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The inner magnetosheath of Venus: An analogue for Earth?

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Abstract. The unmagnetized planets provide examples of solar wind interactions that are free from the complications associated with magnetopause reconnection and with sensitive obstacle response to incident solar wind pressure changes. Using the Venus magnetosheath as a testbed, we search for evidence of standing slow mode "transitions" in the inner subsolar region as reported for Earth by Song et al. [1990a; 1992a; b]. Although the system at Venus is much smaller in scale, the Pioneer Venus Orbiter magnetometer data indicate that for perpendicular interplanetary magnetic field conditions the general behavior of the plasma in the magnetosheath is as expected from the simple depletion layer model. In examples of magnetic field measurements chosen for the apparently steady interplanetary conditions during the spacecraft pass, there is no clear evidence for a slow mode structure near the ionopause as might be expected on the basis of the Song et al. study. The implication is that some aspect of the Venus magnetosheath (such as its small size or the presence of local planetary ion production) makes it physically different from Earth's, that the conditions of the magnetosheath during Song's study differed significantly from those in the Venus study, or that the observations of Song et al. do not represent a steady state.

Introduction

One of the major difficulties associated with the observational study of processes occurring in the Earth's magnetosheath near the magnetopause is that the magnetized magnetosheath plasma reconnects with the magnetic field of the magnetospheric obstacle. The Earth's magnetosheath is also large enough to make the identification of steady conditions difficult, as solar wind plasma and field variations occur on timescales much smaller than spacecraft transit times through the subsolar region. Moreover, the magneto-sphere is a highly "compressible" obstacle so that the magnetopause position is a sensitive function of incident solar wind dynamic pressure. Recently, *Song et al.* [1990, 1992a, b] published several papers reporting the existence of a newly identified region in the inner magnetosheath which they call a "slow mode transition." Earthward of its outer boundary, indicated in the reproduced example in Figure 1, an unsteady density enhancement is observed oscillating in antiphase with low-frequency magnetic field fluctuations [*Song et al.*, 1992a]. This region occurs just outside of the depletion layer in the inner magnetosheath [e.g., *Zwan and Wolf*, 1976; *Crooker et al.*, 1979]. It appears most prominent for low plasma beta (≤ 1) conditions [*Song et al.*, 1990a]. *Southwood and Kivelson* [1992] make theoretical arguments in support of *Song et al.*'s [1992a] suggstion that such a transition region is present because the stationary subsolar magnetopause can create a standing slow mode structure. The waves associated with the structure affect the oncoming solar wind flow and field, reorienting them to directions tangent to the magnetopause inside of the transition. They also suggest, as illustrated by Figure 2, that for a perpendicular interplanetary field a general distortion of the inner magnetosheath field draping occurs in the transition.

Song et al. [1992a] point out that in previous MHD models of the solar wind interaction with an impenetrable obstacle [e.g., *Zwan and Wolf*, 1976], the transition to tangent flow within the magnetosheath is considered to occur in a gradual and continuous fashion. This implies that the MHD forces causing the flow and field deviations are distributed as opposed to localized in the region of the depletion layer. Recent numerical models of three-dimensional MHD flow around a conducting body by *Molvik et al.* [1991], *Wu* [1992], and *Tanaka* [1993] seem to support the picture of smooth transitions of the plasma and field parameters throughout the magnetosheath. Thus there is an apparent disagree-ment concerning the existence of a distinct standing slow mode structure adjacent to the inner boundary, although it must be recognized that these models in general assume isotropic pressure. (Because of this assumption, the model depletion process does not include the physics associated with the growth of pressure or beta anisotropies.)

One potentially useful space plasma "laboratory" experiment for magnetosheath studies is the solar wind interaction with unmagnetized planets (e.g., see the reviews by *Luhmann* [1986] and by *Luhmann and Brace* [1991]). These interactions are free of complications produced by magnetic reconnection with an intrinsic planetary field and have other advantages as well. The solar wind interacts directly with the ionosphere, where the counterpart of the Chapman-Ferraro current system flows. Since the pressure balance of the incoming plasma is with the planetary

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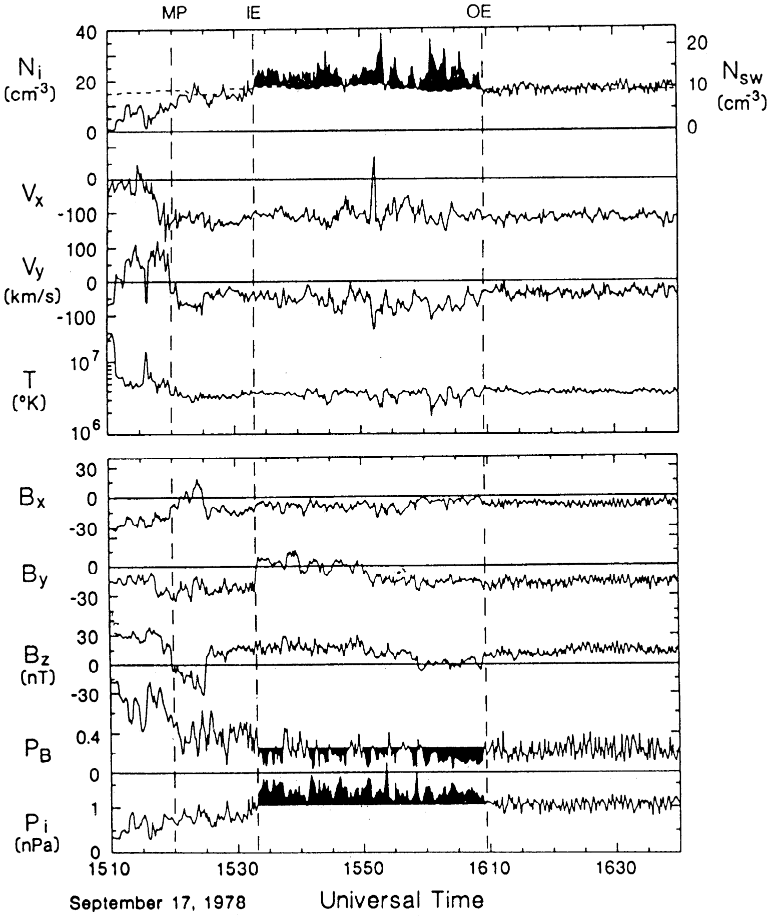

Figure 1. Example of a slow mode transition in Earth's magnetosheath from *Song et al.* [1992a]. Characteristics include the appearance of a lower-frequency waves in the magnetic field accompanied by oscillations in the plasma pressure. The notations OE and IE refer to the outer and inner edges of the structure, respectively.

