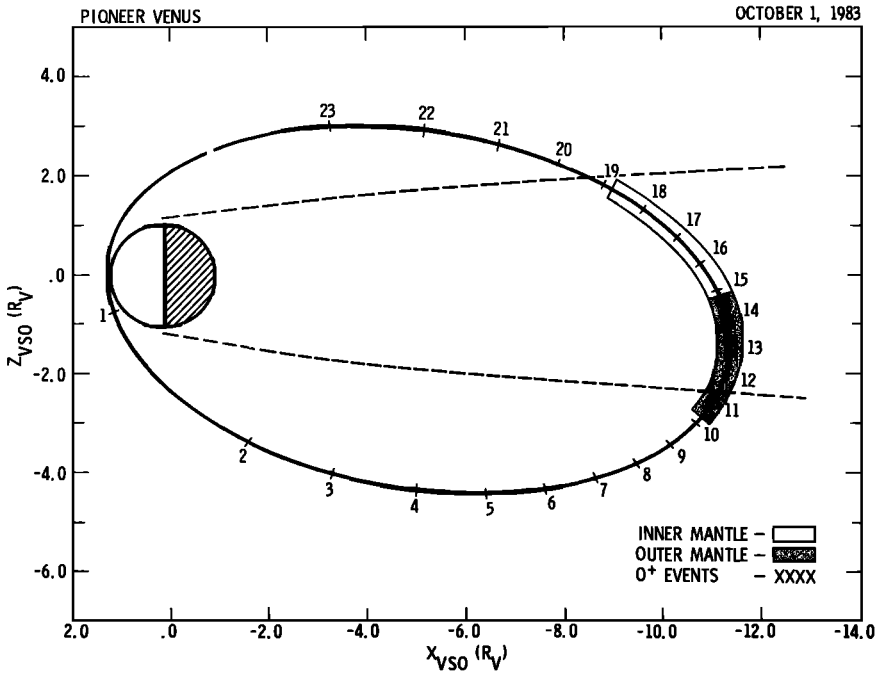

Fig. 4*a*. The Pioneer Venus orbit for October 1, 1983, is plotted with the tail regions indicated as in the previous figures. As in the case of the July 10, 1982, observations, IMF B_y was negative and the O^+ events were observed only south of the Venus orbital plane.

ods were employed to infer upstream IMF orientation transverse to the tail axis during these events. The most direct approach is to examine the polarity of the B_y component of the IMF during the portions of the orbits when PVO is in the distant ionosheath or solar wind. The results are shown in the column at the far right. The primary limitation of this method is that IMF direction cannot always be accurately determined given the small amount of time spent at large distances from the tail and the distorting effects of the bow shock. For this reason average B_y and B_z values of the tail field were also calculated for each tail crossing. Given the draped-field origin of the Venus tail field [e.g., *McComas et al.*, 1986], the direction of the cross-tail field should be identical to that of the upstream IMF for quasi-stationary conditions. Indeed, comparison of the polarities of the average B_y component of the tail field and the IMF B_y in Table 1 shows good consistency with no disagreements when clear sector identifications are listed in the far right-hand column.

As indicated in Table 1, O^+ was observed in the magnetotail during all 12 central tail traversals identified in this study. On these occasions no O^+ was measured outside of the tail as determined by the magnetic field data and the definitions adopted in this study. For 10 of the 12 cases the oxygen ions were observed only on one side of the $Z = 0$ plane during each tail passage. Inspection of the locations of the O^+ events and IMF B_y polarities listed in Table 1 confirms the hypoth-

