Average Dimension and Magnetic Structure of the Distant Venus Magnetotail

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We report the first major statistical investigation of the far wake of an unmagnetized object embedded in the solar wind. The investigation is based on Pioneer Venus Orbiter magnetometer data from 70 crossings of the Venus wake at altitudes between 5 and 11 Venus radii during reasonably steady IMF conditions. We find that Venus has a well-developed tail, flaring with altitude and possibly broader in the direction parallel to the IMF cross-flow component. Tail lobe field polarities and the direction of the cross-tail field are consistent with tail accretion from the solar wind. Average values for the cross-tail field (2 nT) and the distant tail flux (3 MWb) indicate that most distant tail field lines close across the center of the tail and are not rooted in the Venus ionosphere. We illustrate our findings in a three-dimensional schematic.

1. INTRODUCTION

The first suggestions that Venus has a magnetotail came from the wake passages in October 1967 by the Mariner 5 flyby and by the Venera 4 entry probe [Russell, 1976]. Confirmation came in 1975 and 1976 when the Venera 9 and 10 orbiters detected changes in the near wake similar to those seen in crossing the earth's magnetotail [Dolginov et al., 1978]. Did the magnetotail arise from the downstream extension of an intrinsic planetary magnetic field, or did it arise from accretion of interplanetary magnetic flux, as Alfvén [1957] proposed for comet tail formation?

The Pioneer Venus Orbiter (PVO) reached Venus in December 1978 and soon confirmed that Venus's magnetic field was very small (planetary magnetic moment less than 4 × 10⁻⁵ of the terrestrial moment [Russell et al., 1980a]). This finding supported the views of Eroshenko [1979] from Venera 9 and 10 recordings and of Dubinin et al. [1978] from laboratory simulations that the Venus tail is accreted from the solar wind. Studies by Luhmann and Russell [1983] and Marubashi et al. [1985] of magnetic field orientation in the nightside ionospheric density depletions called "holes" further supports this view. The consensus now favors tail accretion, but a detailed examination of distant tail magnetic data has not been made to definitively test this theory. PVO's orbit and extended mission mean the data base for this study now exists.

PVO bisects the wake either near periapsis (∼150- to ∼2500-km altitude) or near apoapsis (∼5–11 Venus radii (RV) altitude); its polar orbit precludes tail encounters at intermediate altitudes. The orbit is fixed in inertial space, so apoapsis crosses the nightside once a Venus year (224.7 days). During each such crossing, PVO makes about 15 passes through the distant tail. Further information on the PVO orbit and its evolution may be found in the article by Fimmel et al. [1983] and Brace and Colin [1984].

Previous PVO studies of the Venus tail used only a limited magnetometer data base. Russell et al. [1981] (also see Russell et al. [1982] and Russell and Vaisberg [1983]) examined magnetometer and plasma wave data from the first nightside apoapsis passage. They identified a well-developed tail with properties resembling expectations for an accreted tail. Slavin et al. [1984], in comparing distant magnetotail structure at Venus and at earth, analyzed plasma, magnetometer, and plasma wave data from a further three apoapsis wake passages. These authors report that both magnetotails possess similar plasma and magnetic field regimes.

Here we extend these initial studies by examining magnetic field recordings from the nine PVO apoapsis wake passages through May 1984. The paper divides as follows: recent examples of typical Venus distant tail magnetometer data are shown in the next section together with examples of high time resolution recordings from clear magnetopause crossings. Section 3 presents our findings for the average dimension of the Venus tail. Statistical results for the tail's average magnetic structure are described in section 4. This section also addresses whether the tail's magnetic geometry is consistent with an accretion origin. Section 5 outlines a simple model interpretation for our findings and includes a three-dimensional schematic for the Venus wake magnetic structure. Conclusions and important remaining questions are in section 6.

2. OBSERVATIONS

2.1. Format and Tail Identification

Figures 1-4 display PVO magnetometer records [Russell et al., 1980b] for four representative passes through the distant Venus magnetotail when the IMF is reasonably steady. These observations are 1-min averages in spacecraft coordinates (approximately solar ecliptic). Apoapsis and periapsis are marked (the latter occurring within the subsolar region of high magnetosheath field strength), together with the interval when PVO is judged to be inside the magnetotail. PVO's position is shown at the base of each figure in Venus radii using Venus Solar Orbital (VSO) coordinates. The VSO system is analogous to GSE coordinates but employs the Venus orbital plane for the X-Y plane with Venus orbital motion in the −ZVSO direction.

We use three criteria for identifying the Venus tail in magnetometer data. It is the region in the wake where (1) the magnetic field strength differs from that in the surrounding magnetosheath, (2) the field direction is oriented more parallel, or antiparallel to the X direction (or the solar wind direction), and (3) the spectrum of field fluctuations sometimes change. Even with these criteria our identification of tail encounters is sometimes uncertain, as our examples will demonstrate.
2.2. Orbit 1087

Figure 1 shows a magnetotail crossing (orbit 1087) during the fifth apoapsis tail passage. Within the tail the field magnitude is generally enhanced, and the field orientation more \(X\) directed compared with the surrounding magnetosheath field.