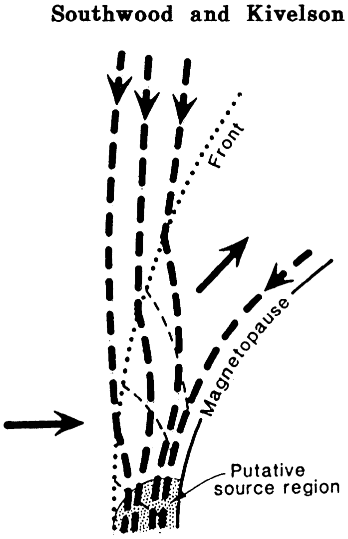

Figure 2. Illustration from *Southwood and Kivelson* [1992] of a possible global structure for explaining the observations of *Song et al.* [1992a] in Figure 1. The dashed lines show the field line geometry in the plane of the field. The contours show the gas pressure. The subsolar magnetopause serves as a source of waves that stand upstream, thereby producing the observed "transition."

ionospheric plasma rather than with an internal magnetic field, the obstacle surface, or ionopause, exhibits much less compressibility in response to solar wind dynamic pressure variations. Moreover, the magnetosheaths in these cases are smaller, making them more nearly ideal in the sense that interplanetary conditions can be practically constant during spacecraft passes. Of course, there are also problems associated with using obstacles of this nature. Because the neutral upper atmosphere scale heights can be large, some planetary ion production takes place within the magnetosheath, adding a potential "cometary" aspect to the solar wind interaction. Finally, if the obstacle is too small, the solar wind proton gyroradii can become significant compared to the subsolar magnetosheath thickness [*Moses et al.*, 1988; *Brecht et al.*, 1991], thereby making the physics of the subsolar magnetosheath non-MHD in character. For the latter two reasons, the solar wind interaction with Venus provides a better Earth magnetosheath analogue than the solar wind interaction with Mars.

From both modeling studies and Pioneer Venus Orbiter (PVO) observations, we know that at Venus planetary ion (mainly O^+) production or "mass-loading" effects appear to be confined mainly to a thin layer adjacent to the obstacle boundary [e.g., *Spreiter and Stahara*, 1992]. According to scaled estimates by *Zwan and Wolf* [1976] and observational analyses of PVO data by *Zhang et al.* [1991], the magnetosheath depletion layer at Venus

