Geofísica Internacional (2001), Vol., 40, Num. 1, pp. 43-52

Plasma channels in the Venus upper ionosphere

H. Pérez de Tejada
Instituto de Geofísica, UNAM, México

Received: December 9, 1999; accepted: May 8, 2000.

RESUMEN

Se modela la estructura de la ionosfera nocturna del planeta Venus con base en una configuración de flujo derivada de la posición de la transición intermedia en la región de transición con el viento solar. Se infiere que el viento solar erosiona la ionosfera del planeta alrededor de las regiones magnéticas polares en donde se producen conductos de plasma en forma de canales que se extienden hacia el hemisferio noche. Los canales de plasma dan lugar a una pérdida limitada de material ionosférico, el cual, se distribuye en una geometría asimétrica através de su estela. La posición de los canales permite la observación de los agujeros ionosféricos detectados a lo largo de la trayectoria del vehículo espacial Pionero Venus. Estos eventos resultan del cruce del vehículo a través de los canales de plasma dependiendo de la orientación de su trayectoria. La distribución de flujo dentro de la estela es consistente con la entrada de plasma desde los polos magnéticos que fue propuesta para explicar la geometría de la ionopausa nocturna (Pérez de Tejada, 1980).

PALABRAS CLAVE: Ionosfera de Venus, canales de plasma, agujeros ionosféricos.

ABSTRACT

The structure of the Venus nightside ionosphere is modeled in terms of a flow configuration derived from the position of the intermediate transition along the flanks of the ionosheath downstream from the magnetic polar regions. It is suggested that the shocked solar wind erodes more strongly the polar ionosphere producing plasma channels that extend downstream from the magnetic polar regions. Such features represent the main source of mass loss along the plasma tail and imply a small overall solar wind-induced depletion of the planetary ionosphere. The plasma channels can account for the observation of ionospheric holes in PVO passes through the Venus wake. The expected flow distribution within the wake is consistent with the entry of plasma fluxes from the magnetic polar regions that was suggested earlier to account for geometry of the nightside ionopause (Pérez de Tejada, 1980).

KEY WORDS: Venus ionosphere, plasma channels, ionospheric holes.

INTRODUCTION

From the most notable results obtained from the *in situ* examination of the Venus plasma environment with various spacecraft [Mariner 5, Venera 9-10, Pioneer Venus Orbiter (PVO)] there is substantial evidence for the observation of important features that characterize the structure of that planet´s ionosphere. In particular, measurements made with the Orbiter Electron Temperature Probe (OETP) instrument of the PVO have shown the existence of separate portions of the ionosphere (plasma clouds) and the presence of deep density troughs (plasma holes) in the nightside ionosphere (Brace *et al*; 1982a, b; 1987). Most often the plasma clouds are detected along the flanks of the ionosheath and represent structures that are distributed all around the wake (Ong *et al*., 1991). By contrast the ionospheric holes are only observed in the deep nightside ionosphere and occur as features mostly located in the inner parts of the wake (Murabashi *et al*., 1985).

Measurements have also shown a general asymmetry in the plasma configuration around the wake. Differences in the plasma distribution are produced by the orientation of the interplanetary magnetic field that drapes around the ionosphere. As a result of the induced magnetic barrier formed around the dayside ionosphere the magnetic fluxes slip gradually over the planet to enter the wake behind the magnetic polar regions. In these regions the magnetic field may exhibit values that are smaller than those encountered downstream from the magnetic barrier (magnetic lobes) and produce a different plasma configuration. Magnetic field data obtained in PVO passes through the near wake have revealed, in particular, the existence of a plasma boundary (intermediate transition) located between the bow shock and the ionopause. Across this transition there are important changes in the magnetic field with lower intensity values in the inner ionosheath and a rotation to directions closer to that of the solar wind motion (Pérez de Tejada *et al*., 1995). Below we will examine the implications of the conditions that are seen downstream from the magnetic polar regions with respect to the plasma properties expected in the polar upper ionosphere.

MAGNETIC FIELD STRUCTURE IN THE NEAR WAKE

From the analysis of the magnetic field data of a large number of PVO passes through the Venus wake it has been possible to determine the main characteristics of the magnetic field geometry in that region. From crossings made in the far wake Saunders and Russell (1986, see Figures1-4) reported the presence of regions with enhanced magnetic field intensity (magnetic lobes) bounded by a sharp rise that marks the outer extent of the magnetic tail. Different from crossings of this boundary there are also cases in which the spacecraft moved through the neutral sheet located between both magnetic lobes with a magnetic signature that does not have a significant increase in the magnetic field intensity.

Magnetic field profiles similar to those observed when the PVO moved through the neutral sheet have been identified in crossings of the near wake. Because of the near polar inclination of the PVO trajectory and the preferential orientation of the interplanetary magnetic field to remain on planes nearly parallel to the ecliptic plane there is a tendency for that spacecraft to observe the region behind the magnetic polar regions (these occur at latitudes where the draped magnetic field lines slip over the planet to enter the wake). In most cases there is evidence of a sharp drop in the magnetic field intensity to low values in the inner ionosheath and it has been possible to suggest the existence of a region that extends downstream from the magnetic polar regions where the magnetic field intensity is smaller than in the outer ionosheath (Pérez de Tejada, 1997). A schematic of the overall configuration of the magnetic field within and around that region (expansion fan) is reproduced in Figure 1. PVO passes traced through that region will produce magnetic field profiles with a significant decrease before entering the ionosphere. Passes that probe outside that region will measure enhanced magnetic field intensities through the magnetic lobes that extend downstream from the magnetic barrier in the dayside ionosphere.

