GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 10, PAGES 991-994, MAY 21, 1993

MAGNETIC FIELD PROPERTIES OF THE INTERMEDIATE TRANSITION OF THE VENUS IONOSHEATH

H. Perez-de-Tejada
Instituto de Geofisica, Universidad Nacional Autonoma de Mexico,
Ensenada, Baja California, Mexico

D.S. Intriligator
Carmel Research Center, Santa Monica, CA

R.J. Strangeway
Institute of Geophysics and Planetary Physics, University of California,
Los Angeles, CA

Abstract. We report new results of a statistical analysis of the electric and magnetic field data of the Pioneer Venus Orbiter (PVO) on the intermediate transition of the Venus ionosheath. This transition marks the outer boundary of an expansion region along the flanks of the inner ionosheath, and is identified by simultaneous observations of weak plasma fluxes and characteristic 30 kHz electric field bursts measured, respectively, with the plasma analyzer and the electric field detector. In many cases, the magnetic field signature across the intermediate transition is characterized by a sudden decrease in intensity and an abrupt rotation so that the direction is more nearly aligned with the Sun-Venus line. In other cases the 30 kHz bursts occur outside a region of enhanced magnetic field reminiscent of the magnetic barrier external to the Venus dayside ionopause. In these cases there is also a rotation of the magnetic field toward the Sun-Venus line associated with the 30 kHz bursts, but, in general, the conditions change more gradually. These variations may result from the expansion of the shocked solar wind at and near the magnetic polar regions of the Venus ionopause around which the draped interplanetary magnetic field lines slip over the planet. The expansion of the ionosheath plasma may result from local heating processes associated with a friction-like interaction between the shocked solar wind and the topside ionospheric plasma.

Introduction

We report the first results of a statistical analysis of the magnetic properties of the intermediate transition of the Venus ionosheath. We show that the transition is often characterized by a substantial decrease in magnetic field intensity and an accompanying rotation to a direction more nearly aligned with the Sun-Venus axis. This association and its connection with other known properties of the intermediate transition has not been reported, neither for a case study nor in a statistical sense. The results presented here are based on the analysis of 83 passes, many of which exhibit the behavior indicated.

We reported (Perez-de-Tejada et al., 1984, 1991) our identification of the intermediate transition in terms of characteristic bursts in the 30 kHz channel of the electric field detector (OEFD) and in associated changes in the intensity of measured plasma fluxes. We show that this transition marks the boundary of a region within the inner ionosheath with quite different plasma properties: downstream the speed and density of the flow are lower but its temperature is higher. These variations are in agreement with those reported from Mariner 5 (Bridge et al., 1967) and Venera 9 and 10 (Vaisberg et al., 1976). All these cases show that the shocked solar wind speed decelerates abruptly within the flanks of the inner ionosheath, and there are equally sudden changes in the density and temperature. Mariner 5 data also showed that in the inner ionosheath the magnetic field is less intense than in the outer ionosheath. Conditions in the ionosheath flanks are different from those in the magnetic barrier surrounding the dayside ionosphere, where rarified plasma fluxes and higher magnetic intensities exist due to the accumulation of interplanetary magnetic flux.

Fedorov et al. (1991) reported the rotation of the magnetic field vector in association with different plasma properties (i.e. a strong velocity gradient) within the inner ionosheath. Perez-de-Tejada et al. (1984) reported similar correlations of the Mariner 5 data with a rotation of the PVO magnetic field vector that coincides with the 30 kHz electric field bursts that identify the plasma transition in the ionosheath flanks. These variations clearly show the strong coupling experienced by the plasma and the magnetic flux of the shocked solar wind as they interact with the Venus ionosphere and also emphasize the fact that other phenomena, in addition to the formation of the magnetic barrier, are operative in the interaction process.