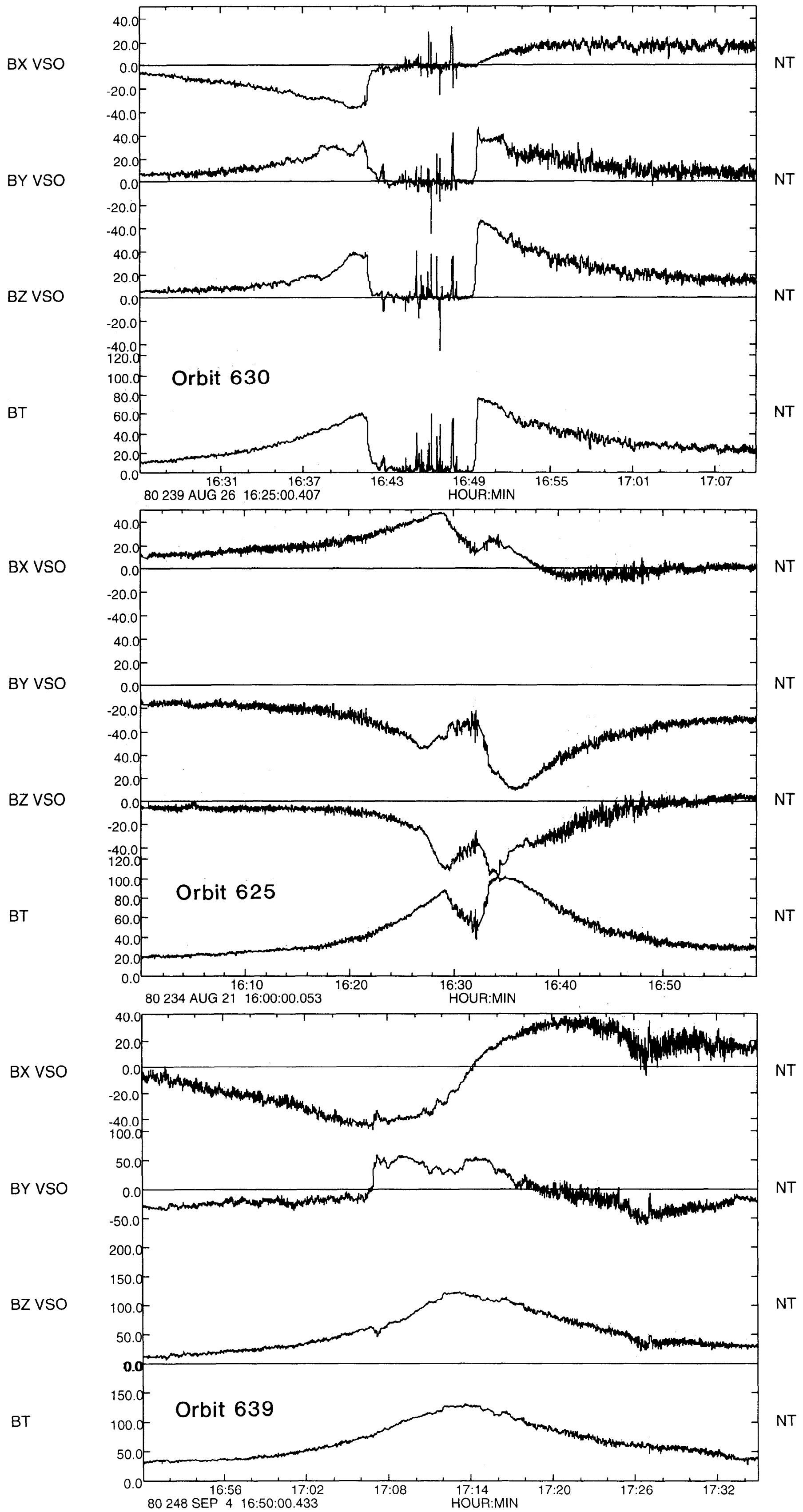

Figure 3. Illustration of magnetic field time series from PVO subsolar magnetosheath passes showing the signatures of (top) deep penetration into the ionosphere, (middle) a shallow ionosphere encounter, and (bottom) intersection of the magnetic barrier only. Only the last type of passes were used in this study.

should be $\sim$100 - 200 km thick in the subsolar region. Solar wind proton gyroradii in the Venus inner magnetosheath are typically $\leq$ 50 km, compared to the $\sim$0.5 R_V (Venus radius = 6052 km) thickness of the subsolar magnetosheath. (At Earth, the proton gyroradii are about the same, and the thicknesses of the depletion layer and subsolar sheath are $\sim$0.25 R_E and $\sim$5 R_E, respectively). Thus Venus provides a magnetosheath that should exhibit some of the same basic MHD behavior as Earth's, although the relative scaling makes the potential importance of any kinetic effects greater at Venus.

Unfortunately, the PVO plasma analyzer, which was designed primarily for solar wind studies, did not have the necessary temporal resolution to obtain detailed measurements of the solar wind plasma density and flow in the dayside magnetosheath [e.g., *Zhang et al.*, 1991]. Hence investigations of both the density depletions in the inner magnetosheath and of the *Song et al.* [1992a] smaller-scale density enhancements are precluded. Nevertheless, the magnetic field observations, at ¼ - ½ s resolution, allow detailed studies of the interplanetary magnetic field (IMF) pile-up and draping against the Venus obstacle [*Luhmann et al.*, 1986; *Zhang et al.*, 1993]. For example, *Zhang et al.* [1993] analyzed the "magnetic barrier" which corresponds to the depletion layer in that it is the region where the magnetic pressure in the magnetosheath makes up the dominant fraction of the incident solar wind pressure. They showed that in this region the gas-dynamic representation of the Venus magnetosheath [*Spreiter and Stahara*, 1980] becomes inadequate due to the effects of magnetic forces, as at Earth. These data also allow us to ask whether a transition in inner magnetosheath field and wave behavior of the type shown by *Song et al.* [1992a] exists at Venus. The value of beta inferred from the upstream dynamic pressure and magnetosheath field in the *Zhang et al.* [1991] study is $\leq$0.1 near the inner boundary of the Venus magnetosheath, fulfilling the condition (low beta) for which the slow mode structures were found at Earth [*Song et al.*, 1990a]. (Beta is $\sim$1 in the upstream solar wind at 0.7 AU, similar to typical 1 AU values.) Here we describe the results of a search for standing structures in the subsolar Venus magnetosheath that are characterized by a regularly occurring rotation of the field and/or a change in the character of the local wave properties. We find no evidence for the type of transition reported by *Song et al.* [1992a, b]. The observations appear to be more consistent with a smooth, continuous behavior.

Observations

The PVO magnetometer is described in detail by *Russell et al.* [1980]. The highest time resolution data, ¼-½ s vectors, depending on the mode of operation, were used in the present study. Because of the size of the Venus obstacle and the PVO orbit, the subsolar magnetosheath was best sampled on the orbiter's third circuit of Venus, when the rising periapsis altitude had reached the neighborhood of the subsolar ionopause (about 300 km). (On the first two passes the low-altitude dayside magnetosheath was crossed primarily at moderate to high solar zenith angles.)

We examined the magnetic field data from selected orbits in the range 625-650, which probed the subsolar magnetosheath near its inner boundary but did not enter the ionosphere proper. As shown by Figure 3, entry into the ionosphere is generally observed in the field as a decrease in magnitude at periapsis together with the appearance of ionospheric fields (such as flux ropes) if the penetration is deep enough. Selection for the present study was further based on the absence of sudden, one-of-a-kind rotations in the field components that suggested the passage of convecting rotational or tangential interplanetary field discontinuities. Although no upstream monitor was present at Venus to ensure steady conditions during these magnetosheath passes, the absence of substantial changes in interplanetary magnetic field (IMF) orientation between inbound and outbound crossings of the bow shock was used as a further discriminator. Cases where it appeared as if waves associated with an upstream quasi-parallel bow shock were present [e.g., *Luhmann et al.*, 1983] were also excluded.

The location of the spacecraft for four particularly "steady" cases is shown in Figure 4. It is notable that for PVO, the inner magnetosheath is crossed along more parallel trajectories than was the case for *Song et al.*'s [1992a] ISEE data. Nevertheless, the relatively small thickness of the Venus magnetosheath depletion layer is such that its outer boundary should still be