FLOW PROPERTIES ACROSS THE INTERMEDIATE TRANSITION

From the early observation of the interplanetary magnetic field draped around the Venus ionosphere it was recognized that there should be differences in the manner in which the ionospheric plasma is modified by the ram pressure of the solar wind. The presence of the magnetic barrier around the dayside ionosphere reduces the direct interaction of both plasma populations in the transport of their statistical properties (a small amount of solar wind momentum can only be transferred to the upper ionospheric plasma if a large fraction of the incident kinetic energy density has been converted into local magnetic energy density). Different conditions should be operative, however, in the vicinity of the magnetic polar regions where a strong accumulation of magnetic field fluxes is not expected around the local ionosphere. In this case the ionospheric particles should be most effectively removed through mechanisms associated with the interaction process. A calculation of the displacement of ionospheric particles from the magnetic polar regions through solar wind momentum was presented by Pérez de Tejada (1980) in terms of the expected altitude of the nightside ionopause. A schematic of the predicted distribution of ionospheric particles downstream from a magnetic polar region is reproduced in Figure 2. The most notable characteristic is the removal of polar ionospheric plasma which is redistributed in a configuration that reaches higher altitudes at lower magnetic latitudes.

The erosion of the Venus polar ionosphere by the solar wind momentum can also be inferred from changes in the

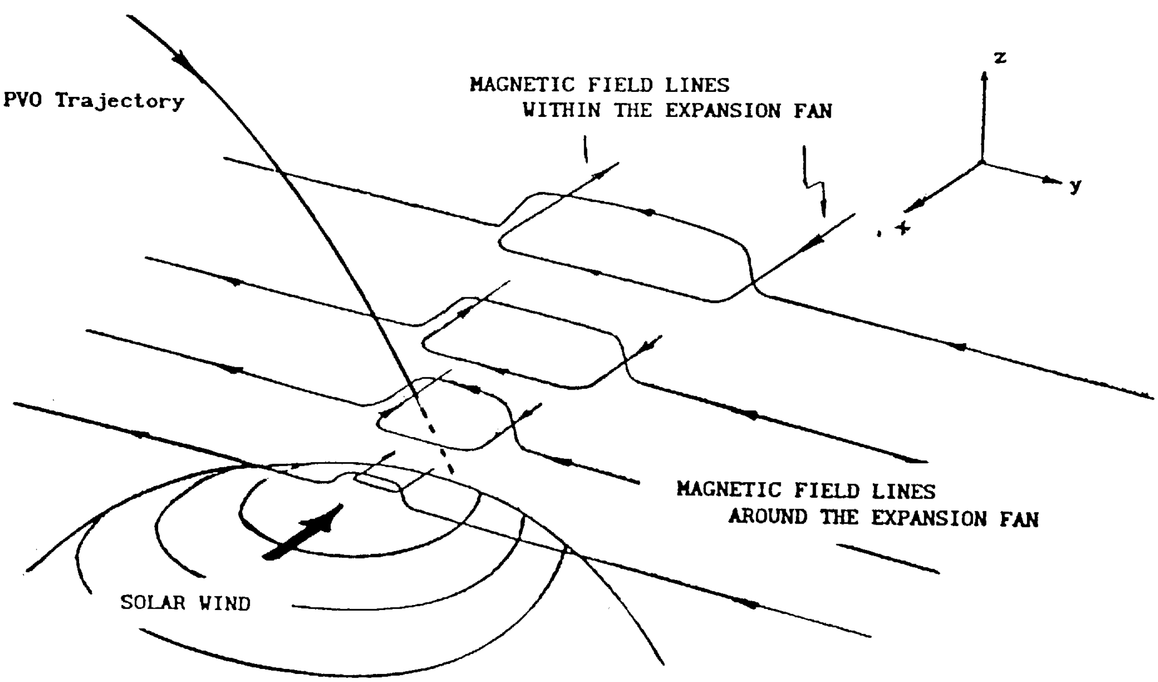


Fig. 1. Schematic expansion fan extending downstream from a magnetic polar region (from Pérez de Tejada, [1997]).

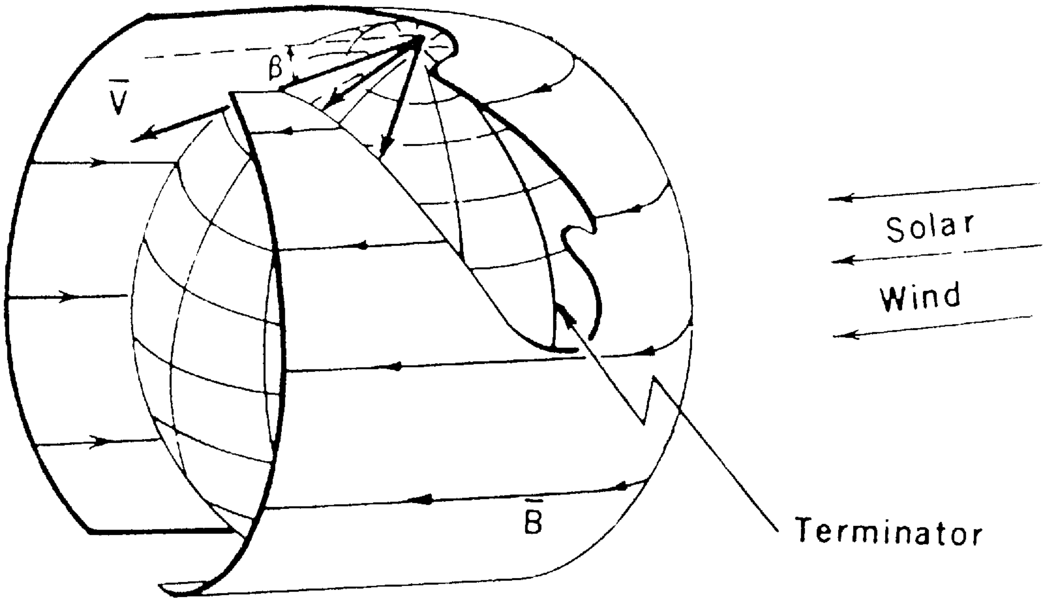


Fig. 2. Schematic diagram of the flow pattern behind Venus. Arrows indicate the motion of the shocked solar wind entering through the magnetic polar regions and subsequently dragging along the upper polar ionospheric plasma. The interplanetary magnetic field lines are shown draped around the dayside ionosphere (from Pérez de Tejada, (1980)).

