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A COMPARATIVE STUDY OF DISTANT MAGNETOTAIL STRUCTURE AT VENUS AND EARTH

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Abstract. Pioneer Venus and ISEE-3 observations are used to conduct a comparative investigation of distant magnetotail structure at Venus and Earth. Both magnetotails are found to be well ordered out to the apoapses of PVO and ISEE-3 which are at 11-12 R_V and 220-240 R_e. The estimated lengths of the Venus and Earth magnetotails are 100-150 R_V and 600-6000 R_e. Despite their very different interactions with the solar wind, the magnetotails of these two planets possess many similarities. The Venus tail appears to have distinct mantle, lobe, plasma sheet boundary layer, and plasma sheet regions much like its terrestrial analogue. It is further shown that the plasma sheet magnetic field distributions in the disant tails of Venus and Earth are consistent with disconnection from the planet. In particular, the $\langle B_Z \rangle = -0.25$ nT observed by ISEE-3 at $X = -210$ to -225 R_e is sufficiently negative on the basis of flux conservation for the average location of the tail neutral line to always earthward of $X = -210$ R_e. Finally the lobe field magnitudes are approximately those expected on the basis of average solar wind conditions, while the mean plasma sheet beta values inferred from pressure balance arguments are 8.5 and 3.8 for Venus and Earth, respectively.

Introduction

All of the planets have been found to possess magnetotails consisting of two magnetic lobes with opposite polarities separated by a plasma sheet. At Mercury, Earth, Jupiter, and Saturn the interaction with the solar wind produces tangential stresses which drag planetary field lines downstream to form the tail as shown in the upper panel of Figure 1. Internal dissipation mechanisms, such as reconnection, return magnetic flux to the forward magnetosphere at highly variable rates which are eventually balanced by flux addition (e.g. Slavin and Holzer, 1979). While less is known about other magnetospheres, the frequent imbalance between magnetic flux supply and return rates at Earth results in a variable strength tail whose length may vary from 600 to 6000 R_e (Oberc, 1983).

The Venera 9, 10 and PVO missions have found that Venus, while lacking an intrinsic magnetic field, also has a well developed magnetotail (Russell et al., 1981). As shown in Figure 1, the Venus tail is believed to form as a result of IMF field lines draping about an ionspheric obstacle. Magnetic flux continuously being added by the draping process is balanced by the loss of field lines down the plasma sheet after they slip around the obstacle. Using Venera 9, 10 magnetic flux residence time of 20-30 minutes (Eroshenko, 1979), Slavin et al. (1980) estimated the length of the Venus tail to be 100-150 R_V. In this study we investigate the Venus and Earth magnetotails for the purpose of better understanding the interaction of the solar wind with these planets.

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Regions of the Tail

Recent ISEE-3 papers (Bame et al., 1983; Slavin et al., 1983) have discussed the regional structure of the distant earth magnetotail. In brief, they have found that the distant tail retains most of its cislunar characteristics. The low beta lobes and high beta plasma sheet remain the dominant features, but with some growth in the extent and strength of the boundary layer regions. With these results in mind, we have examined Pioneer Venus plasma analyzer, magnetometer, and plasma wave observations during the 5th, 6th, and 7th wake passage seasons in 1981-83.

Figure 2 displays two hours of PVO measurements from the UCLA magnetometer and the Ames plasma analyzer on 10 July 1982 when the spacecraft was 8-10 R_V downstream of the planet. The tail encounter interval is perhaps most readily apparent in the plasma analyzer E/Q scans which show no significant ion fluxes prior to about 19:28 at which time PVO entered the ionosheath and observed shocked solar wind plasma. The magnetic field observations indicate that the spacecraft was in the lobe during most of the tail interval with strong fields, $B \sim 18$ nT, oriented generally back toward the planet, $\phi \simeq 0^\circ$. The 18:38-43 period is identified as plasma sheet on the basis of the very low field intensities, brief neutral sheet encounter, and increased field variance. Both regions appear quite similar to their terrestrial counterparts including a slight field depression, 18:43-49, at one of the lobe-plasma sheet interfaces. These 10-20% gradual decreases are the typical magnetic signatures of plasma sheet boundary layer in the ISEE-3 observations (Tsurutani et al., 1984). Finally, the magnetopause crossing at 19:28 closely resembles magnetopause encounters seen by ISEE-3 including draped ionosheath field lines.