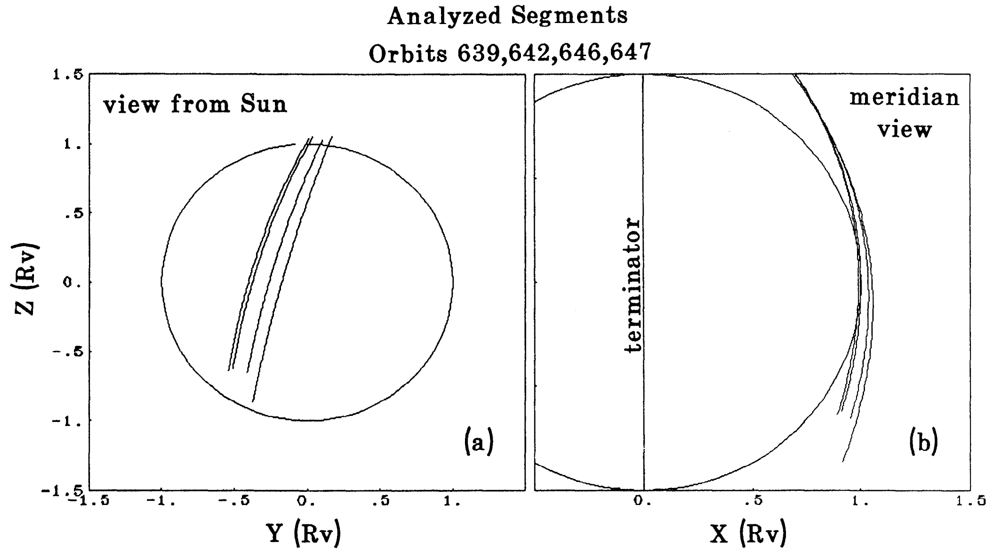

Figure 4. Projections of the orbit segments used in this study of the Venus subsolar magnetosheath. (a) View from Sun. (b) Noon-midnight meridian plane view.

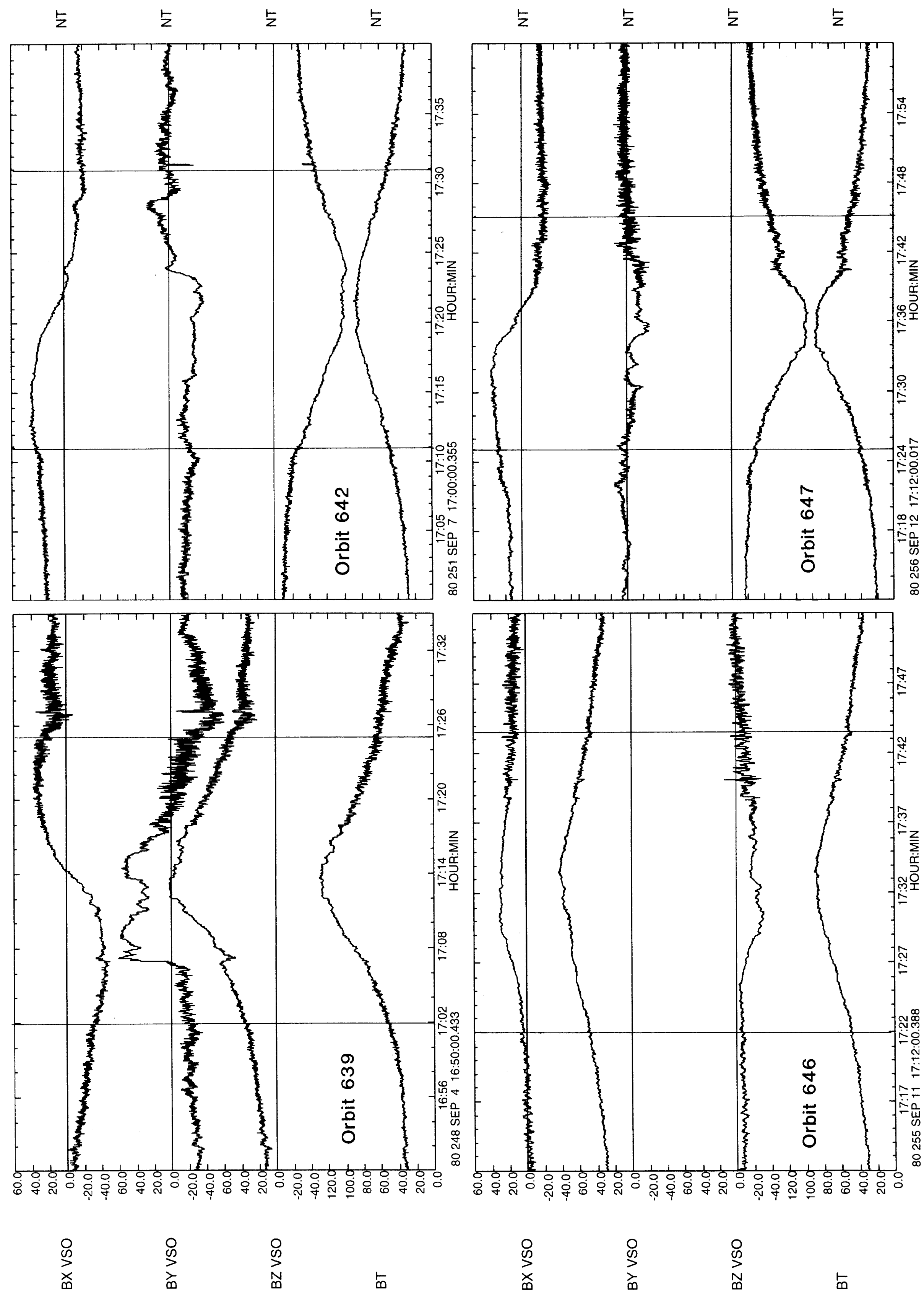

Figure 5. Time series of the PVO magnetic field data for the selected passes through the subsolar magnetosheath. Data adjacent to the intervals of interest (between the vertical lines) are shown for perspective.

intersected within ~45° of the subsolar point. The high time resolution inner magnetosheath field time series for the selected intervals are shown in Figure 5 in the context of the adjacent measurements further down the flanks. Lower time resolution vector projections along the trajectories, for a slightly longer period, are displayed in Figure 6. The cartesian coordinate system is VSO, which is similar to GSE but for Venus.

Examination of Figure 5 shows one clear pattern in the ambient wave activity: apparent damping of the waves as the field becomes stronger (and presumably, the density depletion occurs) near the nose of the obstacle. Neither the time series (Figure 5) nor vector projections (Figure 6) show any indication of a regular, distinctive field rotation at the outer edge of the field pile-up region, nor is there evidence in Figure 5 that low frequency field fluctuations are enhanced just outside of the pile-up region (as reported by *Song et al.* [1992b]). A pattern of rotations is sometimes seen near periapsis in conjunction with a field decrease on adjacent orbits, but this particular signature invariably occurs when the ionospheric plasma is entered (see *Luhmann* [1988] for a model of this effect). Notice from the vector plots (Figure 6) that orthogonal IMF clock angles have been sampled in this selected group of orbits. Thus what is observed is not unique to a particular draping orientation with respect to the spacecraft trajectory.