flow properties seen in the vicinity of the magnetic polar regions. A useful example of that behavior is provided by the observation of particle flux intensities in some of the PVO trajectories that probed the Venus near wake. The energy spectra obtained across the ionosheath when the spacecraft moved in the outbound pass of orbits 39 and 51 are reproduced in Figure 3. Both cases describe a strong decrease in the particle flux intensity from high values measured in the outer ionosheath (spectra II, III) to those obtained in the inner ionosheath (spectrum I). The overall reduction in the plasma flux intensity is applicable, in particular, at those energy channels where peak values were obtained in the spectra of the outer ionosheath. The change is seen to occur at the time where there is evidence of the intermediate transition in the magnetic field data; that is, when the magnetic field intensity decreases to lower values and exhibits a sharp rotation in its orientation (at 1920 UT in orbit 39 and at 2008 UT in orbit 51) as was noted by Pérez de Tejada *et al*., (1995, see Figures 1-4).

Also significant in Figure 3 is an energy shift of the peak fluxes measured in spectrum I with respect to those of the spectra in the outer ionosheath. This is more notable in orbit 51 (lower panel) where the energy of the peak fluxes in spectrum I is nearly twice as high as those in spectra II, III. A possible explanation of this effect is the participation of heavy planetary ions (mostly the dominant O^+ population) that are more abundant in the inner ionosheath. Even though there is no information on the composition of those fluxes it should be noted that they imply flow speeds for O^+ ions that are smaller than those of the peak fluxes of a proton population in the outer ionosheath. In particular, the (~ 1400 Volt/q) peak fluxes of spectrum I in orbit 51 suggests flow speeds of O^+ ions that are at the most one half of the ~ 300 km/s speeds implied by the (700-800 Volt/q) peak fluxes for a solar wind proton population in spectra II and III. On the other hand, since there are no significant particle fluxes in spectrum I at energies comparable to those of the peak fluxes observed in spectra II and III there is no evidence of solar wind protons moving with similar speeds (~ 300 km/s). The implication here is that the solar wind below the intermediate transition does not stream with speeds comparable to those seen above that boundary, and also that planetary particles that may have been locally accelerated by the solar wind do not reach the speeds seen above that transition.

A more representative illustration of the deceleration of the solar wind in the inner ionosheath is available in the Mariner 5 plasma data reproduced in Figure 4 (Bridge *et al*., 1967; Shefer *et al*., 1979). In this case there are measurements made as the spacecraft approached the planet from the wake and exited upstream from it (lower panel). In addition to the bow shock crossings at events 1,5 there is evidence of a different plasma transition located within the shocked solar wind (at events 2,4). Across this latter transition there is an overall decrease of the flow speed to lower values in the inner ionosheath (between events 2 and 4 at the bottom of the middle panel) together with a simultaneous change in the plasma density and magnetic field intensity. The severe decrease of the flow speed seen after event 2 and the sharp rise at event 4 (measured near the terminator) reveal notable differences in the plasma dynamics between the