In contrast with the previous example, Figure 3 displays a tail interval chosen for the large amount of time spent in the plasma sheet and the diffuse tail exit through a boundary layer region. The plasma sheet magnetic field is weaker and more variable in direction than lobe fields. Neutral sheet crossings with the field changing from pointing toward the planet, $\phi \sim 0^\circ$, to away, $\phi \sim 180^\circ$, occurred near 19:15 and 20:11 with a crossing in the opposite sense at 19:23. As with the lobe comparisons, the Venus plasma sheet magnetic fields appear very similar to those seen in the distant tail by ISEE-3. The major difference is that the ISEE-3 plasma sheet encounters are often associated with the rapid tailward motion of large magnetic islands, called plasmoids, which greatly enhance the

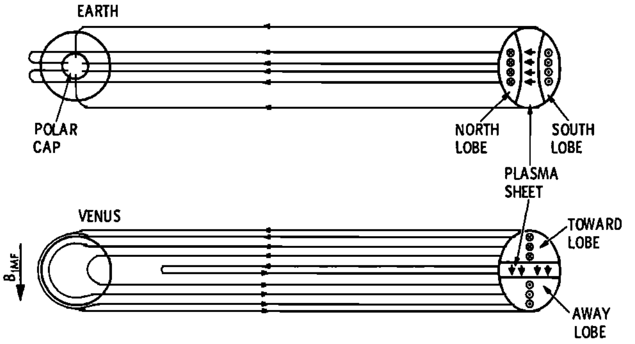

Fig. 1. A qualitative picture of the Venus and Earth magnetotails, viewed from above the ecliptic, is presented. To the right, a slant vertical cut reveals the internal structure. Note the difference in plasma sheet orientation between the intrinsic field and draped field tails. Actual tail radii near ISEE-3 and PVO apoapses are about 30 R_e and 2 R_V, respectively (1 R_e = 6380 km and 1 R_V = 6050 km).

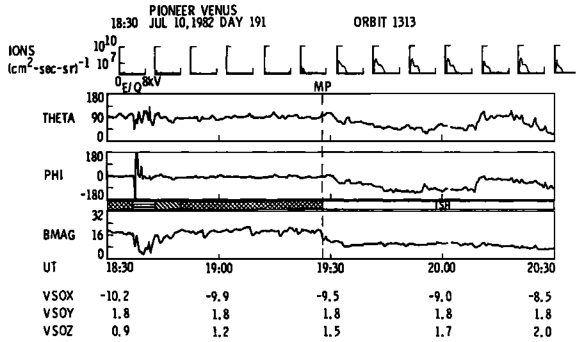

Fig. 2. PVO magnetic field measurements, 12 second averages, are shown in planetocentric spherical coordinates (θ = 90° corresponds to the Venus orbital plane and ϕ = 0° is toward the sun). The plasma analyzer energy steps increase logarithmically in time, but the start and stop points of each cycle are correctly located relative to the magnetic field. The region identifiers are cross-hatch for the lobe, horizontal lines for the plasma sheet, and slant lines for the plasma sheet boundary layer.

thickness of the plasma sheet. If such reconnection phenomena occurred at Venus, then strong east-west or west-east plasma sheet field signatures, depending on IMF direction, would be expected. No plasmoid signatures on the time scales of the PVO plasma sheet encounters were observed.

An interesting aspect of the Venus observations is the apparent lack of 0-8 kV ions in the plasma sheet as shown in the top panel of Figure 3. While more study is needed, this result may indicate that most of the ions in the plasma sheet possess an E/Q in excess of 8 kV. This would be the case if, for example, the ions in the plasma sheet were mostly 0^+ with flow speeds in excess of about 300 km/s. It has been proposed that the Venus plasma sheet may be populated by the viscous entry of solar wind plasma near the north and south "magnetic poles" (Perez-de-Tejada, 1980). In this case predominantly solar wind H^+ would be found in the plasma sheet with some 0^+ of atmospheric origin being picked up via charge exchange. Grebowsky and Curtis (1981) have suggested that the "holes" seen in the nightside ionsphere by PVO may be the result of parallel electric fields transporting ions upward into the tail. These machanisms might produce a high 0^+ content which the plasma analyzer would not see if the ions were accelerated to $V > 300$ km/s.