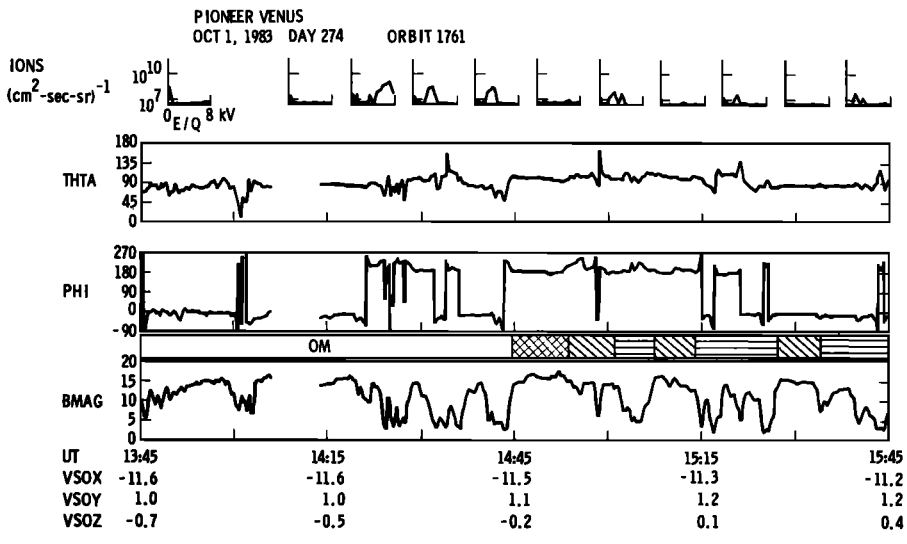

Fig. 4*b*. Plasma spectra and magnetic field observations for 1345–1545 UT are displayed. Note the close correspondence between the observation of O^+ ions in the E/Q spectra and the encounters with the cross-tail current sheet evident in the phi angle of the magnetic field.

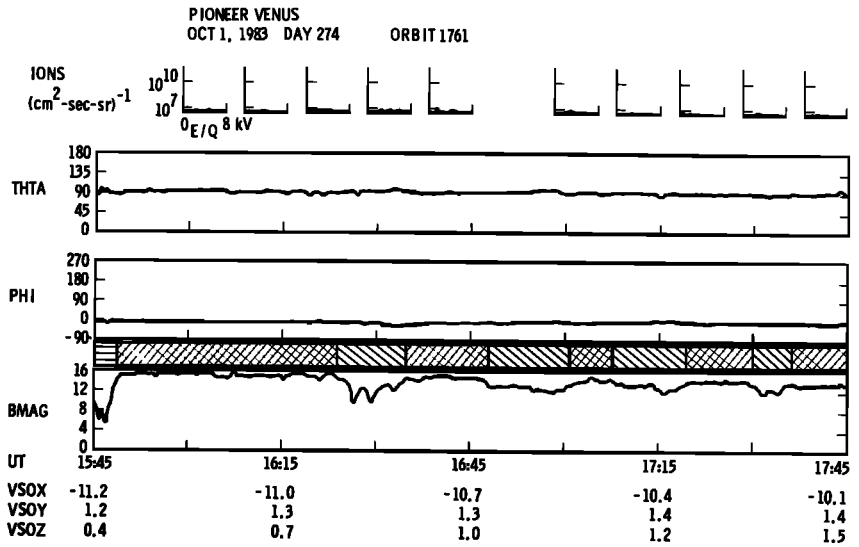

Fig. 4*c*. Plasma spectra and magnetic field observations for 1545–1745 UT are displayed. As in the preceding case studies, no detectable ion fluxes are apparent in the half of the tail downstream of the Venus hemisphere over which the ionosheath motional electric field possesses a component directed in toward the planet.

esis suggested by the case studies considered earlier, i.e., the observation of O^+ ions below the Venus orbital plane is associated with negative IMF B_y and O^+ ions above the orbital plane are accompanied by positive IMF B_y. As will be discussed, this correlation strongly suggests that these ions are indeed associated with the asymmetric "pickup" of newly ionized atmospheric neutrals in agreement with the theoretical model of *Cloutier et al.* [1974].

DISCUSSION

The interplanetary origin of the magnetic flux tubes in the Venus tail was first demonstrated in the Venera 9 and 10 observations as displayed in Figure 7. In the top panel, adapted from *Eroshenko* [1979], the polarity of the tail magnetic fields are plotted in a coordinate system where the VSO Y and Z axes have been rotated about the Sun-planet line until the horizontal axis is parallel to the component of the IMF transverse to the Sun-planet line. As shown, the polarity of the Venus tail lobes were well ordered in this coordinate system and possessed the orientation expected for draping. Indeed, it was largely on this basis that *Eroshenko* [1979] correctly concluded that Venus tail fields must have an interplanetary as opposed to a planetary origin. This finding was confirmed and extended by *Saunders and Russell* [1986] using the much larger PVO data base as depicted in the bottom panel of Figure 7. The result is a $\sim 4\ R_V$ diameter magnetic tail composed of IMF field lines draped about the dayside ionosphere as well as field lines which have just recently slipped past the planet and are in the process of moving downstream.