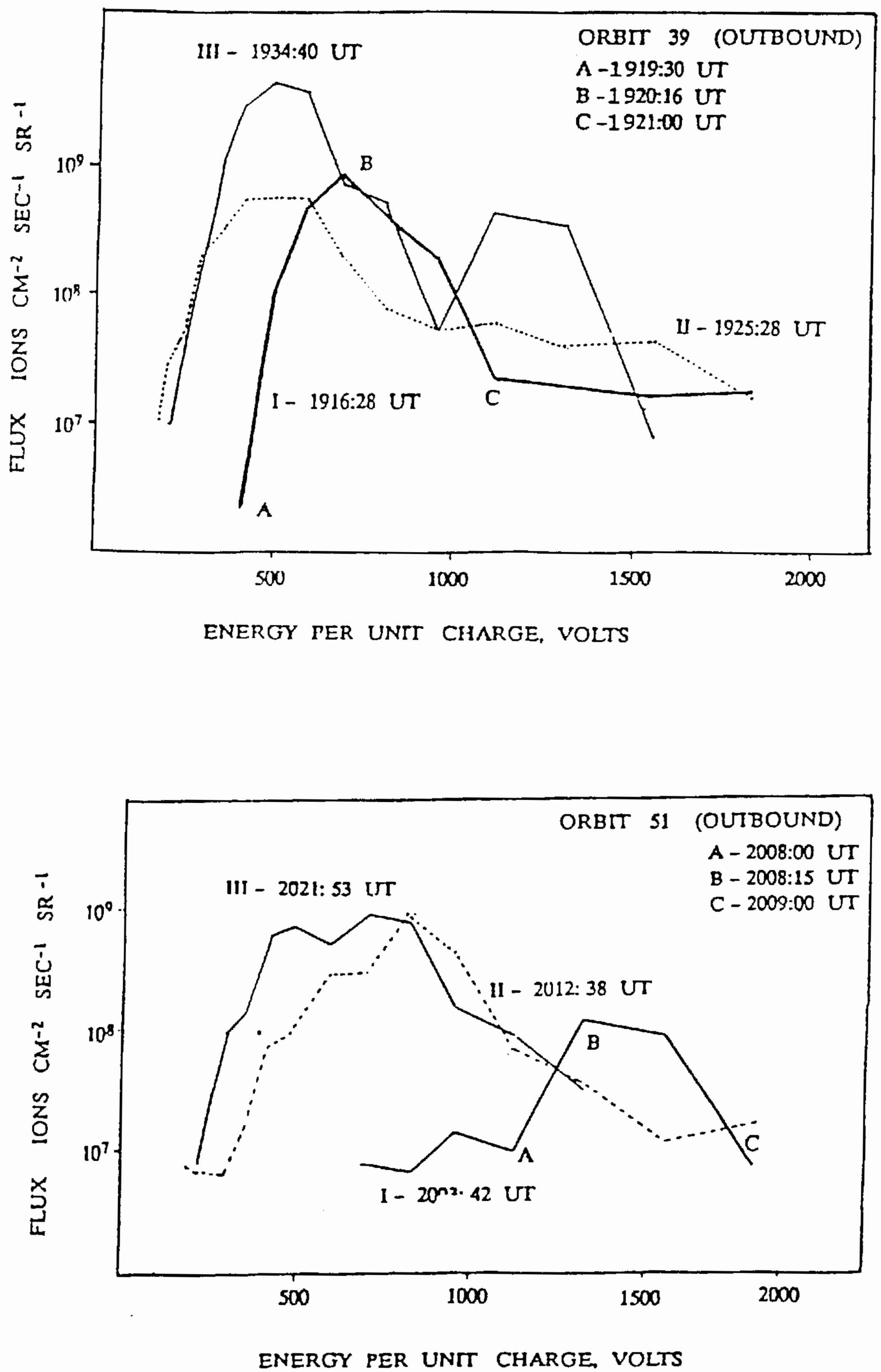


Fig. 3. Ion energy spectra measured with the PVO plasma instrument through the Venus ionosheath in the outbound pass of orbit 39 (top) and in the outbound pass of orbit 51 (bottom). Each spectrum shows the starting time of the energy measurements and positions A, B, and C in spectrum I mark the time interval across the intermediate transition. The spectra labeled II and III were obtained in the outer ionosheath (from Pérez de Tejada *et al.* (1995)).

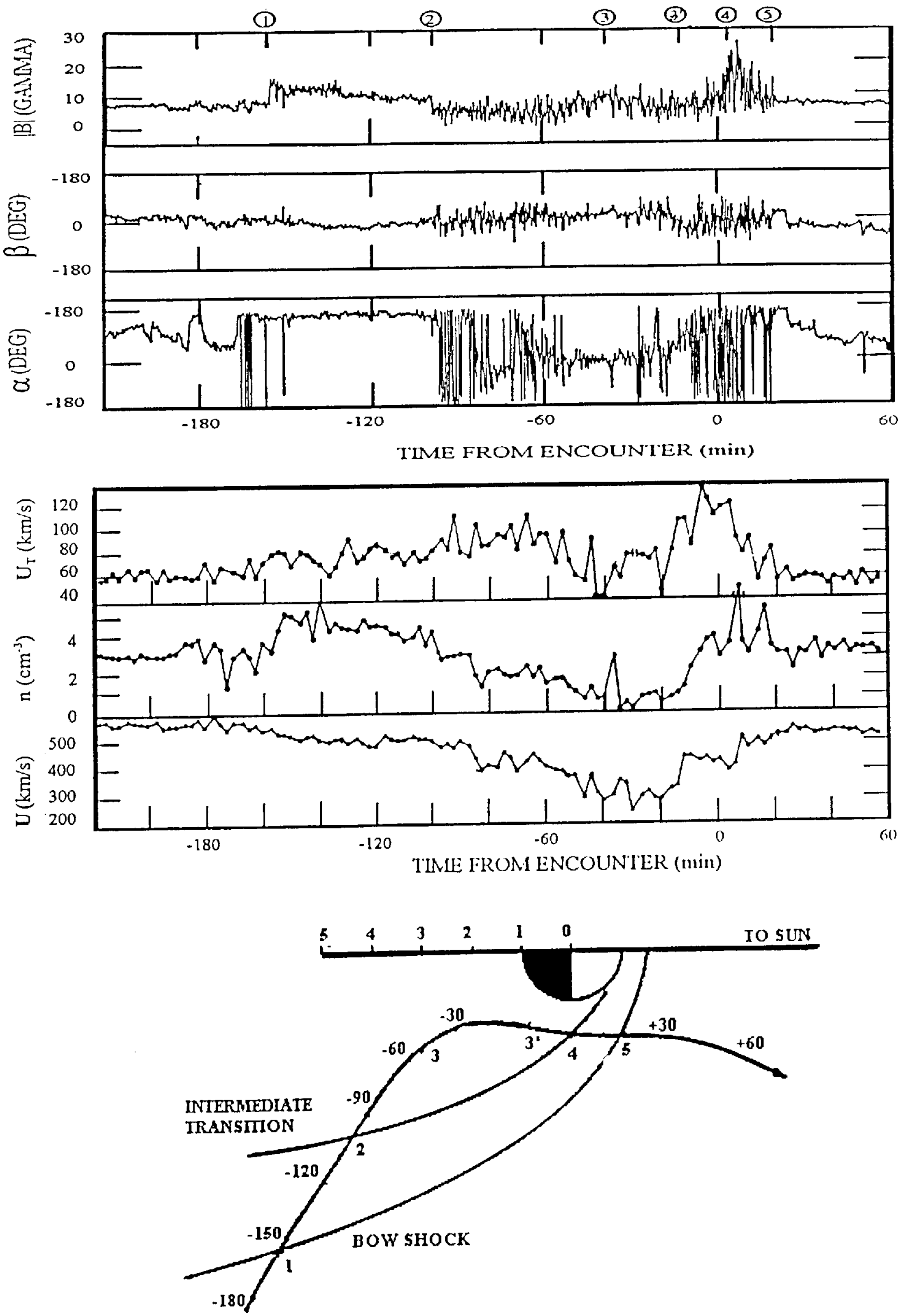


Fig. 4. (Top panel) Magnetic field intensity with the latitudinal and the azimuthal angles of the magnetic field direction measured during the Venus fly-by of the Mariner 5 spacecraft; (middle panel) thermal speed, plasma density, and flow speed of the solar wind measured during the Mariner 5 fly-by. Events 1, 5, and 2, 4 refer to crossings of the bow shock and the intermediate transition. (lower panel) Trajectory of the Mariner 5 on a plane in which the vertical ordinate is the distance to the Sun-Venus axis (after Bridge *et al.* (1967); and Shefer *et al.* (1979)).

outer and the inner ionosheath, and at the same time they imply a significant deficiency of the incident solar wind momentum along the flanks of the inner ionosheath.