We identify these regions as the lobes; on this orbit they have mainly a positive \(B_x\) character. Field strength decreases below IMF values are also apparent. We associate these regions with the Venus equivalent of the terrestrial central tail current sheet and plasma sheet. (In the accreted magnetotail picture (Figures 19 and 20) these are located between the two tail lobes of

Fig. 2. One-minute average magnetic field measurements in spacecraft coordinates spanning 19\(\frac{1}{2}\) hours during orbits 1760 outbound and 1761 inbound on October 1 and 2, 1983. This interesting magnetotail crossing occurs during fairly steady IMF conditions and shows characteristic features such as the two tail lobes of opposite field polarity and the central tail current sheet.
opposite field polarity on formerly hung up field lines which are reaccelerating to the solar wind speed. The magnetic geometry resembles that downstream of the tail X line at earth).

The tail boundary (magnetopause) traversal at 2030 UT appears well defined. Tail entry, however, is less certain and could be placed as early as 1330 UT, though our criteria favor a time close to that indicated. These identifications indicate that entry occurs into the plasma sheet, with exit from the lobe.

The interplanetary magnetic field (IMF) is encountered outside the bow shock at 0205 UT. Although more than 11 hours have passed since the initial tail encounter, there is no indication that the IMF changes direction in the interim. We note that the IMF cross-flow or YZ component is directed mainly in the −Y direction. In the tail accretion model it is this IMF component which should control magnetic field structure within the tail.

2.3. Orbit 1760/1761

Our second data example (orbit 1760/1761) comes from the eighth apoapsis wake crossing and is shown in Figure 2. The format is identical to Figure 1. Due to equatorward motion with time of orbit periapsis, this magnetotail traversal is centered close to apoapsis than that on orbit 1087.

The $B_z$ component in Figure 2 reveals the presence of both positive and negative polarity lobe fields, with the positive polarity dominant later. The extended interval of unidirectional field during the latter third of the crossing indicates that steady lobe fields can persist for at least $2\frac{1}{2}$ hours (also see the 1715–1930 UT interval in Figure 1). As in Figure 1 the lobe field is oriented closer to the $X$ direction than the magnetosheath field.

The tail magnetopause crossings are well defined with entry occurring into the plasma sheet and exit taking place from the positive polarity tail lobe. The IMF appears to be fairly steady throughout the tail passage, with its cross-flow component pointing principally in the −$Y$ direction.

2.4. Orbit 1765/1766

The tail recordings in Figure 3 were made five orbits after those in Figure 2 and illustrate an important point when compared with our two previous examples. The IMF in Figure 3 (encountered between 0025 and 0310 UT) is directed opposite to that in Figures 1 and 2, having an upstream cross-flow component oriented mainly in the +$Y$ direction. The dominant tail lobe polarity in Figure 3 is also opposite to that in Figures 1 and 2. In each case when account is taken of PVO's position, the sign of the lobe field polarity is consistent with an accreted magnetotail.

The tail passage on orbit 1765/1766 is briefer than our other examples because PVO, as shown by its larger $V_{X0}$ position coordinate, does not bisect so closely the central wake in its south-north trajectory through the tail. The tail magnetopause crossings in Figure 3 are studied in section 2.6.

2.5. Orbit 1312/1313

Figure 4 displays our final Venus tail example (orbit 1312/1313), this coming from the sixth apoapsis wake crossing. Slavin et al. [1984] recently published plasma recordings for the 1830–2030 UT interval on this orbit. These demonstrate that the tail exit at 1928 UT is clear in both plasma and magnetic field data sets; the plasma records only show significant ion fluxes after 1928 UT. We examine this magnetopause crossing in greater detail in section 2.6. The tail entry, in contrast, is difficult to identify, occurring somewhere between 1200 and 1400 UT.

The Figure 4 data also illustrate the difficulty in sometimes determining a reliable IMF direction for a tail passage. When the solar wind is encountered at 0155 UT the IMF has a positive $B_z$ component, which agrees with the direction of the draped magnetosheath field close to periapsis. In contrast, the directions of the magnetosheath field draped outside the tail and of the $B_z$ field within the tail both suggest a negative IMF $B_z$ component at this earlier time. An explanation could be that the IMF rotates at about 0005 UT. The uncertainty in
IMF direction, however, means that this tail pass is not included in our statistical survey.

2.6. Magnetopause Structure

Russell et al. [1982] and Russell and Vaisberg [1983] studied the magnetic structure of a single Venus magnetopause crossing by PVO and found evidence for connection between magnetotail and magnetosheath fields. In Figures 5–8 we extend this first observation by presenting magnetometer records for four further magnetopause crossings. Our examples come from the orbits in Figures 1–4 and are chosen because they represent unambiguous boundary encounters.

Fig. 4. Magnetic field recordings in spacecraft coordinates spanning 19.5 hours on orbits 1312 and 1313. This interval includes the period for which Slavin et al. [1984] published tail plasma measurements. The IMF direction is uncertain for this tail crossing.

Fig. 5. High-resolution (1 sample per second) magnetometer records for 15 min centered on the outbound Venus tail magnetopause crossing (tail lobe to magnetosheath) on orbit 1313. This boundary traversal resembles a rotational discontinuity. The main current sheet is bracketed by the vertical lines at 1927.28 and 1933.50 UT. The hodogram pair is plotted for this interval in minimum variance (i, j, k) coordinates. Eigenvalues associated with the minimum variance system are \((20.7, 9.4, 0.3) \text{ nT}^2\) and the direction of the eigenvector associated with the minimum eigenvalue is \((0.038, -0.621, -0.783)\) in spacecraft coordinates. The average field component \(B_x\) normal to the discontinuity is \((3.01 \pm 2.73) \text{ nT}\).
Unlike our statistical results in sections 3 and 4, our findings here should be considered as only an initial survey illustrating the types of discontinuities occurring at the Venus magnetopause.