The plasma environment of the Venus magnetotail was also first investigated by Venera 9 and 10 [*Gringauz et al.*, 1976; *Vaisberg et al.*, 1976; *Verigin et al.*, 1978]. Figure 8, adapted from *Verigin et al.* [1978], summarizes some of their results with respect to the ions and electrons within the tail lobes and the cross-tail current layer. The low-to-medium inclination of the Venera 9 and 10 orbits caused these spacecraft to spend

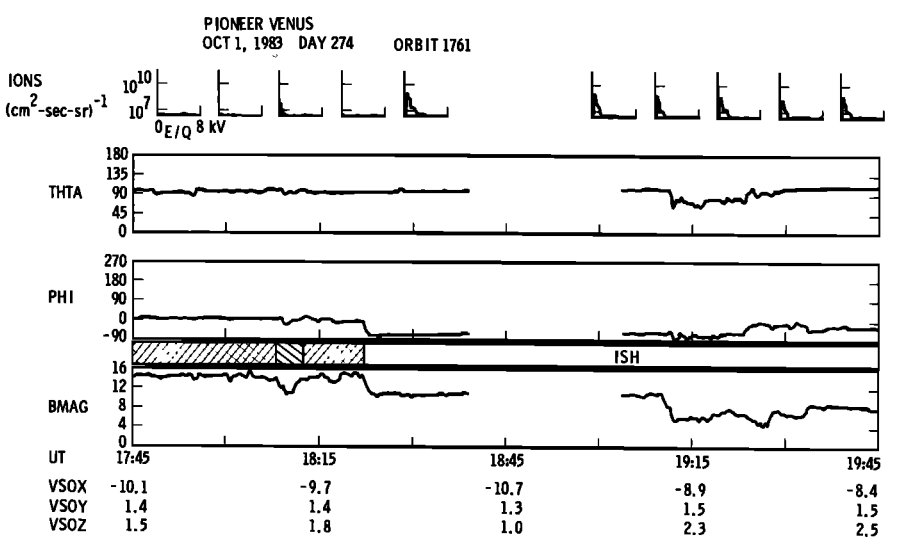

Fig. 4*d*. Plasma spectra and magnetic field observations for 1745–1945 are displayed. The exit from the magnetotail was very rapid with little or no outer mantle adjacent to the outer boundary.

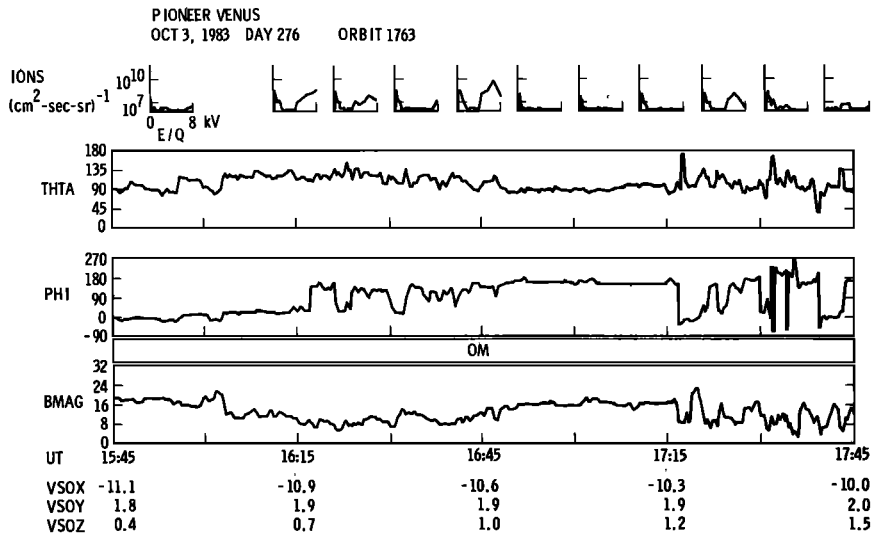

Fig. 5. Plasma spectra and magnetic field measurements for 1545–1745 UT on October 3, 1983. Note the correlation between the appearance of O^+ in the plasma ion spectra and encounters with the cross-tail current sheet in the magnetic field observations.