Electric and Magnetic Field Measurements

We examined 320 PVO orbits, containing 559 passes of the Venus ionosheath. We analyzed the plasma, magnetic, and electric field data for 83 passes in which there were strong and well localized ionosheath bursts in the OEFD 30 kHz channel. As in earlier case studies (Perez-de-Tejada et al., 1984, 1991), we find indications of consistent agreement between the 30 kHz bursts and the position where important changes occur in the plasma and magnetic fields. Most of the 30 kHz bursts are associated with either one of the following two magnetic field patterns: *i*) In "magnetic drop cases" magnetic intensity in the inner ionosheath decreases appreciably when the 30 kHz bursts occur. Usually this is associated with a sudden and strong rotation of the magnetic field toward the Sun-Venus aligned direction so that the weak magnetic flux between the ionopause and

Paper number 93GL00488
0094-8534/93/93GL-00488$03.00

the position where the 30 kHz bursts are detected show a strongly draped configuration. *ii*) In "magnetic non-drop cases" the 30 kHz bursts are not accompanied by a drop in magnetic intensity but appear just upstream from a region where the magnetic intensity increases prior to the ionopause crossing. The increase of the magnetic intensity is reminiscent of the magnetic barrier around the dayside ionosphere; the 30 kHz signals sit just outside the region of enhanced magnetic flux.

Table 1 summarizes these results. The magnetic drop cases occur in 41 passes; of these, 29 show an abrupt drop and 12 drop more gradually. The magnetic non-drop cases occur in 43 passes exhibiting any one of the following three magnetic field profiles: *i*) In the 25 passes labeled "outside," the 30 kHz bursts occur near but outside the initial downstream rise in magnetic intensity that leads to the peculiar magnetic barrier geometry (in all these cases there is also a rotation of the magnetic vector toward the Sun-Venus line); *ii*) In the 15 passes labeled "level," the 30 kHz bursts occur near a region where the magnetic profile changes slope from a general decreasing trend, inbound in the outer ionosheath, to a level configuration in the inner ionosheath (in 11 of these passes a similar rotation toward the Sun-Venus line is observed); *iii*) In the "inside" passes, the 30 kHz bursts are seen in the region where the magnetic intensity rises prior to the ionopause crossing. These cases do not represent clear-cut differences in the shape of the magnetic profile; their overall variety offers an almost continuous range of shapes that may differ only slightly from one another. Some of the level-profile cases also could be interpreted as a weak accumulation of magnetic flux around the ionopause. An odd case (outbound on orbit 535) has been left out of Table 1 since strong 30 kHz bursts are seen upstream from the sharp drop in magnetic intensity. The 85 cases reported here thus apply to the 83 passes, including 2 in which there are two separate 30 kHz burst events.

The data of orbit 87 (Figure 1) show both the sharp magnetic drop and the outside magnetic barrier cases. Enhanced 30 kHz signals (upper panel) are present at and upstream from the bow shock crossings (~1905 UT and ~2007 UT, respectively). These bursts occur when the solar wind density is ~10 cm^{-3}. Downstream from the bow shock no signals are recorded because the higher local densities lead to plasma frequencies above 30 kHz. In Figure 1, however, the 30 kHz signal shows brief but intense bursts in the inner ionosheath (~1920 UT inbound and ~1952 UT outbound), similar to that seen on the inbound pass of orbits 72 and 80 (Perez-de-Tejada et al., 1984) and consistent with a sudden expansion of the shocked solar wind plasma in the inner ionosheath. (As the density drops from high (> 10 cm^{-3}) to low (< 10 cm^{-3}) values the 30 kHz channel becomes responsive to local wave activity.) The strong 30 kHz bursts occur well upstream from the ionopause and do not result from wave activity at this boundary (the ionopause locations at ~1928 and ~1944 UT were obtained from the electron temperature probe data). The positions on orbit 87 of the bow shock, ionopause, and intermediate transition (identified by the 30 kHz bursts) are shown in Figure 2.