We employ the minimum variance technique [Sonnerup and Cahill, 1967], a procedure widely used in studying the magnetic structure of the terrestrial magnetopause. It gives the direction, \( \mathbf{k} \), of the minimum variance in the magnetic field through a current layer. The \( \mathbf{k} \) direction defines the normal to the local magnetopause surface. The latter contains the directions of maximum, \( \mathbf{i} \), and intermediate, \( \mathbf{j} \), magnetic field variance such that \( \mathbf{i}, \mathbf{j}, \) and \( \mathbf{k} \) form a right-hand orthogonal set. Figure 5 illustrates the format of our magnetopause data presentation (the same format is employed in Figures 6–8). The left panel displays a time series of high-resolution magnetometer recordings in spacecraft coordinates centered on the mag-

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**Fig. 6.** Magnetometer data at 12-s resolution in spacecraft coordinates for 3 hours spanning the tail exit on orbit 1761. The minimum variance hodograms are computed for the interval 1821.30–1826.30 UT. The eigenvalues associated with this analysis are \((45.8, 0.6, 0.1)\) nT\(^2\), and the direction of the minimum eigenvector is \((0.046, -0.088, -0.995)\) in spacecraft coordinates. The average \( B_s \) value across the current sheet is \((1.86 \pm 3.60)\) nT.

**Fig. 7.** Five-second average magnetic field measurements in spacecraft coordinates for 70 min centered on the Venus tail exit on orbit 1766. The hodogram pair is calculated for the interval bracketed by the vertical lines \((1505:55–1544:55\) UT). This analysis has eigenvalues of \((52.1, 3.6, 1.6)\) nT\(^2\), a minimum eigenvector direction of \((0.065, 0.937, 0.344)\), and an average \( B_s \) value of \((4.76 \pm 4.37)\) nT.
netopause crossing. The two right-hand panels show hodo-
grams of the magnetic field vector tip projected in two mini-
mum variance coordinate planes for the interval across the
main current sheet bracketed in the left panel by the vertical
lines. The first hodogram ($B_x$ versus $B_y$) illustrates the vari-
ation in the normal field component $B_N$, and the second ($B_y$
versus $B_z$) shows the behavior of the field tangential to the
magnetopause.

The magnetopause crossing in Figure 5 comes from the tail
exit on orbit 1313 (also see Figure 4). The field vector rotates
and decreases in magnitude across this current sheet. The ho-
dogram pair indicates a magnetic structure resembling a rota-
tional discontinuity (see, for example, Sonnerup and Ledley
[1979] for a discussion of magnetic discontinuities and their
different hodogram signatures). However, this current sheet is
not a rotational discontinuity in the strict MHD steady state
description for an isotropic plasma because the field mag-
nitude, $B_L$, changes across the feature. The minimum variance
normal to this discontinuity has a direction (0.038, −0.621,
−0.783) in spacecraft (SC) coordinates which is consistent
with the expected normal to the boundary of an aberrated
cylindrical tail at PVO's location (northern poleward bound-
ary on the duskside). The average magnitude and uncertainty
of the field component $B_N$ along the normal direction is
(3.01 ± 2.73) nT. (The error in the mean is calculated using the
formula on p. 8140 of Berchem and Russell [1982]). Thus $B_N$
is statistically significant, indicating that tail lobe and mag-
netsheath fields are interconnected. $B_N$ also has the correct
direction, pointing into the tail, to add flux to the positive polari-
ty tail lobe adjacent to the magnetopause crossing.

The tail exit on orbit 1761 forms our second study of mag-
netopause structure. Figure 6 displays data at the highest time
resolution (12 s) recorded during this boundary crossing. The
magnetic signature resembles that in Figure 5 and is like a rota-
tional discontinuity, though the average magnitude along the
minimum variance direction (1.86 ± 3.60) nT does not exceed
the uncertainty, and the field magnitude changes across the
 discontinuity. The direction of the magnetopause normal
(0.046, −0.088, −0.995) agrees with the normal to an ab-
errated tail at PVO's expected location on the northern pole-
ward boundary. $B_N$ points into the tail, in the correct direction
for flux addition to the positive polarity lobe.

The two remaining Venus magnetopause examples come
from orbit 1766 (this is the tail crossing shown in Figure 3).
Figures 7 and 8 illustrate the tail exit from lobe to mag-
netsheath and the tail entry from magnetheshell to plasma
sheet. The magnetic character of these two current sheet cross-
ings is distinctly different.

Let us consider first Figure 7. This magnetotail exit takes
about 30 min, which is far longer than the exits in Figures 5
and 6. The magnetopause current sheet has an average $B_x$ of
(4.76 ± 4.37) nT and, apart from the change in $B_T$, again
resembles a rotational discontinuity. The statistically signifi-
cant $B_x$ is independent of the interval we choose for analysis
(selecting the 1525:00–1530:40 UT period gives an average $B_x$
of (6.01 ± 3.04) nT). The magnetopause normal (0.065, 0.937,
0.344) is directed mainly east-west, agreeing with the space-
craft location (equatorial boundary on the northern duskside)
and indicating that this tail exit occurs closer to the magnetic
equator than the examples in Figures 5 and 6. $B_N$ points out-
ward, in the correct sense to give flux addition to the negative
polarity tail lobe which abuts the magnetopause.