MOMENTUM TRANSPORT TO THE UPPER IONOSPHERE

The lower flow speeds in the inner ionosheath seen in Figure 4 have important implications on the behavior of the upper ionospheric plasma. It should be first noted that the 'missing' momentum flux of the solar wind implied by the velocity boundary layer above the ionosphere can be transferred to planetary mass loading particles that are accelerated by the convective electric field of the solar wind and/or communicated through wave particle interactions to the plasma within the ionosphere. An important issue to be noted with both options is the conservation of the altitude-integrated momentum flux which requires that the deficiency of solar wind momentum flux be acquired by the planetary particles. A calculation of the transport of the 'missing' momentum flux was presented in a previous report through the analysis of the momentum flux conservation relation (Pérez de Tejada, 1986):

$$\int_0^z \left[m_{sw} n'_{sw} U'^2_{sw} - m_{sw} n_{sw} U^2_{sw} \right] dz = \int_{-z}^0 m_i n_i U_i^2 \, dz \qquad (1)$$

where n_{sw}, n_i and U_{sw}, U_i are, respectively, the density and speed of the solar wind and the ionospheric particles of mass m_{sw} and m_i with the prime superscript indicating freestream values. This equation states that the altitude-integrated deficiency of momentum flux in the solar wind (left side) should be equal to the altitude-integrated momentum flux carried by a plasma flow formed by ionospheric particles (right side). The latter can be operative either within the ionosphere and/or across the velocity boundary layer whose thickness can be assumed to be ~2000 km near the terminator as is indicated by the position of the intermediate transition in Figure 4. Thus, the integration in the right side can be conducted either across this latter region (if the momentum is only transferred to the mass loading particles) or across the width of the ionosphere at the terminator (if the momentum is transferred to that region). An approximated solution of equation (1) can be obtained by replacing the integration intervals in terms of equivalent momentum flux thickness where constant values for the flow speed and density are assumed. In this interpretation it is possible to derive the following relation between the momentum flux of the solar wind and the planetary particles:

$$n_i m_i U_i^2 / (n'_{sw} m_{sw} U'^2_{sw}) = \delta \left[1 - n''_{sw} U''^2_{sw} / n'_{sw} U'^2_{sw} \right] \qquad (2)$$

with $\delta = \delta_{sw}/\delta_i$ being the ratio of the momentum thickness δ_{sw} of the velocity boundary layer to the momentum thickness δ_i of a planetary flow (the double prime superscript refers to conditions at the ionopause).

An upper limit for the momentum flux of the planetary ions $n_i m_i U_i^2$ can be obtained for the case in which the momentum flux of the solar wind at the ionopause is very small compared with that in the freestream flow; that is: $n''_{sw} U''^2_{sw} / n'_{sw} U'^2_{sw} << 1$. Under such conditions it is possible to relate values of the speed and density of the solar wind and the planetary ions solely from estimates of the δ parameter. If the momentum flux is delivered to the ionosphere (whose thickness is ~ 1000 km at the terminator) we can take $\delta \cong 2$ and use U_{sw} = 400 km/s, n_{sw} = 4 cm^{-3} from the Mariner 5 data in Figure 4. With values for the plasma density $n_i \cong 10^4$ cm^{-3} for the upper ionosphere near the terminator that are available from the PVO data (Theis *et al*., 1980, Table 2) it is possible to derive $U_i \cong$ 4-5 km/s which is in adequate agreement with the ionospheric speeds observed across the terminator [Knudsen *et al*., 1980].

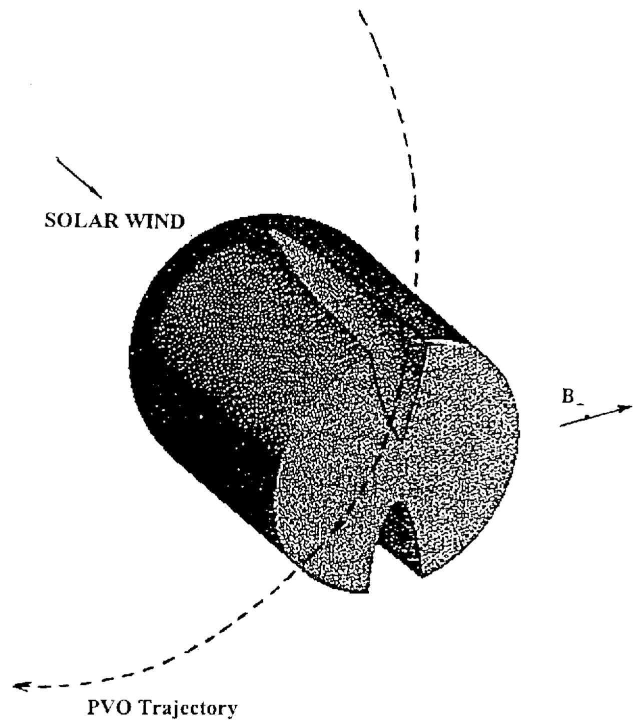
An alternative calculation can be made if the solar wind momentum is locally conveyed to the mass loading particles within the velocity boundary layer. For this case we can take $\delta \cong 1$ but their flow speed should be equal to that of the solar wind since the planetary particles are accelerated by the convective electric field. Thus, by using n_{sw} = 4 cm^{-3} from the Mariner 5 data, equation (2) leads to: $n_i \cong 0.25$ cm^{-3} given the $m_i = 16\, m_{sw}$ value for the dominant O^+ ion population. Even though the Mariner 5 data do not yield information on the composition of the plasma it is possible to estimate that the low (≤ 1 cm^{-3}) densities observed deep within the velocity boundary layer (where $U_i \cong$ 300 km/s) are most likely solar wind protons rather than planetary ions. The reason here is that the thermal speed (upper panel in the center frame of Figure 4) is only a small fraction (≤ 0.25) of the bulk speed and thus is insufficient to account for the thermal speeds expected in gyrotropic motion (in that case the bulk speed in a cycloidal trajectory should be at most twice as large as that along directions transverse to the main motion). As a result the particles reported in the Mariner 5 data represent most likely solar wind protons rather than accelerated planetary ions.