Table 1. 30 kHz bursts and magnetic field profiles

	Magnetic drop cases		Magnetic non-drop cases		
	sharp	gradual	level	outside	inside
Sharp, toward	28	3	2	8	–
Gradual, toward	–	9	9	17	3
Away	1	–	1	–	–
Variable	–	–	3	–	–
Totals	29	12	15	25	3

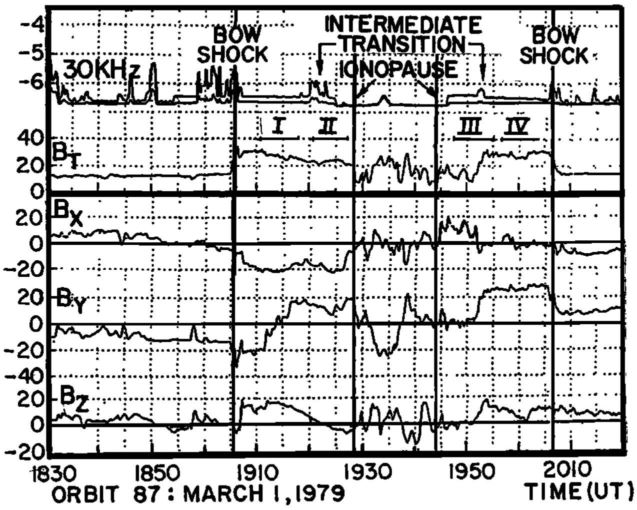

Fig. 1. (Upper panel) Electric field 30 kHz signal and magnetic field intensity, measured inbound and outbound on orbit 87, and (lower panels) simultaneous magnetic field components.

Figure 1 shows that outbound on orbit 87 the 30 kHz bursts at 1952 UT– 1953 UT occur when magnetic intensity drops from ~30 γ upstream to ~10 γ downstream. The magnetic vector shows strong rotation from a preferred Y–Z orientation upstream (in the plane perpendicular to the Sun Venus line) to a direction nearly aligned with the X-axis downstream (lower panel). This strongly draped orientation of the field lines persists throughout the region between the intermediate transition and the outbound (~1944 UT) crossing at the ionopause (where there is a series of irregular oscillations).

Inbound, the magnetic field across the intermediate transition is entirely different. The 30 kHz bursts occur when the magnetic intensity changes slope. Upstream from this location there is a gradual decrease of this quantity as PVO moves inbound. After ~1921 UT the profile levels off and shows a rise downstream. After ~1951 UT, B_X tends to rise until the inbound ionopause crossing occurs (lower panel); but B_Y is strong during this time, so the field line draping around Venus is not as accentuated in this case as in the outbound pass.

Plasma Measurements

To investigate the association of 30 kHz bursts with important changes in ionosheath plasma, we extensively examined

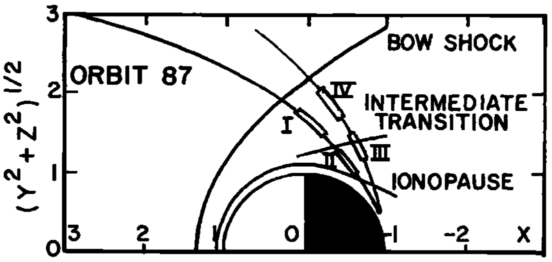

Fig. 2. Orbit 87 bow shock, intermediate transition, ionopause, and PVO trajectory, projected on a plane in which the vertical coordinate gives the distance to the Sun-Venus axis. The white boxes correspond to respective data in Figures 1 and 3.

the Orbiter Plasma Analyzer (OPA) data for many of the passes in the two groups indicated above. Perez-de-Tejada et al. (1984, 1991) showed that much weaker plasma fluxes were recorded downstream from the position where the 30 kHz bursts occurred and that the change in plasma flux intensity when such bursts are detected can be very abrupt.