Let us now turn to Figure 8, which shows the tail entry
into the plasma sheet) on orbit 1766. This magnetopause
crossing resembles a tangential discontinuity. The initial entry
at 1013 UT appears sharp, but a further 20 min elapse before
a steady plasma sheet field is encountered. We use the longer interval for the analysis shown here, though a shorter interval bracketing the current sheet at 1013 UT gives almost identical results (see figure caption for details). The minimum variance normal to the magnetopause (0.557, 0.069, -0.828)_{BC} is directed mainly north-south, as expected for a crossing of the southern polarward duskside boundary of an abberated cylindrical tail. The average B_{n} value across the current sheet of (0.05 ± 1.15) nT indicates no interconnection between plasma sheet and magnetosheath fields.

In summary, a study of four unambiguous tail boundary crossings shows that the Venus magnetopause exhibits magnetic properties resembling both a rotational and a tangential discontinuity. The rotational discontinuities are observed for tail lobe/magnetosheath crossings, and the tangential discontinuity case occurs at a plasma sheet/magnetosheath interface. The statistically significant field components B_{n} normal to the magnetopause imply that the tail lobe and magnetosheath fields are interconnected. In these cases, B_{n} has a typical magnitude of a few nanoteslas and the correct direction to give flux addition to the tail. The reason for the change in field magnitude across these discontinuities is unclear, but anisotropic plasma pressure may be important.

3. Average Tail Dimension

3.1. Coordinate Systems and Data Base

We employ three coordinate systems for displaying our statistical results. Each assumes an average 5° aberration angle for the Venus tail, corresponding to an average solar wind speed of 400 km s^{-1} and a Venus orbital velocity of 35 km s^{-1}. Our first display type is called abberated VSO coordinates (X', Y', Z'_{VSO}) and differs from ordinary VSO coordinates (X, Y, Z_{VSO}) by a 5° rotation in the XY plane such that -X'_{VSO} aligns with the abberated tail axis.

We call our second display system "magnetic coordinates" and denote it (X', Y', Z'_{VSO}). It has its Z'_{VSO} coordinate aligned with the cross-flow or B_{n} component of the upstream IMF and thus differs from abberated VSO coordinates by rotation about the X_{VSO} axis. Magnetic coordinates are used to order tail phenomena controlled by the IMF B_{n} component. We use the terms "magnetic equator" and "magnetic pole" to describe locations on the Venus tail boundary where the Z'_{VSO} and Y'_{VSO} position coordinates are zero.

Solar cylindrical coordinates form our third type of display and are used for studying interactions which are cylindrically symmetric. Its abscissa is directed along the abberated tail axis, and its ordinate is distance perpendicular to that axis.

The orbit numbers when PVO intercepts the distant tail are 180–194, 405–420, 626–641, 780–787, 1078–1092, 1299–1314, 1524–1538, 1751–1767, and 1975–1991. A question mark is given for the start of the fourth pass because tracking coverage at that time was restricted due to Venus being at superior conjunction.

From this wake data set we identified 70 orbits (48 penetrating the tail, the remainder passing near the tail in the magnetosheath) when the IMF was steady enough that we...
could determine its direction and be confident that this direction was similar during a tail encounter possibly 12 hours earlier or later. A few of the early tail orbits, when periapsis was low, did not enter the solar wind or did so only briefly. Thus for consistency we used the direction of the subsolar magnetosheath magnetic field for our measure of the IMF direction in the solar ecliptic YZ plane. By studying orbits when the IMF was also sampled we found that in this plane the directions of the subsolar magnetosheath field and the IMF agreed to within 10°-20°. All magnetosheath field measurements were made at a solar zenith angle of less than 40°.

The 48 tail orbits divide 27 (21) for negative (positive) IMF $B_T$ orientations. To exclude uncertain magnetopause crossings from our statistics, we only include intervals for the 48 orbits where PVO is definitely in the magnetosheath or tail. Our catalog consists of 12,494 min of tail data of which 8897 min come from the $-10 - R_T$ to $-12 - R_T$ aberrated downtail distance range.

3.2. Sampling Coverage

Figure 9 displays the cross-tail coverage of our 70-orbit data base in aberrated VSO coordinates. We employ 1-min averages of the magnetic field, and we divide the Venus wake into bins of area $R_T^2/9$. The numbers signify the number of minutes of data within individual $R_T/3$ by $R_T/3$ bins. The inner circle is the Venus optical shadow (appropriate for an $X_{VSO}$ distance of $-9 R_T$), and the outer circle, of radius 2.3 $R_T$, represents the average tail radius at 11-$R_T$ altitude. The data coverage is fairly uniform apart from within the optical shadow, where in order to conserve spacecraft power the instruments are usually switched off.

Figure 10 illustrates the same data as in Figure 9 but using magnetic coordinates. The ellipse, centered at $Y_{VSO''} = -0.2 R_T$, $Z_{VSO''} = 0.0 R_T$, indicates the average tail boundary for this $-5 R_T$ to $-12 R_T$ $X_{VSO}$ distance range (see section 3.4). There is clearly good cross-tail data sampling in magnetic coordinates.