most of their tail passages in the lobe regions with only relatively rapid crossings of the plasma sheet [*Verigin et al.*, 1984]. The Venera electron and ion observations in the lower panels of Figure 8 show a gradual decrease in the flux levels as the spacecraft moves closer to the tail axis. This region of decreasing plasma flux within the magnetic tail was termed the "penumbra" or "mantle" [e.g., *Verigin et al.*, 1978; *Vaisberg and Zeleny*, 1984]. While not specifically addressed by the Venera investigations, the distribution of plasma within the Venus magnetotail has generally been assumed to possess axial or bilateral symmetry with respect to the X axis and the plane of the IMF, respectively [e.g., *Vaisberg and Zeleny*, 1984]. However, careful inspection of well documented Venera 9 and 10 tail passages at $X = -3$ to -6 R_V, e.g., Dec. 17, 1976 [*Verigin et al.*, 1984], does appear to show asymmetries in ion flux similar to those present in the Pioneer Venus measurements.

The top panel of Figure 8 displays ion spectra taken with the Venera plasma analyzer spectrum, $E = 0$–4 keV, just as the spacecraft encountered the cross-tail current layer as is evident from the reversal in the B_x component of the magnetic field. The appearance of a higher-energy ion population in the current layer was interpreted as evidence for substormlike acceleration processes in the Venus tail with both populations being assumed to be H^+ [*Verigin et al.*, 1978]. The PVO observations of escaping atomic O and O^+ at lower altitudes [*Brace et al.*, 1987], and the frequent measurements of ions separated from the H^+ peak by a factor of 16 in the vicinity of the cross-tail current layer reported by this study, strongly suggest that both missions were observing singlely charged oxygen ions. Moreover, the observations of these ions in the cross-tail current by Venera also lends independent support to the correlation between O^+ and current sheet crossings reported here.

The most important result of this study is probably the strong north-south asymmetry in the magnetotail magnetic

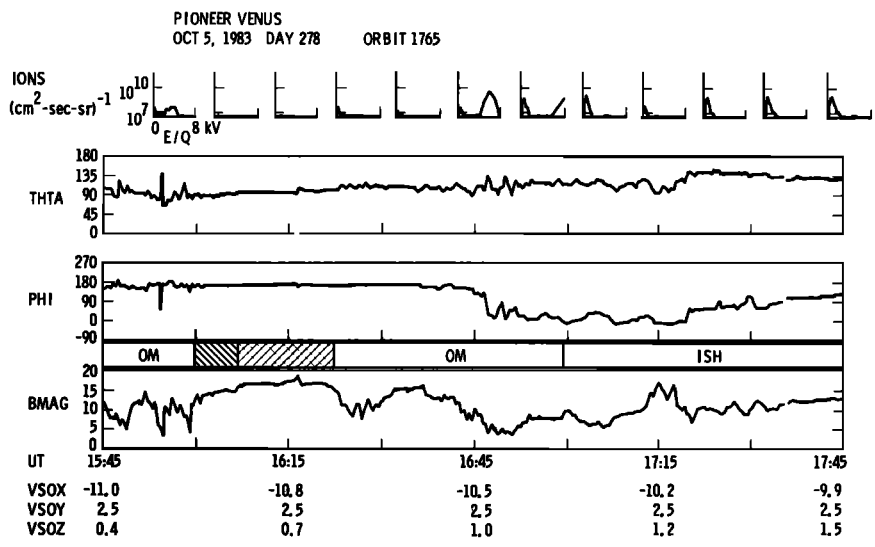

Fig. 6. Plasma spectra and magnetic field observations for 1545–1745 UT are displayed. The 1645 UT event is a very clean example of oxygen ions in the cross-tail current layer of the Venus magnetotail.