Evidence that further supports these findings has now been obtained from the analysis of the new data. Figure 3 shows ion spectra recorded on orbit 87. Each panel shows the spectra of the two energy scans obtained in that region of space, indicated by the white boxes along the PVO trajectory in Figure 2. Spectrum I was initiated at 1910:41 UT, after the spacecraft crossed the bow shock, and reflects the conditions present in the outer ionosheath where fairly intense plasma fluxes are usually recorded. Spectrum II shows much weaker values; it was initiated at 1919:47 UT, near the time when the 30 kHz bursts were first recorded (see Figure 1), and thus reflects the conditions present downstream from that feature. These spectra are similar to those previously reported (Perez-de-Tejada et al., 1991). These variations indicate that the plasma fluxes measured in the inner ionosheath are much weaker, and have lower bulk speeds, than those in the outer ionosheath. The very different peak intensity of the plasma flux in each spectrum is entirely consistent with the identification of the 30 kHz bursts as markers of the boundary of a region in the inner ionosheath within which the shocked solar wind moves more slowly and expands severely.

Further substantiation is obtained by examining the spectra measured outbound on orbit 87. In this case, spectrum IV describes conditions in the outer ionosheath (a fairly good distribution with strong peak fluxes). Spectrum III is peculiar in that it contains one main high energy maximum with peak fluxes comparable to those seen in the outer ionosheath (spectrum IV), and one main low energy maximum with peak flux comparable to that of the distribution measured in the inner ionosheath in the inbound pass (spectrum II). This unusual spectrum began at 1947:27 UT and ended at 1954:41 UT, and thus extends across the (1952 UT–1953 UT) time interval in which the 30 kHz bursts are detected outbound. Significantly, the sudden increase in the plasma flux that separates both main maxima occurs nearly at the time when the 30 kHz bursts are detected. The peak plasma flux measured in the 494.8 volt step (at 1950:44 UT) is 3.3 10^7 ions cm^{-2} sec^{-1} sr^{-1} while that measured in the 1321.3 volt step (recorded at 1952:10 UT) is 4.2 10^8 ions cm^{-2} sec^{-1} sr^{-1}. Thus the weak low-energy flux measured before this later energy step was detected downstream from the 30 kHz burst event and reflects conditions similar to those seen inbound downstream from the same feature. Conversely, the strong plasma fluxes of the high-energy peak reflect flow conditions applicable to the outer ionosheath flow.

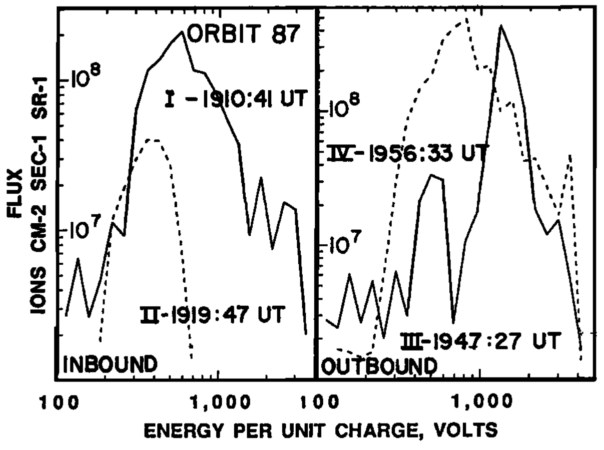

Fig. 3. OPA ion spectra. The start time of each scan is shown.

Discussion

The layer of rarified plasma fluxes in the inner ionosheath, as inferred from our analysis of the above measurements, is not contrary to the conditions expected within and downstream from the magnetic barrier that forms around the dayside ionopause, where the enhanced local magnetic pressure compensates for the lower plasma energy densities (from the depletion of stream tubes pressed against the ionopause). However, the association of lower plasma densities with decreased magnetic field intensities in the inner flank ionosheath, as in the outbound pass of orbit 87 and in many others of the first group of passes reported in Table I, deserves closer examination.