Let us now consider Figure 11. This figure contains fewer samples than Figures 9 and 10, for it includes only recordings made within the tail and illustrates this number only for the $-10 R_T > X_{VSO} > -12 R_T$ distance regime. The ellipse again indicates the average tail boundary, though here it is centered at $Y_{VSO''} = -0.2 R_T$, $Z_{VSO''} = 0.2 R_T$ due to the different altitude range of the acquired data. Since it represents the average boundary (see sections 3.3 and 3.4), the ellipse does not include every bin containing tail data. Despite the smaller number of samples the cross-tail coverage remains fairly good. We shall show several statistical results whose significance depends upon this good sampling coverage.
3.3. Tail Shape in Cylindrical Coordinates

Figure 12 illustrates the Venus tail average dimension in aberrated solar cylindrical coordinates. The different symbols within the wake mark the location of 110 clear tail boundary (magnetopause) crossings by PVO and by earlier missions to Venus. These show increasing scatter with downstream distance due possibly to variations in solar wind speed, direction, and dynamic pressure.

In order to determine the average size and flaring angle of the Venus tail we partition the wake region into $0.5 \times 0.2 R_V$ segments. We then combine 1-min averages of the magnetic field from all 70 orbits to calculate the percentage of time for a particular bin that PVO is within the tail. These percentages are indicated by the different shadings. As in all our further
Fig. 13. Venus tail cross-section in aberrated VSO coordinates based on data from the $X_{vso}$' distance range from $-5$ $R_V$ to $-12$ $R_V$. The view is toward the planet, and contours are computed and illustrated as in Figure 12. The outer circle represents the boundary of a cylindrically symmetric tail of radius 2.3 $R_V$ centered at the origin, while the inner circle of radius 1 $R_V$ is the optical shadow as seen at $X_{vso} = -9$ $R_V$.

diagrams showing statistical results, the percentages in Figure 12 are smoothed four times using a Gaussian filter of order 3 with matrix elements 121, 242, 121. This filter operates on a two-dimensional spatial array, such as

$$X_1 X_2 X_3 X_4$$
$$X_5 X_6 X_7 X_8$$
$$X_9 X_{10} X_{11} X_{12}$$
as follows. The filtered values at, for example, the positions $X_6$ and $X_7$ would be

$$X_6' = (X_1 + 2X_2 + X_3 + 2X_5 + 4X_6 + 2X_7 + X_9 + 2X_{10} + X_{11})/16$$

$$X_7' = (X_2 + 2X_3 + X_4 + 2X_6 + 4X_7 + 2X_8 + X_{10} + 2X_{11} + X_{12})/16$$

respectively. When using this filter we took care to ensure that no artificial spreading the region of data coverage occurred.

Fig. 14. Venus tail cross-section computed using the same data as in Figure 13 but now plotted in magnetic coordinates. As described in the text, the ellipse is a best fit to the 50% contour and indicates a broader tail in the direction aligned with IMF $B_z$. 
Fig. 15. Venus tail cross-section in magnetic coordinates computed for the $X_{VSOS}$ distance range $-10 \, R_V$ to $-12 \, R_V$. The ellipse, centered at $Y_{VSOS} = -0.2 \, R_V$, $Z_{VSOS} = 0.2 \, R_V$, indicates the average tail configuration and shows flattening of the tail in the direction parallel to IMF $B_z$.

by calculating averages only when the sum of the weights of the points present equaled or exceeded 8. We applied smoothing to remove the high-frequency statistical variations in order to highlight the major physical result.

We define the average tail boundary as the 50% contour, and we indicate it by the dashed line. Thus the tail has an average cross-sectional radius of $2.3 \, R_V$ at $-12 \, R_V$ and still appears to be flaring by a few degrees at this distance. Indeed, flaring is evident at all percentage levels except within the 91–100% range. This flaring could be caused by tail wagging.

The shaded area indicates the region of the distant wake which PVO explores (the shading is terminated at $X_{VSOS} > -4 \, R_V$). Clearly, only certain portions of the tail are probed. There is a data void in the interesting altitude regime between 2500 km (maximum nightside periapsis height) and $5 \, R_V$, and only near apoaopis at $-10 \, R_V > X_{VSOS} > -12 \, R_V$ is the complete tail cross section sampled. We use this latter region for several of our statistical investigations.

3.4. Tail Cross-Sectional Shape

Let us consider now the Venus tail cross section. Figures 13 and 14 illustrate our findings in aberrated and magnetic coor-

Fig. 16. Venus tail magnetic field polarity displayed in magnetic coordinates. The figure incorporates data from 48 tail orbits during nine PVO apoaopis wake passages. The ellipse marks the average tail boundary as determined in section 3.4. The location and division of field polarities is consistent with the tail being accreted from the solar wind in the manner proposed by Alfèn [1957] for comet tails.
Fig. 17. Venus cross-tail magnetic field displayed in magnetic coordinates. At this $-10 R_V \geq X_{VSO} > -12 R_V$ downstream distance, $B_{trunc}$ is parallel to the upstream $B_z$ direction and has a typical magnitude of 2 nT.

Dinates for the downtail aberrated distance range between $-5 R_V$ and $-12 R_V$. These figures resemble Figures 9 and 10 except that each bin now contains a smoothed percentage showing the fraction of time within the tail. The percentage ranges and shading system are the same as in Figure 12.