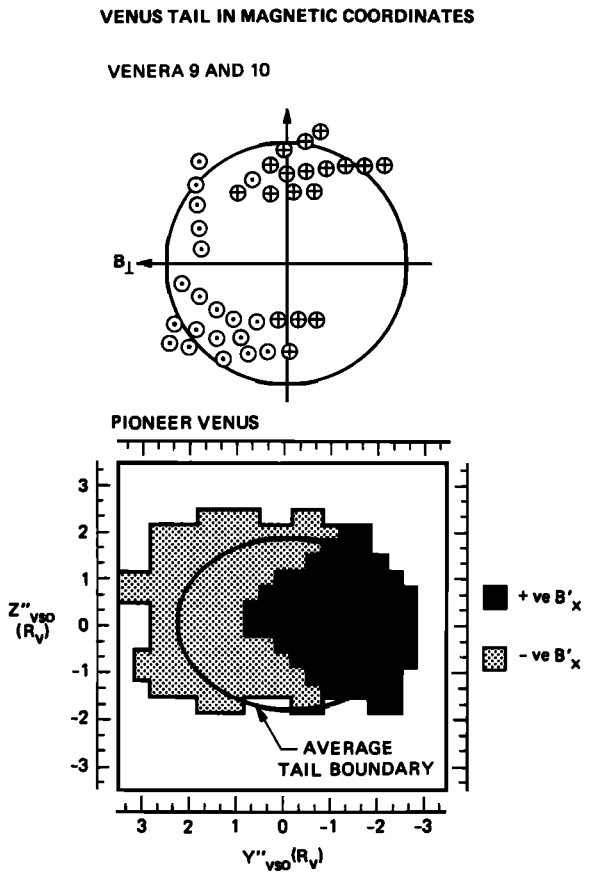

Fig. 7. The interplanetary origin of the Venus magnetic tail is evident in both the Venera 9/10 [*Eroshenko*, 1979] and PVO [*Saunders and Russell*, 1986] magnetometer observations when the polarity of the X component of the field is plotted as a function of spacecraft location in the Y-Z plane where these axes have been rotated so that the transverse component of the upstream magnetic field is along the $+Y''$ axis.

fields and plasma populations with respect to the plane of the IMF. The half of the tail downstream of the Venus hemisphere over which the ionosheath motional electric field, $E_{sw} = V_{sw} \times B_{sw}$, is directed inward contains few or no measurable 0–8 kV ions. The outer boundary on this side of the tail is a magnetopauselike current layer across which magnetic pressure appears sufficient to balance the ionosheath pressure [e.g., see *Slavin et al.*, 1984]. Downstream of the opposite hemisphere, however, increasing fluxes of 0–8 kV, H^+ and O^+ ions are observed as PVO moves outward from tail axis and periodically encounters the cross-tail current layer. Indeed, the boundary on this side of the Venus magnetotail resembles a broad, slow mode expansion fan with plasma density increasing as less strongly draped field lines are encountered.

While the finding of strong asymmetries in the Venus magnetotail represents a departure from the quasi-axially symmetric tail generally assumed on the basis of the Venera 9 and 10 investigations, they are in fact consistent the earlier PVO magnetic field draping and tail studies. The top panel of Figure 9, adapted from *Luhmann et al.* [1985], displays the intensity of the ionosheath magnetic field near the terminator plane as a function of altitude and IMF sector polarity. The solid (dashed) trace represents the PVO observations above (below) the orbital plane. The results for positive IMF B_y are displayed on the left and the negative B_y profiles are on the right. They show that the ionosheath magnetic field over the hemisphere where $E_{sw} = -V_{sw} \times B_{sw}$ is directed outward from the planet is greater than over the opposite hemisphere. They attributed this result to the braking/compressional effect of enhanced mass loading over the hemisphere favored by the finite gyroradius effects according to *Cloutier et al.* [1974]. The bottom panel, adapted from *Saunders and Russell* [1986], displays the magnitude of the cross-tail magnetic field in the $Y'' - Z''$ coordinates. Again, a strong asymmetry is present with the magnetic field normal to the cross-tail current layer being 2–4 times as large downstream of the outward directed $-V_{sw} \times B_{sw}$ hemisphere. This Saunders and Russell result is in agreement with the much smaller jumps in the phi angle of the magnetic field across the tail current observed on this side of the tail reported here (i.e., Δphi = 180° corresponds geometrically to very weak normal field components while Δphi = 140°–160° indicates much stronger normal components). Accordingly, the previous PVO magnetic field analyses, which have also been interpreted in terms of asymmetric mass loading, are consistent with the correlated magnetic field and pickup ion observations in the distant tail reported here.