Finally, the exit from the Venus tail on 27 November 1981 was very gradual. At 20:20 the magnetic field strength starts to weaken and vary in magnitude, 5.4 kHz electric field emissions appear, and low energy paticles become visible in the ion spectra. It took approximately an hour for the magnetic field lines to move away from their lobe orientation and the ions to assume a typical ionosheath distribution. We interpret this region as being a boundary layer composed of ionosheath flux tubes and solar wind H^+ leaking into the outer portions of the lobes and generating plasma waves (Intriligator and Scarf, 1984). Following standard terminology for Earth and Venus we have labeled this boundary layer region adjacent to the magnetopause as the mantle.

Average Magnetic Field Structure

For the purpose of making more detailed comparisons, lists of lobe and plasma sheet intervals in both the PVO and ISE-3 observations have been compiled. To limit contamination by other regions, only clear lobe and plasma sheet intervals of greater than approximately 5 and 30 minutes duration at Venus and Earth, respectively, have been included. In addition, only ISEE-3 observations between X = -210 and -225 R_e from the second geotail orbit were used to avoid spatial aliasing and provide a comparable distant tail interval for comparison with PVO.

As shown in Figure 4, the lobe magnetic fields have a strong tendency to point toward or away from the planet depending upon the lobe in which the spacecraft resides. In general, the lobe field angular distributions for Venus and Earth are quite similar and suggest that they are coherent, well bundled flux tubes with little flaring present. The small offset in field direction away from ϕ = 0°, 180° is caused

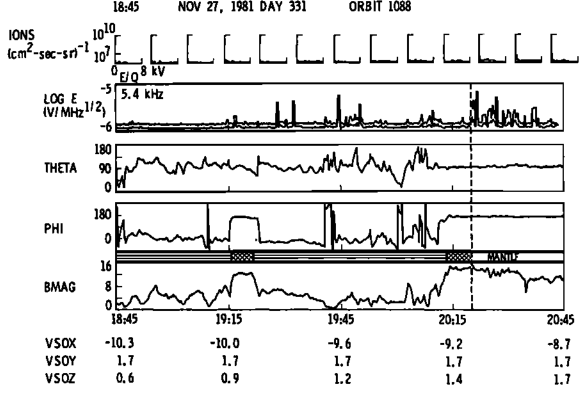

Fig. 3. Pioneer Venus plasma, magnetic field, and 5.4 kHz electric field observations for 18:45-20:45, 27 November 1981 are displayed. Both 12 second means and peaks are shown for the electric field measurements.

by aberration due to planetary motion about the sun and is larger at Venus due to its higher orbital speed.

The plasma sheet distributions in Figure 5 resemble those seen in the lobe, but with weaker fields and much larger variances due to plasma motion, waves, and dynamics. When comparing the plasma sheet fields it is very important to note the north-south nature of the Venus plasma sheet in contrast with the east-west orientation at Earth. As shown in Figure 1, Venus field lines returning to the solar wind after having interacted with the planet will favor orientations near $\phi \sim 90°$ or $270°$, depending upon IMF sector, while the orientation of the Earth's dipole requires disconnected fields to have southward components (i.e. $\theta > 90°$). Detailed analysis of Figure 5 shows a greater abundance of east-west fields in the Venus plasma sheet and a theta distribution for the terrestrial plasma sheet which is skewed toward $\theta > 90°$ with a mean B_Z = -0.25 nT when the components are averaged. These results suggest that PVO and ISEE-3 at apoapsis are on disconnected field lines moving down the plasma sheet to return to the solar wind.