Further examination of the wave behavior in the examples in Figure 5 is accomplished by spectral analysis. Figures 7 and 8, respectively, show frequency spectra obtained from the regions of maximum field strength between the vertical lines in Figure 5, and from the adjacent regions in the flanks where the amplitude of fluctuations seems to increase. Both transverse and compressional power are shown. It appears that in the outer and inner magnetosheath region, the transverse power is consistently comparable to or greater than the compressional power. The spectra from the inner region appear smooth, while a broad shoulder seems to develop at frequencies $\leq 0.5\ F_p$ in the outer region spectra obtained at higher solar zenith angles. For reference, the proton cyclotron frequency, F_p, in an 80-nT field is ~1 Hz, which is the approximate upper limit of the frequency spectrum for the PVO data used here. The constancy of the magnetosheath compressional wave spectrum in the inner region is apparent in the dynamic spectra of the field magnitudes shown in Figure 9. Such dynamic spectra are a compact means of illustrating how the spectrum appears throughout the region of space under study. The general damping of wave amplitude with increasing field strength (and presumably decreasing density) mentioned above is clearly visible, but there is no particular evidence in the centers of these displays for a new population of low-frequency waves at low altitudes. As a whole, these analyses do not reveal the "slow mode" transition characteristics considered by *Song et al.* [1992a, b] as typical for Earth dayside magnetopause crossings. From Figure 1, one might expect to regularly observe a rather sharp transition in spectral behavior

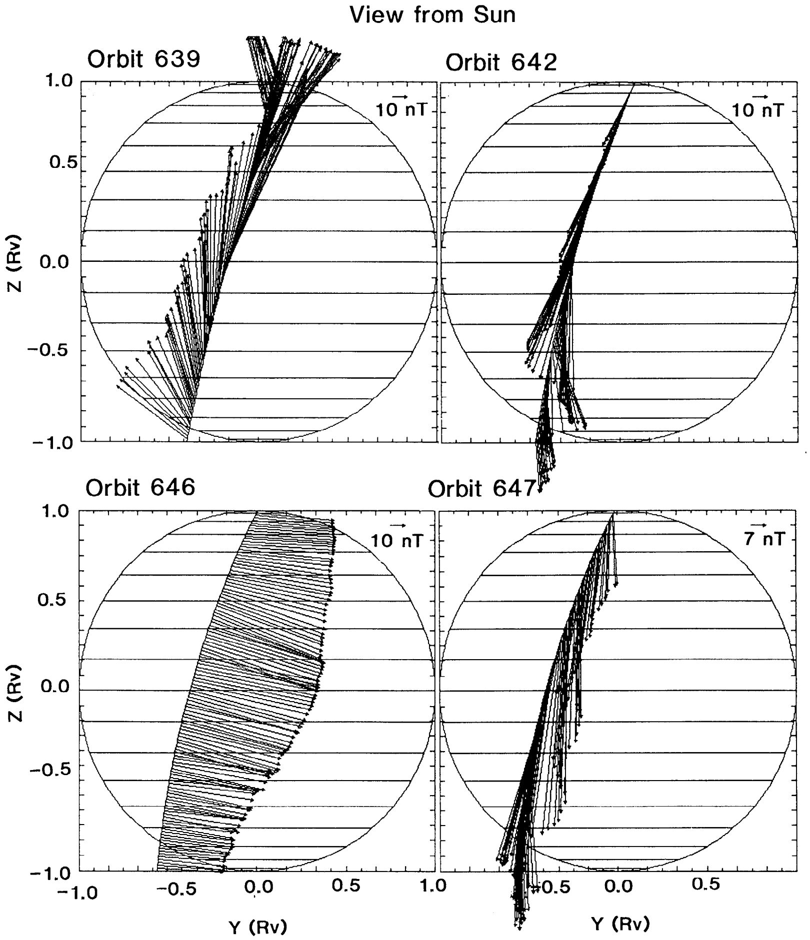

Figure 6. Magnetic vector projections as viewed from the Sun, for the data in Figure 5. The vectors are plotted at lower time resolution for clarity.

within the apparent depletion layer, with enhanced power appearing at the lower frequencies.

Although mode identification is precluded by the limited data, wave analyses (by the method of Born and Wolf, as described by *Rankin and Kurtz* [1970]) of the time series in Figure 5 can be used to determine characteristics such as the ellipticity, the angle between the wave vector **k** and the underlying magnetic field **b**, and the direction of the field fluctuations with respect to the previous two vectors. As shown by Figure 10, the field fluctuations tend to be linearly polarized (ellipticities ≤ 0.2) and have large angles of propagation with respect to the field ($\geq 50°$) in both the outer and inner regions. While such properties can be characteristic of mirror mode waves like those common in the magnetosheath of Earth [e.g., *Anderson and Fuselier*, 1993; *Anderson et al.*, 1994; *Phan et al.*, 1994], the present waves tend to be more uniformly transverse than compressional. Moreover, as shown by the spectra in Figure 8, when a shoulder is present the spectral power decreases rather sharply above ½ the proton cyclotron frequency (Ω_p). These are essentially the same wave properties as were reported by *Song et al.* [1990b] for their analysis of the terrestrial magnetosheath depletion layer region for northward IMF. *Anderson and Fuselier* [1993] and also *Anderson et al.* [1994] found what they identified as linearly polarized transverse low-frequency electromagnetic ion cyclotron waves in the Earth's magnetosheath spectrum. In a complementary theoretical study, *Denton et al.* [1993] postulated that such waves could be generated at frequencies below ½ F_p by the temperature anisotropy in the solar wind alpha particles in the magnetosheath plasma (also see *Denton et al.* [1994] and *Gary et al.* [1994]). The time series of Earth magnetosheath field magnitudes shown by *Anderson and Fuselier* [1993] also appear at least qualitatively similar to those from PVO in that the overall level of wave activity is markedly reduced in the depletion layer. Thus the waves observed in the subsolar Venus magnetosheath under conditions of a subsolar perpendicular bow shock would appear to be ion cyclotron mode. However, the above authors did not remark on the wave vector directions. As they point out [*Anderson et al.*, 1994], ion cyclotron instabilities have maximum growth rates at wave vectors parallel to the background field. The consistently large angles between k and b found here ($\geq 50°$, typically) then constitute a paradox.