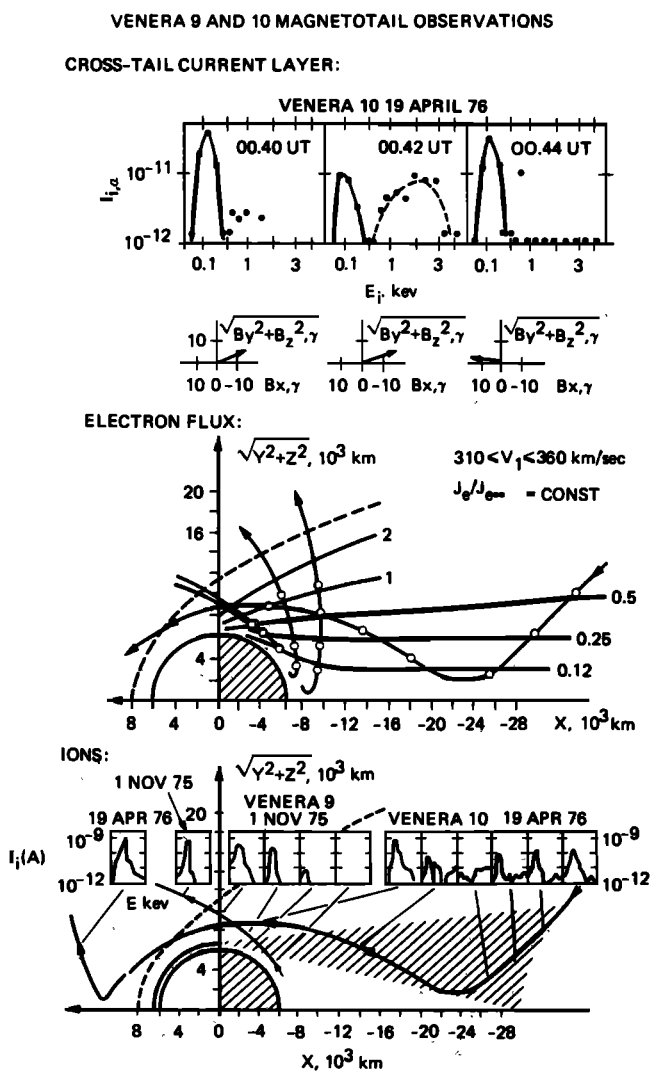

Fig. 8. (top) Venera 9 and 10 cross-tail current layer, (middle) electron flux, and (bottom) ion flux observations are displayed above (adapted from *Verigin et al.* [1978]). Note the presence of a second, higher-energy ion population in the cross-tail current layer (i.e., the region where B_x reverses polarity).