There are three important points to make from Figures 13 and 14. First, the magnetotail is well developed when the IMF is steady. Second, the IMF cross-flow component, $B_L$, may influence the tail cross-section shape. The contours in the VSO coordinate display (Figure 13) are reasonably cylindrically symmetric, but those in the magnetic coordinate display are not. The contours in Figure 14 are broader in the direction parallel to the IMF $B_L$ component. To model these contours, we use ellipses having their major axis parallel to IMF $B_L$. The ellipse marked on Figure 14 gives the best fit to the 50% contour (our definition of the average tail boundary) and has a major axis to minor axis ratio of 1.2.

The third point which Figures 13 and 14 address (also see Figure 15) is whether the average tail location is consistent with aberration by about 5°. The ellipse fit in Figure 14 is centered only 1° from the origin (at $Y_{VSO} = -0.2 R_V$, $Z_{VSO} = 0.0 R_V$) and thus supports aberration by about 5°. In contrast the contours in the Figure 13 VSO coordinate display suggest that 5° is an overestimate for the average aberration angle. The 50% contour is displaced from the origin in the $-Y_{VSO}$ direction by about $R_V/3$ (or 2°). Although this offset may arise from the spatial uncertainty associated with the limited bin size, it might be due to the tail shape control exerted by IMF $B_L$.

The magnetic coordinate display in Figure 15 includes only measurements made close to apoapsis, at $X_{VSO}$ distances between $-10$ and $-12 R_V$. It therefore shows the tail shape at a more constant $X_{VSO}$ distance than Figure 14. The contours in Figure 15 are asymmetric in the same sense as those in Figure 14, with tail flattening occurring in the IMF $B_z$ direction. We show the ellipse with its major axis parallel to IMF $B_z$, which matches best the 50% contour. This ellipse has a major axis to minor axis ratio of 1.4. The greater tail cross-section asymmetry in Figure 15 than in Figure 14 suggests that flattening may increase with distance downtail. We note the recent reports by Sibeck [1984] and Sibeck et al. [1985] of an identical asymmetry in the shape of the earth's distant magnetotail. These authors argue that flattening arises from the anisotropic pressure of draped IMF field lines with the magnetic tension force "squeezing" the tail in the sense observed. This explanation may be appropriate for our Venus observations. However, we note that it is most difficult to distinguish tail from magnetosheath at the top and bottom of the tail (i.e., large positive $Z^+$ and negative $Z^-$ values). Thus we may have underestimated the amount of time spent within the tail and hence the tail cross section in this region.

4. DISTANT TAIL AVERAGE MAGNETIC STRUCTURE

4.1. Magnetic Polarity

Russell et al. [1985] report the first examination of field polarities in the distant Venus tail. They find that plotting cross-tail trajectories in magnetic coordinates produces a separation of sunward and antisunward pointing lobe fields consistent with tail accretion from the solar wind. Plotting these same data in VSO coordinates gives a random distribution to the lobe polarities; the two-cell pattern one would expect if tail field lines are of planetary origin is absent.

Here we extend the Russell et al. [1985] study by (1) using a larger data base, (2) examining the tail field polarities separately as a function of sign of IMF $B_y$, and (3) incorporating both lobe and plasma sheet fields in the polarity statistics.

Our major result is displayed in Figure 16 using magnetic coordinates. All field values within the tail ($-10 R_V$ to $-12 R_V X_{VSO}$ distance range) are combined to determine the dominant polarity of the $B_L$ field component within each bin using $\langle \sum B(L)^+ - \sum B(L)^- \rangle / N$. Here, $\sum B(L)^+ (+)$ and $\sum B(L)^-$ ($-$) are the number of field values having positive and negative $B_L$ field polarities, while $N$ represents the number of points within each bin. Shading distinguishes the two field polarities in Figure 16. Before smoothing, the plot contained bins which disagreed with the striking two-cell division. We feel that such anomalies are unlikely to represent real physical
effects; instead they result from statistical perturbations caused, for example, by fluctuations in the IMF $B_1$ direction during a tail encounter.

Figure 16 shows that sunward pointing fields dominate in the right hemisphere, with antisunward fields dominant in the left hemisphere. Since the view is from the tail toward Venus and the IMF $B_1$ points from right to left, this field polarity pattern is just that expected for an accreted tail of solar wind origin. The curved nature of the boundary separating positive and negative polarity fields is puzzling but may relate either to poor statistics (Figure 11) or to the IMF x component. Sixty percent of the tail data are recorded when IMF $B_x$ is positive, and the curvature in Figure 16 is consistent with such a bias. If we display the occurrence of negative and positive $B'_x$ fields for inward and outward sectors separately, we see roughly the same pattern as in Figure 16.

4.2. Cross-Tail Magnetic Field

We now look at the average magnitude and direction of the Venus cross-tail magnetic field, $B_{T \mathrm{tail}}$. In Figure 17 we illustrate results from apoapsis data, once more using magnetic coordinates. The shading code shows that $B_{T \mathrm{tail}}$ is almost exclusively parallel to the upstream $B_1$ field; negative field projections are observed rarely. The vertical panel on the figure's right shows average values for $B_{T \mathrm{tail}}$ with distance from the magnetic equatorial plane. The value is typically 2 nT, though there is evidence for a latitudinal asymmetry with larger cross-tail fields in the upper tail magnetic hemisphere. A possible explanation for this asymmetry is given later. The important point to make now is that the cross-tail field is always positive, a result consistent with the induced magnetotail picture, which we illustrate in Figures 19 and 20.