Discussion

Crooker et al. [1979] describe the scenario that leads to the formation of the depletion layer as proposed by earlier authors

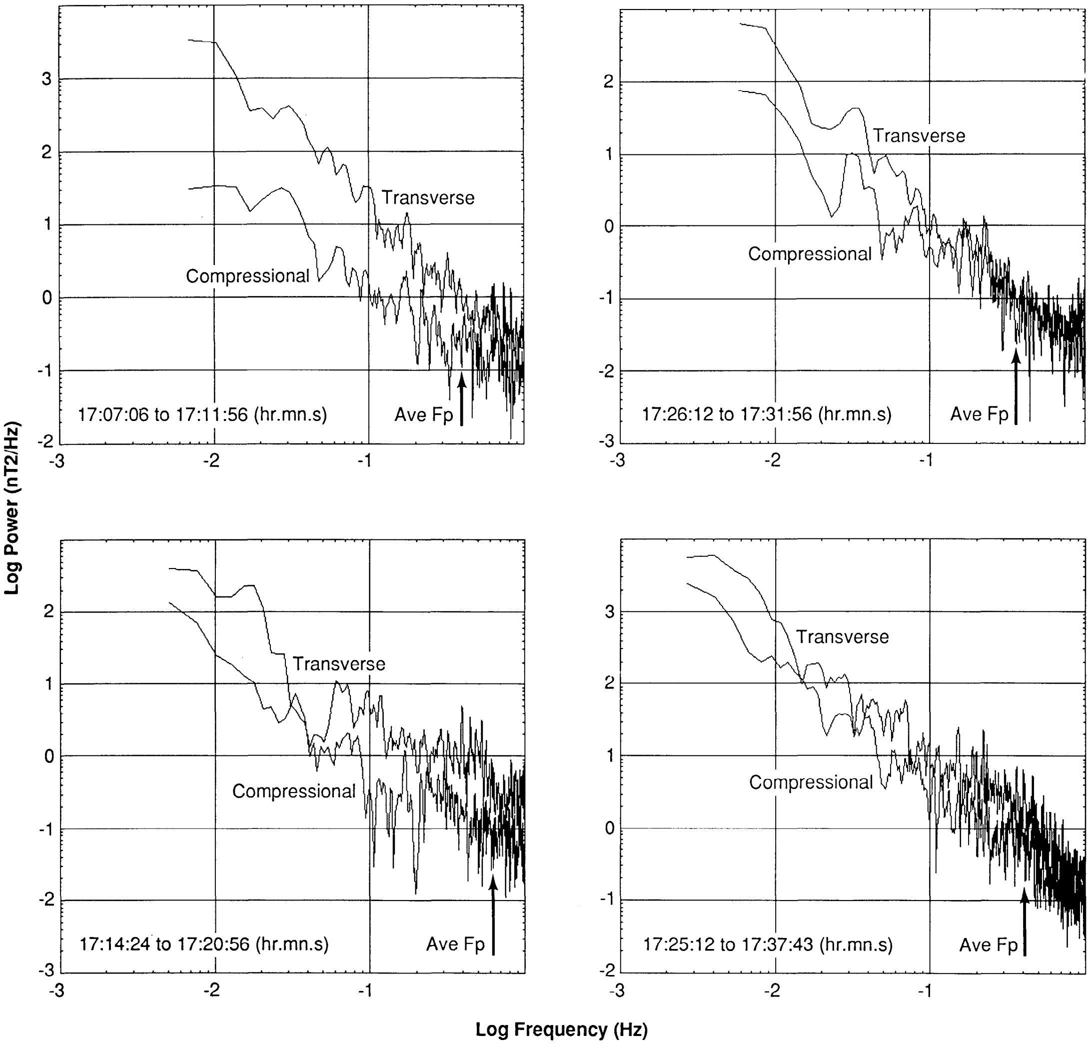

Figure 7. Sample power spectra obtained from detrended data within the vertical lines in Figure 5.