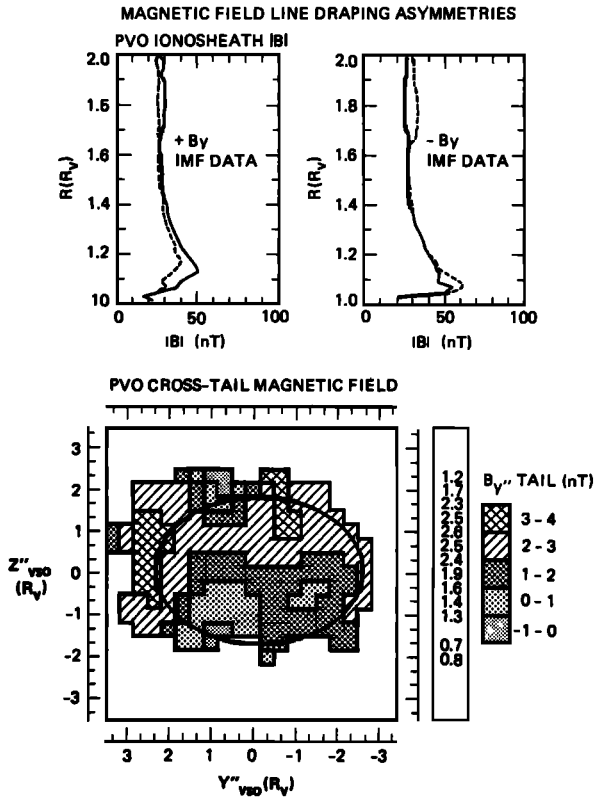

Fig. 9. Evidence for asymmetry in the pickup of ions at Venus has been reported in previously in the dependence of ionosheath magnetic field intensity over the north (solid line) and south (dashed line) geographic poles as a function of IMF B_y [*Luhmann et al.*, 1985] and in the mean B_y'' component of the magnetotail magnetic field [*Saunders and Russell*, 1986].

Figure 10 summarizes many of our results concerning the downstream effects of field line draping/mass loading at Venus. As shown, IMF B_y is assumed positive to the left for this diagram. Within the inner mantle the lobe field lines are depleted of plasma and bent back hairpin fashion to produce two lobes separated by a strong cross-tail current layer (i.e., Δphi $\sim$ 160°–180° or, equivalently, the normal field component to the sheet is relatively weak). This region is located predominantly downstream of the Venus hemisphere over which the $E_{sw} = -V_{sw} \times B_{sw}$ electric field has an inward directed component. As the spacecraft moves northward into the opposite hemisphere, a broad outer mantle region is encountered. The lobe magnetic field gradually weakens and rotates toward a less severely draped orientation as field lines possessing higher fluxes of H^+ and O^+ ions are observed. When motion of the tail sweeps the cross-tail current layer over the spacecraft, PVO observes less strongly kinked fields (i.e., Δphi = 140°–160°) and slow moving H^+ and O^+ ions. The tendency for the O^+ to be observed near the current sheet is an important new result which is consistent with these heavy ions being dynamically concentrated near the bend in the field lines as the Maxwell stress in the field lines attempts to accelerate the ions up to solar wind speeds [e.g., *McComas et al.*, 1986]. As a flux tube slips past the dayside ionosphere, pickup ions with significant velocity parallel to **B** will rapidly move down the field lines and be lost while 90° pitch angle ions will remain in the cross-tail current sheet.

This study has also found the tail boundary downstream of Venus hemisphere over which the motional electric field is outward to possess a broad, expansion fanlike structure while the boundary downstream of the opposite hemisphere resembles a thin magnetopauselike current layer (i.e., a tangential discontinuity). The results suggest the possibility that the draped field magnetotail of Venus may be resupplied with magnetic flux tubes in an asymmetrical fashion. In this case the interplanetary flux tubes would become slowed and bent back into the tail predominantly over the hemisphere favored for ion pickup by virtue of its outward directed ionosheath motional electric field. Ionosheath field lines slipping past the other hemisphere would experience much less slowing due to mass loading and not be bent back into the tail. The strongly draped "inner mantle" flux tubes at $X = -8$ to -12 R_V found in this study to be relatively depleted of plasma may then correspond to "older" flux tubes which were bent back into the tail over the hemisphere favored for mass loading, slipped past the planet, and then were eventually transported into the region downstream of the opposite hemisphere. The reason for this meridional transport of flux tubes from the half of tail containing more plasma to the opposite half would be a pressure gradient produced by the reduced rate of flux tube addition over the Venus hemisphere not favored for ion pickup. The absence of detectable H^+ and O^+ in the inner mantle downstream of the nonmass loaded hemisphere of Venus is then caused by the loss of small pitch angle ions to flow parallel these field lines while the flux tubes were being transported from one side of the tail to the other.