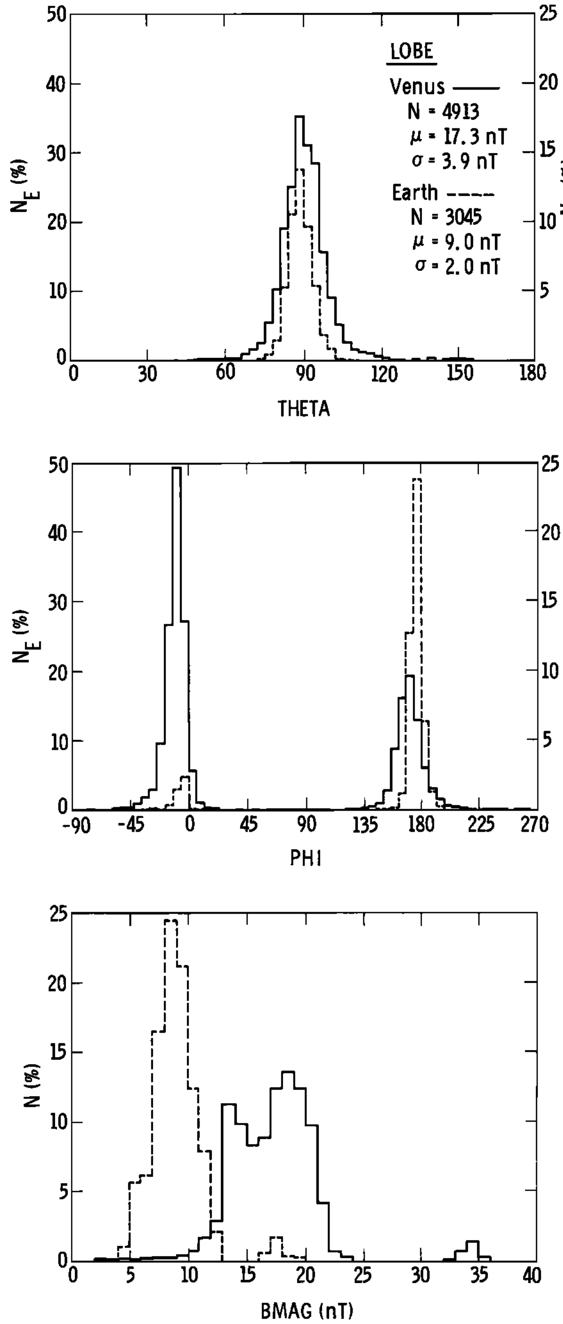

Fig. 4. Histograms of lobe magnetic field intensity and orientation are displayed for the distant magnetotails of Venus and Earth. The data sets were 1 minute and 12 second averaged for ISEE-3 and Pioneer Venus, respectively.