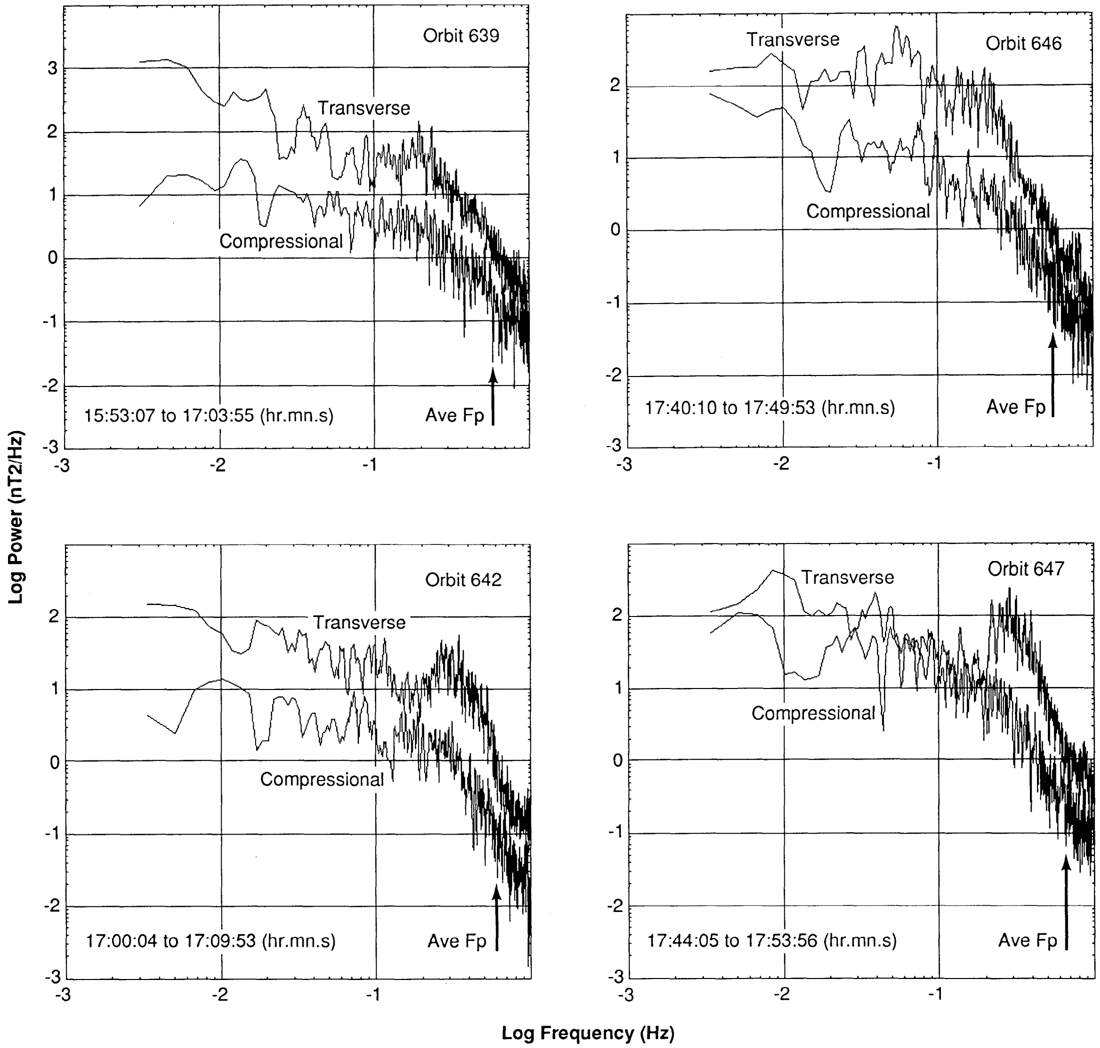

Figure 8. Power spectra obtained from regions outside of the vertical lines in Figure 5.

[e.g., *Zwan and Wolf,* 1976]. They note that a plasma pressure anisotropy, favoring the growth of the perpendicular component, develops as the solar wind plasma adjacent to the magnetopause preferentially runs out the ends of the draped and compressed magnetosheath flux tubes. They also note that the magnitude of the measured pressure anisotropy near Earth's magnetopause indicates the plasma there is marginally unstable to growth of mirror mode waves. Yet they observe the signature structure of oppositely phased quasi-sinusoidal plasma density and magnetic field magnitude variations in the depletion layer on only one of their 17 magnetopause crossings. They suggest that either recognizable waves are confined to a small region very near the stagnation streamline or that the instability does not generally have time to develop in the depletion layer. *Phan et al.* [1994], on the other hand, suggests that mirror mode waves are unstable in much of the magnetosheath, but become stable in the depletion layer where the plasma beta falls below 1. *Anderson and Fuselier* [1993] and *Anderson et al.* [1994] argue that mirror mode gives way to higher-frequency ion cyclotron wave activity as the spacecraft enters the depletion layer behind a perpendicular subsolar shock. This behavior appears to be consistent with the theory of instabilities expected in the anisotropic magnetosheath plasma [*Denton et al.*, 1993, 1994; *Gary et al.*, 1994].

The structures observed just outside of the depletion layer by *Song et al.* [1992a] have the attribute of counterbalanced plasma and magnetic pressure, but their location and the interpretation of their origin is different. In their picture [also see *Southwood and Kivelson*, 1992], a region near the stagnation point radiates a slow mode wave that stands in the magnetosheath flow upstream of the magnetopause. The primary difference between these pictures (that of Song et al. compared to that described in the preceding paragraph) seems to concern the role of the local plasma pressure anisotropy as opposed to a "remote" source. Local pressure anisotropy is not the driver in the *Song et al.* [1992a] picture. Instead, their wave is akin to the whistler mode structure that has been observed standing upstream of the laminar bow shock.

One of the problems in analyzing terrestrial magnetopause structure, mentioned above, is that the interplanetary medium can be highly variable on the timescale of a spacecraft traversal of the subsolar magnetosheath. This variability introduces many apparent "boundaries" into the magnetosheath plasma and field (e.g., J. R. Spreiter and S. S. Stahara, manuscript in preparation, 1995). The problem is especially severe near the stagnation point, where the compression and hence accumulation of interplanetary medium history is greatest. At Venus, we have the