ACCELERATION OF THE POLAR UPPER IONOSPHERE

Since the speed of the ionospheric plasma that is predicted from the momentum balance conservation in equation (1) is comparable to those reported from PVO measurements in that region, it is possible that a large fraction of the 'missing' momentum flux of the solar wind is transferred to the upper ionosphere. The views expressed above regarding the ability of the solar wind to remove planetary ions from the magnetic polar regions agree with that transport process even though the total mass of material removed from the planet should be smaller than that expected in a global erosion configuration. An important implication is that a significant fraction of the solar wind momentum is used to carve out some of the upper ionospheric plasma over the magnetic polar regions and thus produce plasma channels that extend toward the nightside hemisphere. It should be noted that the momentum flux used to produce the channels should have an effect on the ionospheric plasma present in their vicinity and thus lead to the ionospheric flow seen across the terminator (Knudsen *et al*., 1980); that is, the latter is produced in conjunction with the formation of the polar ionospheric channels.

Issues on the manner in which the solar wind momentum can be transferred to the upper ionosphere are the subject of important current research. Wave-particle interactions are believed to be ultimately responsible for the transport process but specific mechanisms need to be identified. A contribution in this direction was presented by Shapiro *et al.* (1995) in terms of the Landau damping of low speed waves (planetary ions are accelerated through the non-linear interaction of waves generated in electrostatic mode oscillations). While other mechanisms could also lead to comparable effects, collective wave-particle motion seems to be fundamental to account for the momentum transport process.

The removal of the upper ionospheric plasma through plasma channels downstream from the magnetic polar regions should lead to a 3-D configuration similar to that depicted in the upper panel of Figure 5. The channels imply a downstream flux of ionospheric particles with a component directed toward the magnetic equatorial plane. Since, in many cases, this plane is nearly parallel to the ecliptic plane the predicted flow accounts for the dominant entry of O^+ ions in the direction of the ecliptic plane that has been reported by Kasprzak *et al*. (1987) from the Orbiter Neutral Mass Spectrometer (ONMS) observations made with the PVO. The solar wind material within the ionospheric channels has been decelerated as it moves past the magnetic polar regions. It should also be noted that the configuration shown in the upper panel of Figure 5 is schematic since plasma clouds and tail rays (Brace *et al*., 1982a) will disrupt the uniform density geometry within the wake. The main implication of the ionospheric channels is that the material within them has been eroded and lost through the wake. Part of that material is used to form plasma clouds and tail rays according to changes in the magnetic field orientation and thus implies that the Venus ionosphere is not eroded globally but mainly through plasma panaches that extend downstream from the magnetic polar regions. No such an erosion is expected at non-polar magnetic latitudes since the interplanetary magnetic field accumulates over most of the dayside ionosphere. While plasma clouds and tail rays are observed scattered around the wake (Ong *et al*., 1991), ionospheric holes are more frequently seen within about 2 hours local time away from the midnight plane (Marubashi *et al*., 1985). This difference should result from the effects of short time-scale fluctuations in the magnetic field orientation that first produce plasma clouds and later form the ionospheric channels as the end product of erosion under steady state conditions. The eroded shape of



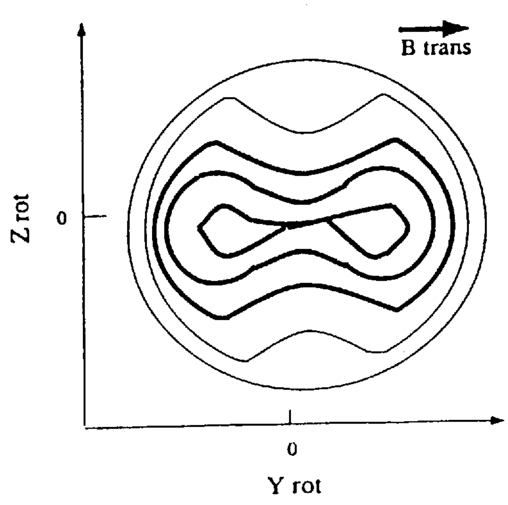


Fig. 5. (Top) 3-D view of the Venus nightside ionosphere with ionospheric channels that extend behind the magnetic polar regions. The magnetic field orientation is indicated in the plane transverse to the solar wind direction (from Pérez de Tejada, 1999); (bottom) Contour density plot of plasma tail rays inferred from PVO measurements in the Venus wake (from Ong *et al,* 1991).

the plasma wake indicated in the upper panel of Figure 5 should lead to an overall geometry where planetary ions can reach larger distances at and near the magnetic equatorial plane (defined by the interplanetary magnetic field direction) rather than in the perpendicular direction. In this respect the expected plasma configuration may be similar to the asymmetric distribution of tail rays that was reported by Ong *et al*. (1991) from PVO measurements and that is reproduced in the lower panel of Figure 5.

PVO CROSSINGS OF THE PLASMA CHANNELS

An important consequence of the shape of the plasma channels shown in the upper panel of in Figure 5 is the large change in the plasma density that they imply across the wake. The ionosheath plasma that carves out the polar upper ionosphere has densities much smaller than that of the material around the channels and thus the latter may appear as distinguishable rarefied features immersed in the high density nightside ionosphere. This peculiarity is important because it can account for the observation of the ionospheric holes reported from the PVO measurements. Brace *et al*. (1982b) have noted the presence of deep troughs in the density profiles obtained in some of the PVO passes through the nightside ionosphere. A suitable example is reproduced in Figure 6 with holes detected in the north and south hemispheres as the spacecraft moved across the nightside ionosphere. The density at the bottom of each feature is larger than in the solar wind since it contains a population of ionospheric particles that has been dragged along by the streaming flow. In other PVO passes there is evidence of only one hole in the entire ionosphere and in many cases holes are not observed as the PVO scans behind Venus.