To further investigate this we examined the Y–Z projection of the magnetic field (transverse to the Sun-Venus line) on orbit 87. This is shown in Figure 4 along the trajectory of the spacecraft as it moved from north to south behind the planet. Since the orientation changes little during the outbound pass, we can define the position of the magnetic polar region (the section of the ionopause where the draped magnetic field lines slip over the planet). Figure 4 shows that this region (the arc section P) is close to where the 30 kHz bursts were detected outbound. During this pass PVO probably moved downstream from the southern magnetic pole. A similar consideration cannot be made for the inbound pass due to the strong rotation of the magnetic field as PVO moved from the freestream solar wind across the ionosheath. Increased magnetic intensity between 1922 UT and 1928 UT (upper panel of Figure 1) suggests that PVO may have moved downstream from the magnetic barrier.

Perez-de-Tejada (1986) argued that conditions at and near the magnetic polar regions, where the accumulation of magnetic flux is not severe, should allow more direct plasma–plasma interaction between the shocked solar wind and the ionospheric

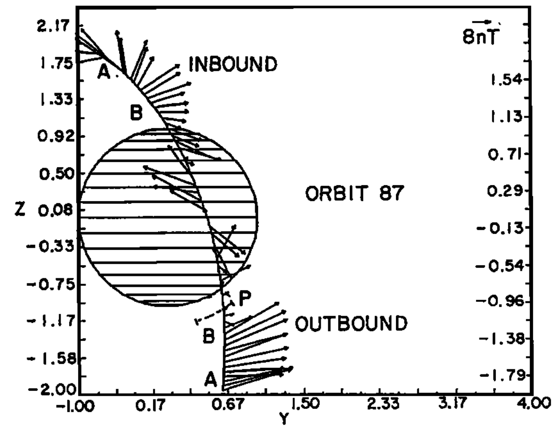

Fig. 4. Magnetic vectors measured along the PVO trajectory, projected on the Y–Z plane (transverse to the Sun-Venus axis). The A and B positions correspond, respectively, to the freestream solar wind and near where the 30 kHz bursts are detected in the inner ionosheath, both inbound and outbound. The arc section labeled P indicates the location of the magnetic polar region on the outbound pass.

plasma. Friction processes resulting from such interactions will produce variations in the plasma properties like those observed. To match the external flow pressure, the transport of solar wind momentum to the upper ionosphere results in local heating leading to lower plasma densities.

Thus, decreased plasma densities should accompany the decelerated shocked solar wind flow in the inner ionosheath. Many of these concepts have been traced to momentum scattering interactions involving turbulent wave fields in connection with conditions seen at the Mars magnetopause, where similar effects also appear to occur (Perez-de-Tejada, 1991). Local expansion of the plasma from frictional heating seems compatible with the decrease and rotation of the magnetic field seen across the intermediate transition. As the hot plasma of the inner ionosheath expands, the convected magnetic flux decreases, but the stream tubes of frictionally decelerated flows must increase their cross section. This implies deflection of the oncoming flow away from the ionopause as the shocked solar wind slows near the terminator. The distribution of plasma and magnetic disturbances generated at the ionopause should modify flow conditions there. We expect the draped magnetic field configuration over the magnetic polar regions, where the friction interaction is more favorable, to be convected by the plasma parcels as they are forced away from the ionopause and that the magnetic field will exhibit a more draped configuration at and downstream from the intermediate transition.

The most remarkable aspect of the observations is the sudden change in the plasma properties across the intermediate transition. Friction layers in supersonic flows are sharply bounded features because the limited transverse distribution of disturbances can only affect a layer of the streaming flow adjacent to an obstacle (Perez-de-Tejada, 1991). At Venus the intermediate transition may represent the outer boundary of a friction layer, external to the ionopause, whose thickness increases with downstream distance. The suggested stratification of the Venus ionosheath may be a property shared with the Mars magnetosheath, where evidence of an intrinsic layering of that region has recently been reported from the Phobos plasma data analysis (Lundin et al., 1990). Much of the dynamics behind these effects is ultimately related to the planetary pickup ions (Intriligator, 1982, 1989; Breus et al., 1989), but it is not evident that the presence and assimilation of that population is sufficient to explain the flow stratification. Since the intermediate transition is seen both near and far downstream from Venus, its interpretation as a mass loading boundary would require that the processes producing it be independent of the local density of neutral particles. The remarkable changes of the plasma properties seen across the intermediate transition probably result from the downstream distribution and convection of disturbances generated at the ionospheric obstacle.