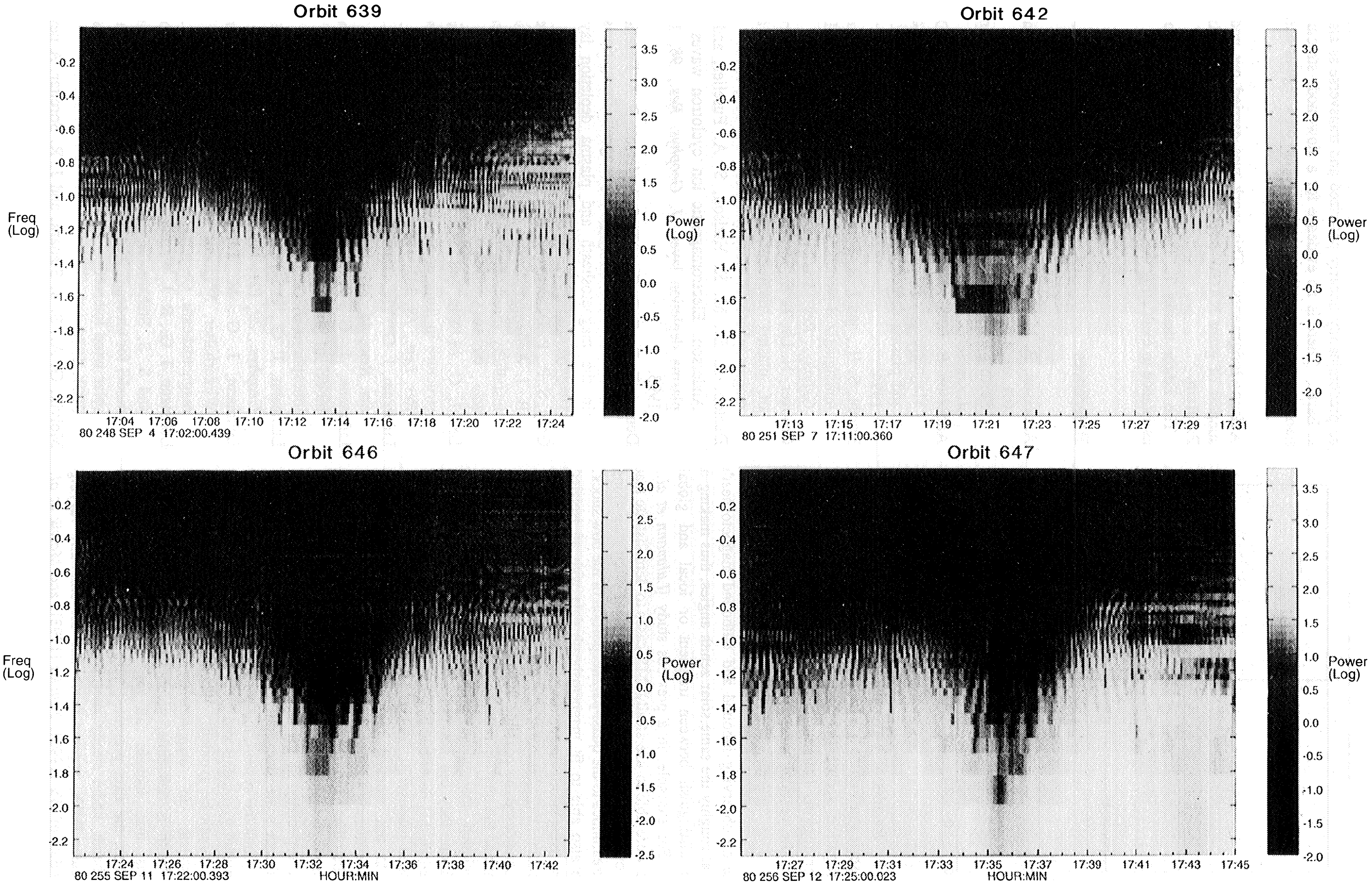

Figure 9. Dynamic spectra for the field magnitude for the same intervals as shown in Figures 7 and 8.

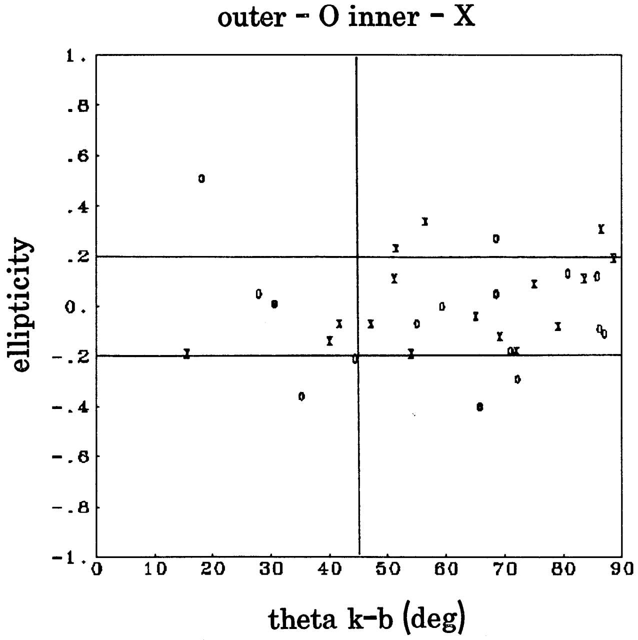

Figure 10. Results of wave analysis of 5-min segments of the time series in Figure 5. Ellipticities and angles between the propagation vector (**k**) and background field (**b**) are shown for regions both inside (crosses) and outside (open circles) of the vertical bars.

advantage of observing inbound and outbound magnetosheath structure at roughly the same solar zenith angles, thus making it easier to distinguish between transient or local and global features. For example, in a previous study [*Luhmann et al.*, 1983] we were able to use steady IMF cases to demonstrate that intervals of strongly fluctuating magnetic field often map along plasma streamlines to the quasi-parallel portion of the bow shock. We were also able to fit magnetosheath data with an isolated rotation by using steady magnetosheath models for two successive IMF orientations [*Luhmann et al.*, 1986]. Although *Song et al.* [1992a] considered the possible influence of changing upstream conditions and the quasi-parallel bow shock on their observations and concluded that these effects would not alter their interpretation, they did not use a very sophisticated mapping technique like that described by J. R. Spreiter and S. S. Stahara (unpublished manuscript, 1995). Without such mapping, it is difficult to tell whether their assessment of interplanetary variability effects is accurate.

On the other hand, there are differences between the Venus and Earth magnetosheaths that can arguably produce distinctive behavior, especially in the depletion layer region. Besides magnetosheath scale size, and the transit time of solar wind plasma through the system, the complicating issues of the larger relative proton gyroradius and local atmospheric ion production at Venus cannot be avoided. Whether these make the Venus magneto-sheath an inappropriate analogue for Earth's magnetosheath is debatable, given that we do not yet have simulations that include all of the necessary physics. Nevertheless, the data presented here suggest that the Venus magnetosheath, under steady interplanetary conditions and for perpendicular IMFs, appears much like the smoothly varying MHD models of *Wu* [1992], *Tanaka* [1993], and *Molvik et al.* [1991]. As at the Earth, one observes the magneto-sheath wave activity diminishing in the depletion layer [e.g., *Phan et al.*, 1994; *Anderson and Fuselier,* 1993]. The waves here appear to be predominantly linearly polarized and transverse as also seen at Earth. There is no evidence for a slow-mode structure that stands in the low-altitude subsolar region on a regular basis.

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