4.3. Variation Along Tail Axis

Figure 18 displays average values for various parameters with distance along the aberrated tail. The bottom panel gives the number of minutes, $N$, of tail data within each 0.5-$R_V$ range of altitude. We noted earlier that the spacecraft spends most of its time within the tail near apoapsis.

The top panel shows average values for the tail magnetic field (lobe and plasma sheet combined). The decrease in $B_{T \mathrm{tail}}$ at $X_{\mathrm{VSO}} > -8 R_V$ arises from incomplete sampling of the tail cross section by PVO and is unphysical. The average tail field strength near apoapsis is about 11.5 nT. This value is very similar to the average 10-nT magnitude of the interplanetary field at Venus [Slavin and Holzer, 1981].

The second panel displays the average field component, $B_{T \mathrm{tail}}$, along the aberrated tail axis. Below is plotted the average magnetic flux per hemisphere of the tail, $\Phi_{\mathrm{lobe}}$, where $\Phi_{\mathrm{lobe}} = B_{T \mathrm{tail}} R^2 / 2$ and the average tail radius $R$ is determined from Figure 12. The magnetic flux within a hemisphere of the tail near apoapsis is 2.5–3 MWb.

The remaining parameter in Figure 18 is $B_{T \mathrm{tail}}$, the average cross-tail magnetic field. $B_{T \mathrm{tail}}$ is clearly parallel to the upstream $B_1$ at all latitudes, not just near apoapsis as in Figure 17. The mean $B_{T \mathrm{tail}}$ for our entire tail data set (12,494 min) is 1.99 nT.

5. SIMPLE MODEL INTERPRETATIONS

5.1. Magnetic Equatorial Plane View

Figures 19 and 20 illustrate a simple model for the magnetic structure and formation of the Venus tail which is consistent with our findings. These diagrams are approximately to scale and are drawn for a steady IMF pointing in the Y_{\mathrm{VSO}} direction. Since our interpretations are based on recordings from the distant tail, the magnetic topology in the near tail could differ from the one we depict.

Figure 19 is a two-dimensional view of the solar wind interaction with Venus in the magnetic equatorial ($X'Y'$)_{\mathrm{VSO}} plane. Field lines are shown projected into this plane, which passes through the planet center. Shading represents the Venus nightside, and field lines are slipping over and not through the planet. (The three-dimensional shape of tail field lines is indicated in Figure 20).

Near the magnetic equator the magnetopause resembles a rotational discontinuity, allowing magnetic flux and plasma to be transferred across the tail boundary. Most of the interplanetary flux entering the tail should do so near the magnetic equator (see Figures 19 and 20) because the slab of IMF flux supplying the tail is expected to be less than 0.5 $R_V$ thick. If the average value for $B_z$ over the tail magnetopause at $X_{\mathrm{VSO}} = -12 R_V$ is 1 nT, which is consistent with our initial findings in section 2.6, then for a tail radius of 2.3 $R_V$ and an IMF $B_1$ of 6 nT (IMF field of magnitude 10 nT directed along the spiral axis) the region of incident IMF flux which supplies the tail is 0.43 $R_V$ (2600 km) thick. This implies a cross-tail potential drop of 10 kV.

The electric field associated with the flux addition causes convection of field and plasma toward the tail center. Field lines escape in the antisolar direction due to the release of Maxwell field tension the central tail region of strong field...
curvature. These “escaping” field lines, located between the two tail lobes of opposite field polarity and accelerating to the solar wind speed, are expected to form the Venus analog of the terrestrial central tail current sheet and plasma sheet.

The circled dots and crosses in Figure 19 indicate the flow directions of electric current, J. The electric field, E, is directed everywhere out of the plane of the diagram. Thus the circled crosses indicate regions where \( J \cdot E < 0 \) and energy is transferred from the plasma to the field, while the circled dots indicate regions where \( J \cdot E > 0 \) and energy is lost from the field to the plasma. These energy exchanges can also be pictured in terms of the flow of electromagnetic energy described by the Poynting vector \( S = E \times B/\mu_0 \). S is directed inward from the bow shock and magnetopause toward the tail current sheet where electromagnetic energy is dissipated.

5.2. Tail Magnetic Structure: Three-Dimensional View

In Figure 20 we illustrate a quadrant of the Venus tail and the downstream progress of three field lines incident on the ionosphere at different distances from the subsolar point. These field lines are sketched at seven equally separated times \( t_1-t_7 \), with the heavy portion of each line indicating the part within the tail. The dashed lines indicate the streamlines along which the field lines move. The subsolar streamline projects to the tail center, and the upper streamline maps to the tail per-

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**Fig. 19.** Schematic illustrating electromagnetic aspects of the solar wind interaction with Venus during steady east-west interplanetary magnetic field conditions. Field lines are shown projected into the magnetic equatorial plane.

**Fig. 20.** Three-dimensional schematic illustrating a quadrant of the Venus tail and our interpretation for the average magnetic field structure therein (see text for details).
ipheny. Field lines moving along the subsolar streamline receive the greatest slowing due to mass loading by ion pickup and consequently lag behind tail field lines moving along the other streamlines. Thus a cross-sectional cut through the distant tail would reveal field lines with different solar wind histories—the "oldest" field lines occurring near the tail center. Other features of the Venus tail such as the lobes, the plasma sheet, the smallness of the region of incident magnetosheath flux which supplies the tail, and the expected asymmetric distribution of $B_n$ around the tail magnetopause (with $B_n$ maximizing at the magnetic equator and diminishing toward the magnetic poles where the tail boundary may resemble a tangential discontinuity) are also apparent in Figure 20.