SUMMARY

In this investigation Pioneer Venus magnetic field and plasma measurements have been examined during 12 well observed traversals of the central magnetotail at downstream distances of $X = -8$ to -12 R_V. The results indicate that (1) H^+ and O^+ ions were observed for all 12 traversals in the portions of the lobes and plasma sheet downstream of the Venus hemisphere over which the $E = -V_{sw} \times B_{sw}$ motional electric field in the ionosheath is directed outward from the planet. (2) The O^+ distributions were measured most completely in the cross-tail current layer where the bulk antisunward flow speed is inferred to be slowest. No O^+ ions were observed exterior the tail where the ionosheath flow speeds are typically too high to allow their detection with the PVO plasma analyzer. (3) The outer boundary of the Venus tail varies from a thin, magnetopauselike current layer downstream of the Venus hemisphere over which the $-V_{sw} \times B_{sw}$ motional electric field has an inward component to a broad, slow mode expansion fan over the half of the tail surface downstream of the opposite hemisphere. (4) Independent of whether O^+ ions exist only in the cross-tail current layer, or if it is only in that region that their speeds are low enough to be observable by the PVO plasma analyzer, the results of this study demonstrating strong IMF control of distribution of plasma within the tail argue convincingly for the heavy ions in the Venus tail originating with the ionization and pickup of atmospheric neutrals. (5) Finally, the strong asymmetries within tail and the nature of the outer boundary suggest the possibility that new magnetic flux tubes are supplied to the tail preferentially over only one Venus hemisphere at any given time, i.e., the hemisphere adjacent to the portion of the ionosheath where the $-V_{sw} \times B_{sw}$ motional electric field is directed outward from the planet and the ion pickup rate is highest. These observations are in qualitative agreement with the mass loading models of magnetic tail formation at Venus

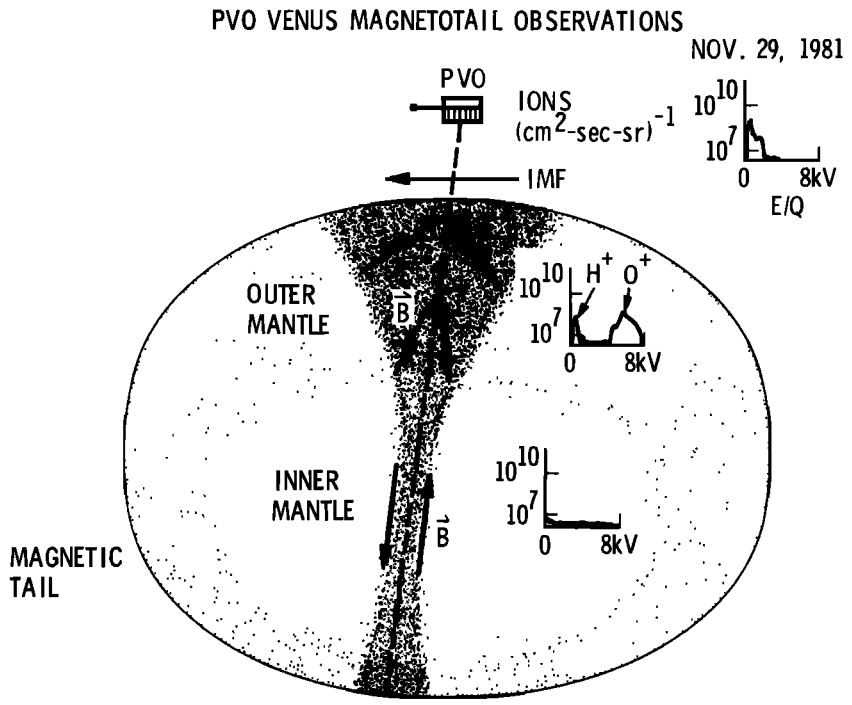

Fig. 10. A schematic diagram of the magnetic field and plasma conditions within the Venus magnetotail based upon the PVO observations reported in this study.

[*Vaisberg and Zeleney*, 1984; *McComas et al.*, 1986]. However, not included in these MHD models are the tail asymmetries reported here which appear to be associated with the IMF control of new ion pickup in the manner predicted by *Cloutier et al.* [1974]. It appears clear that further experimental and theoretical modeling will be necessary before these new aspects of the Venus magnetic tail can be quantified and their implications for the global interaction understood.

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