Acknowledgements

C.T. Russell and L.H. Brace provided magnetic field and electron density data. Funding by the Consejo Nacional de Ciencia y Tecnologia de Mexico (CONACyT) and by the Pioneer Venus Project Office, under contracts NAS2–12912 (CRC) and NAG 2–485 (UCLA), and services provided by NOAA's Space Environment Laboratory are appreciated.

References

Breus, T.K., S.J. Bauer, A.M. Krymskii and V. Ya. Mitniskii, Mass loading in the solar wind interaction with Venus and Mars, *J. Geophys. Res.*, *94*, 2375–2382, 1989.

Bridge, H.S., A.J. Lazarus, C.W. Snyder, E.J. Smith, L. Davis, P.J. Coleman and D.E. Jones, Plasma and magnetic field observed near Venus, *Science*, *158*, 1669–1673, 1967.

Fedorov, A.O., O.L. Vaisberg, D.S. Intriligator, R.Z. Sagdeev, and A.A. Galeev, A large amplitude rotational wave in the venusian ionosheath, *J. Geophys. Res.*, *96*, 87–99, 1991.

Intriligator, D.S., Observations of mass addition to the shocked solar wind in the Venus ionosheath, *Geophys. Res. Lett.*, *9*, 727–730, 1982.

Intriligator, D.S., Results of the first statistical study of PVO plasma observations in the distant Venus tail: Evidence for a hemispheric asymmetry in the pickup of ionospheric ions, *Geophys. Res. Lett.*, *16*, 167–170, 1989.

Lundin, R., A. Zakharov, R. Pellinen, H. Borg, B. Hultqvist, N. Pissarenko, E.M. Dubinin, S.W. Barabash, I. Liede, and H. Koskinen, Plasma composition measurements of the martian magnetosphere morphology, *Geophys. Res. Lett.*, *17*, 877–880, 1990.

Perez-de-Tejada, H., Distribution of plasma and magnetic fluxes in the Venus near wake, *J. Geophys. Res.* *91*, 8039–8044, 1986.

Perez-de-Tejada, H., Momentum transport at the Mars magnetopause, *J. Geophys. Res.* *96*, 11,155–11,163, 1991.

Perez-de-Tejada, H., D. Intriligator, and F. Scarf, Plasma and electric field measurements of the PVO in the Venus ionosheath, *Geophys. Res. Lett.*, *11*, 31–34, 1984.

Perez-de-Tejada, D.S. Intriligator, and R.J. Strangeway, Steady state plasma transition in the Venus ionosheath, *Geophys. Res. Lett.*, *18*, 131–134, 1991.

Vaisberg, O.L., S.A. Romanov, V.N. Smirnov, I.P. Karpinsky, B.I. Khazanov, B.V. Polenov, A.V. Bogdanov, and N.M. Antonov, Ion flux parameters in the solar wind-Venus interaction region according to Venera 9 and Venera 10 data. *Physics of Solar Planetary Environment, Vol. 2*, (ed. Williams, D.) 904–917, American Geophysical Union, Washington, D. C., 1976.

D.S. Intriligator, Carmel Research Center, P.O. Box 1732, Santa Monica, CA 90406.

H. Perez-de-Tejada, Instituto de Geofisica, Universidad Nacional Autonoma de Mexico, Ensenada, Baja California, Mexico.

R.J. Strangeway, Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90024–1567.

(Received September 10, 1992;
revised November 16, 1992;
accepted January 21, 1993.)