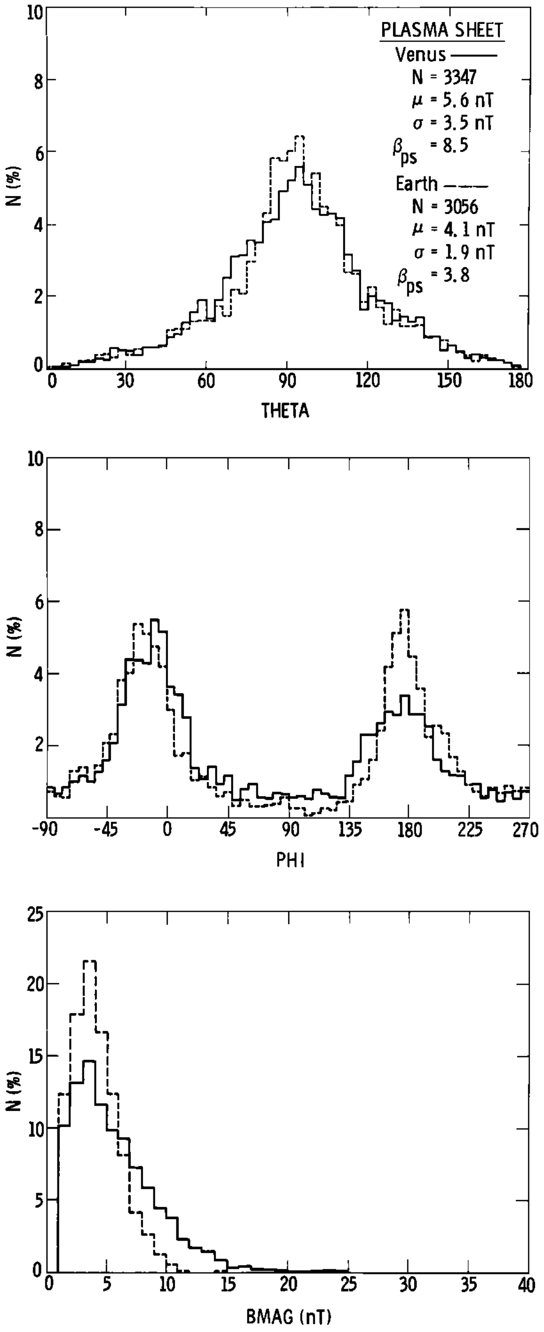

Fig. 5. Histograms of plasma sheet magnetic fields intensity and orientation in the distant magnetotails of Venus and Earth are displayed.

At Venus such a conclusion is not surprising and supports the interaction model shown in Figure 1.

However, for Earth the distance at which tail field lines become disconnected is an unknown parameter of some importance. Previous studies have determined that approximately 10% of the incident southward IMF undergoes reconnection at the dayside magnetopause and is added to the tail (Slavin and Holzer, 1979). Since the plasma sheet flow speeds in the distant tail are usually within a factor of 2 of solar wind speeds, conservation of magnetic flux requires a southward plasma sheet magnetic field that is about 10-20% that of the interplanetary B_z component. Given that B_z in the solar wind is normally a few nanoteslas, the $\langle B_z \rangle = -0.25$ nT at $-225 < X < -210$ R_e found in this study satisfies the flux conservation requirement and is consistent with ISEE-3 at these distances being immersed in disconnected plasma sheet field lines returning to the solar wind. The position of the classical reconnection neutral line is thus on average earthward of $X = -210$ R_e. Based upon the comparison with Venus in Figure 5, we would expect the positive portion of the B_z distribution to be associated with local fluctuations in the high beta plasma sheet fields as opposed to the repeated movements of the neutral line over ISEE-3 as hypothesized by some studies (e.g. Tsurutani et al., 1984).

The magnitudes of the tail fields are also of interest. As discussed by Slavin et al. (1983), the pressure balance condition between the lobe and solar wind beyond about $X = -100$ R_e is

$$B_L^2/8\pi = nk(T_i + T_e)_{sw} + B_{sw}^2/8\pi \qquad (1)$$

Assuming typical 1 AU solar wind parameters they found $B_L = 9.6$ nT in close agreement with the 9.0 nT magnitude in Figure 4. Scaling these values to 0.7 AU (i.e. $n = 14$ cm^{-3}, $B_{sw} = 14$ nT, $T_p = 1 \times 10^5$°K, and $T_e = 1.7 \times 10^5$°K) gives $B_L = 15.2$ nT which is near the 17.3 nT observed at Venus. A more detailed study would be needed to determine if this small discrepancy indicates that some tail flaring is present, or it merely reflects errors in the assumed solar wind values.

Finally, pressure balance calculations across the lobe-plasma sheet interface can also be instructive. If plasma pressure is assumed negligible in the lobe (i.e. $\beta_L = 8\pi n_L k(T_e+T_i)_L/B_L^2 \ll 1$), then beta for the plasma sheet may be computed from the magnetic field parameters alone

$$\beta_{ps} = (B_L/B_{ps})^2 - 1 \qquad (2)$$

Inserting the average field magnitudes from Figures 4 and 5 yields mean plasma sheet beta values of 3.8 and 8.5 for Earth and Venus, respectively. The implication is that the Venus plasma sheet must be denser and/or hotter than its terrestrial counterpart. The source, composition, and heating mechanisms for the plasma sheet remains perhaps the most poorly understood aspect of the Venus plasma environment.

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