5.3. Tail Field Line Closure

The distant tail field lines in Figures 19 and 20 are shown closing mainly across the center of the tail rather than being hung up on the ionospheric obstacle. A range of evidence supports this conclusion.

We know from Figure 18 that the flux content of the distant tail is about 3 MWe. This flux cannot close above the dayside ionosphere, for it would fill the entire magnetosheath directly in front of the planet out to the bow shock (~2000-km altitude) with 100-nT field strengths. The 3-MWe flux also exceeds, by at least an order of magnitude, estimates for the magnetic flux either in the dayside ionosphere or in the nightside ionosphere radial fields [Luhmann et al., 1981]. The flux content in the plasma mantle (the region separating the ionosphere from the magnetosheath [Spener et al., 1980]) is about 1 MWe at the dawn-dusk meridian (based on an average $B_x$ field of 20- nT and a thickness of 1500 km). Thus from conservation of flux, some of the 3 MWe of distant tail flux may close above the ionosphere in the plasma mantle, but most of this flux must close across the tail center plane [Russell et al., 1985].

A second point supporting this conclusion is our 1.99-nT average magnitude for the cross-tail magnetic field (section 4.3). If a 1.99-nT average field normal to the tail current sheet existed over an average tail width of 4 $R_e$ between the planet and 11-$R_e$ altitude, all the tail flux at 11 $R_e$ could close behind the planet.

Another indication that magnetotail field lines slip by Venus rapidly comes from the average field component $B_n$ normal to the tail magnetopause. Our preliminary analysis in section 2.6 suggests this is about 1 nT. In that case the 3 MWe of tail flux at 11 $R_e$ would exit the tail within a further downstream distance of 13 $R_e$. Since the magnetosheath plasma flows at about 400 km s⁻¹, or 4 $R_e$/min, the tail flux can be resupplied in only a few minutes. This time depends sensitively on the $B_n$ value one uses, but we note the agreement with a result of Eroshenko [1979], who, from examining simultaneous Venera 9 and 10 magnetic field recordings, finds a case where a field change in the central near-Venus wake lags a reorientation in the upstream IMF by 10–20 min. Thus various findings support the tail field line closure geometry in Figures 19 and 20.

6. CONCLUSIONS AND KEY REMAINING QUESTIONS

PVO's polar orbit and extended mission (now exceeding 10 Venus years) has produced a magnetometer data base well suited for statistical study of the distant Venus magnetotail. During steady IMF conditions the Venus tail is prominent, flares with altitude, and possibly is broader in the direction parallel to IMF $B_x$. A magnetic coordinate system based on the IMF $B_z$ direction orders the Venus tail magnetic structure. Field polarities rotate as the IMF $B_x$ rotates, and the cross-tail field parallels the upstream $B_x$. These properties argue strongly that the Venus tail is accreted from the solar wind in a manner resembling Alfvén's [1957] proposal for comet tails. The comet analogy, however, should not be taken too far. Various tail observations indicate that the Venus ionosphere is far more impenetrable than a comet ionosphere to the solar wind. Tail field lines appear to slip by Venus on a time scale of only minutes, with field lines near the tail center (near the tail boundary) slipping less rapidly (more rapidly) than the average.

An important remaining question is the nature of the plasma sheet. Data sets such as Figures 1–4 suggest that to maintain pressure balance with the tail lobe field, the plasma sheet must have an energy density (nkT) approaching 1 keV cm⁻³. However, to date there exists no clear identification of this plasma [Slavin et al., 1984]. There is a need for early study of electron density measurements from the PVO retarding potential analyzer [Knudsen et al., 1979] to determine the plasma sheet ion temperature.

A topic requiring extensive study is the magnetopause. Is there, as we suggest, a systematic change in the nature of the discontinuity in moving from the magnetic equator to the magnetic pole? Also, one needs a better average value for $B_n$ to obtain a reliable time for tail flux replenishment.

Another topic that should be investigated is the influence IMF $B_x$ has on tail magnetic structure. Spreiter and Stahara's [1980] gas dynamic computer model suggests this may be significant (J. G. Luhmann, personal communication, 1985).

An intriguing question concerns the hemispheric asymmetry in the cross-tail magnetic field (Figure 17). The larger cross-tail fields in the upper magnetic hemisphere may indicate that flux addition to the tail is asymmetric, occurring preferentially over the upper magnetic pole. This sense would agree with the initial trajectory of ionospheric ions following pickup by the solar wind electric field and agrees with asymmetries seen in the magnetosheath magnetic field by Luhmann et al. [1985].

Acknowledgments. This work was supported by NASA under research contract NAS 2-9491 and was performed while one of us (M.A.S.) held an ESA Research Fellowship. Special thanks go to Gordon Maclean for generous computing assistance and to Marj Ishiwata for careful drafting of figures. It is a pleasure to thank D. J. Southwood, D. G. Sibeck, and the two referees for thoughtful comments on the manuscript and many colleagues for helpful discussions, in particular, J. G. Luhmann, R. C. Elphic, D. J. McComas, and H. E. Spence.

The Editor thanks J. R. Spreiter and J. M. Grebowsky for their assistance in evaluating this paper.

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(Received July 2, 1985; revised January 7, 1986; accepted January 8, 1986.)