A useful manner in which density profiles with ionospheric holes are produced in PVO passes through the Venus wake can be derived by considering the near ($\lambda \approx 74°$) polar orientation of the spacecraft trajectory [Colin, 1980]. Since the orbit position remains fixed in space as the planet moves around the Sun the spacecraft trajectory traced in the upper panel of Figure 5 (dashed curve) can be assumed to enter the wake downstream from the northern magnetic pole and exit in the southern hemisphere. Under such conditions it is possible that the spacecraft moved first through a portion of the upper nightside ionosphere, then crossed the plasma channel that extends downstream from the northern magnetic pole,

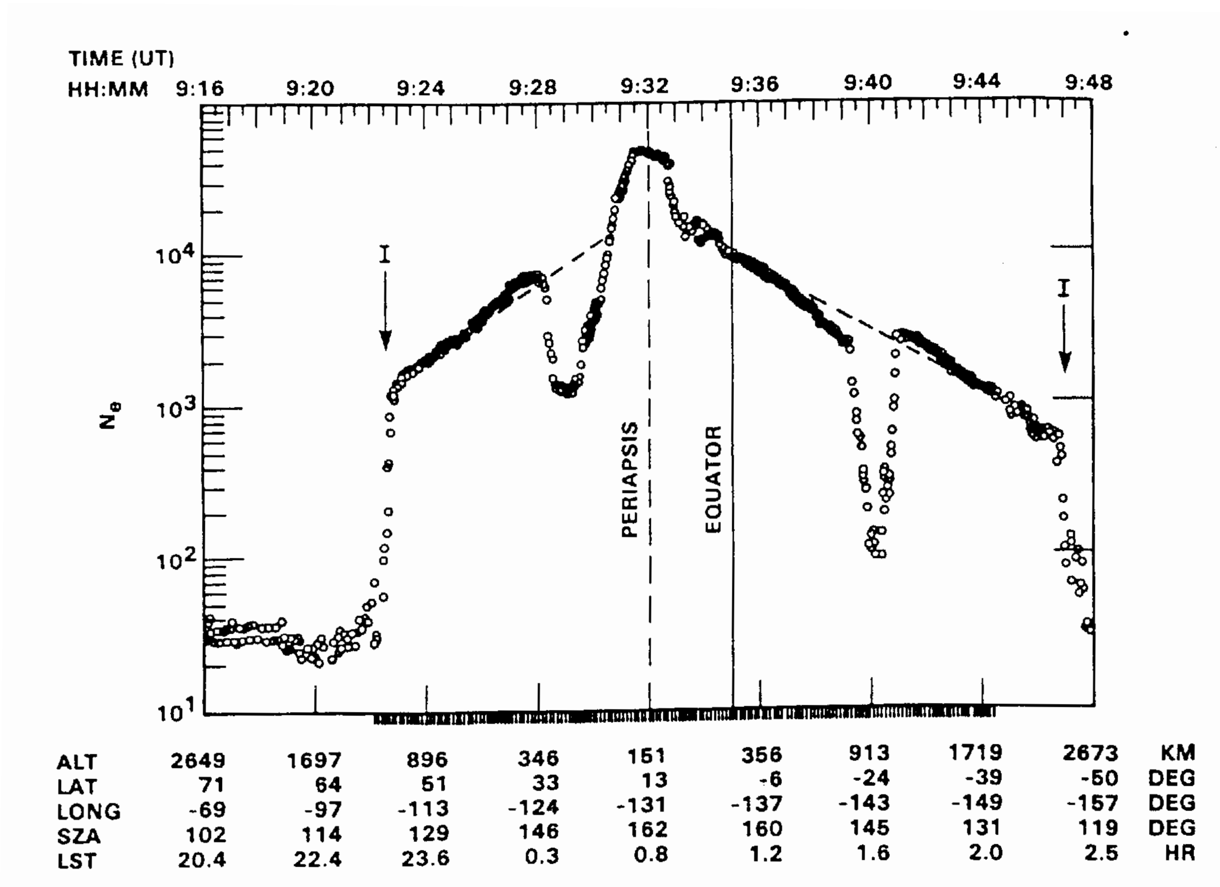


Fig. 6. Electron density profile obtained across the nightside ionosphere in the Pioneer Venus orbit 530. Ionospheric holes are seen at 9:30 UT and at 9:40 UT (from Brace *et al*., 1982b).

and entered later the low altitude ionosphere near the orbit periapsis. An inverse sequence of events could also have occurred in some orbits as the spacecraft moved outbound in the southern hemisphere. The implication here is that crossings through the low density plasma channels in the nightside hemisphere may have appeared to be the ionospheric holes that have been identified in the PVO data. In this interpretation the ionospheric holes are not low density regions immersed in the ionosphere but result from the crossing of plasma ditches that extend downstream from the magnetic poles. It should be noted that crossings of the plasma channels depend on the orbit position with respect to the wake. In some cases the trajectory could only have allowed passes through one of the 2 channels or even probe regions far away from them. Under such conditions ionospheric hole crossings should be limited to certain PVO passes rather than being observed in all trajectories through the wake. A further complication is that the position of the magnetic polar regions with respect to the planet, and hence to the PVO trajectory, also depends on the inclination of the interplanetary magnetic field IMF with respect to the ecliptic plane. Thus, there should be instances in which the IMF is highly inclined with respect to this plane and, therefore, the magnetic polar regions could occur near the planet's equatorial plane. As a result the observation of ionospheric holes is highly restricted to both the position of the PVO trajectory in the wake and also to the solar wind conditions.

A geometry similar to that indicated in the upper panel of Figure 5 should also be applicable to the solar wind interaction with the Mars ionosphere where measurements made with the Phobos and the Mars Global Surveyor (MGS) indicate the extensive erosion of the Mars ionosphere and the existence of plasma clouds and ionospheric holes (Lundin *et al*. 1990; Dubinin *et al*. 1996; Acuña *et al*., 1998). Issues related to the shape of the Mars ionosphere and the manner in which plasma escapes from the planet have been further addressed by the detection of features with characteristics similar to those of the plasma channels suggested for the Venus ionosphere (Mitchell *et al*., 1998; Cloutier *et al*., 1998). In particular, measurements of the position of the Mars bow shock show a large (~ 5 10^3 km) altitude range near the terminator (Acuña *et al*., 1998; Mazelle *et al*., 1998) which may imply a strong axial asymmetry in the shape of the ionospheric obstacle or the effects of a strong crustal magnetic field. A configuration similar to that inferred in the upper panel of Figure 5 for the Venus ionosphere would lead to very different bow shock altitudes at the terminator with a more favorable entry of plasma through the magnetic polar regions (the latter has in fact been reported from the Phobos plasma data, Kotova *et al*., (1997)). Further research should be conducted to determine the overall geometry of the Mars wake and the existence of plasma channels similar to those derived from observations of ionospheric holes in the Venus nightside ionosphere.

BIBLIOGRAPHY

ACUÑA *et al*., 1998. Magnetic field and plasma observations at Mars: Initial results of the Mars Global Surveyor Mission. *Science, 279*, 1676.

BRACE, L. H., R. THEIS and W. HOEGY, 1982a. Plasma clouds above the ionosphere of Venus and their implications. *Planet. Space Sci., 30*, 29.

BRACE, L. H., R. THEIS and S. CURTIS, 1982b. Holes in the nightside ionosphere of Venus. *J. Geophys. Res., 87*, 199.

BRACE, L. H., W. KASPRZAK, H. TAYLOR, R. THEIS, C. RUSSELL, A. BARNES, J. MIHALOV and D. HUNTEN, 1987. The Ionotail of Venus: Its configuration and evidence for ion escape. *J. Geophys. Res., 92*, 15.

BRIDGE, H., A. LAZARUS, C. SNYDER, E. SMITH, I. DAVIES, P. COLEMAN and D. JONES, 1967. Plasma and magnetic fields observed near Venus. *Science, 158*, 1669.

CLOUTIER, P. *et al*., 1998. Mechanisms of the post shock magnetic pile-up at Mars. *EOS, 79*, F527.

COLIN, L., 1980. The Pioneer Venus program. *J. Geophys. Res., 85*, 7575.

DUBININ, E., K. SAUER, R. LUNDIN, O. NORBERG, J-G. TROTIGNON, K. SHWINGENSCHUH and W. RIEDLER, 1996. Plasma characteristics of the boundary layer in the martian magnetosphere. *J. Geophys. Res., 101*, 27061.

KASPRZAK, W., B. NIEMANN and P. MAHAFFY, 1987. Observations of energetic ions on the nightside of Venus. *J. Geophys. Res., 92*, 291.

KNUDSEN, W., K. SPENNER, K. MILLER and V. NOVAK, 1980. Transport of ionospheric O^+ ions across the Venus terminator and implications. *J. Geophys. Res., 85*, 71803.

KOTOVA, G., M. VERIGIN, N. SHUTTE, A. REMIZOV, H. ROSENBAUER, W. RIEDLER, K. SHWINGENSCHUH, M. DELVA, K. SZEGO and M. TATRALLYAY, 1997. Planetary heavy ions in the magnetotail of Mars: Results of the Taus and Magma experiments aboard Phobos. *Adv. Space Res. 20(2)*, 173.

LUNDIN, R., A. ZAKHAROV, R. PELLINEN, S. BARABASJ, H. BORG, E. DUBININ, B. HULTQVIST,

H. KOSKINEN, I. LIEDE and N. PISSARENKO, 1990. ASPERA/PHOBOS Measurements of the ion outflow from the Martian ionosphere. *Geophys. Res. Lett., 17*, 873.

MAZELLE, C. *et al*., 1998. Analysis of the magnetic Pile-Up boundary at Mars. *EOS, 79*, F531.

MITCHELL, D. *et al*., 1998. Observation of 1 keV to 20 keV electrons within the Martian Ionosphere. *EOS, 79*, F525.

MURABASHI, K., J. GREBOWSKY, H. TAYLOR Jr., G. LUHMANN, C. RUSSELL and A. BARNES, 1985. Magnetic field in the wake of Venus and the formation of ionospheric holes. *J. Geophys. Res., 90*, 1385.

ONG, M., J. LUHMANN, C. RUSSELL, R. STRANGEWAY and L. BRACE, 1991. Venus ionospheric tail rays: Spatial distributions and interplanetary magnetic field control. *J. Geophys. Res., 96*, 17751.

PEREZ DE TEJADA, H., 1980. Viscous Flow circulation of the solar wind behind Venus. *Science, 207,* 981.

PEREZ DE TEJADA, H., 1986. Fluid dynamic constraints in the Venus ionospheric flow. *J. Geophys. Res., 91,* 6765.

PEREZ DE TEJADA, H., D. INTRILIGATOR, R. STRANGEWAY, 1995. Intermediate transition in the Venus ionosheath. *J. Geophys. Res., 100*, 14523.

PEREZ DE TEJADA, H., 1997. Polar expansion fan in the Venus ionosheath. *J. Geophys. Res., 102,* 2585.

PEREZ DE TEJADA, H., 1999. Solar wind erosion of the Venus polar ionosphere, Planetary and Lunar Science Conference XXXV, Houston, Texas, March.

SAUNDERS, M. and C. RUSSELL, 1986. Average dimensions and magnetic structure of the distant Venus magnetotail. *J. Geophys. Res., 91*, 5589.

SHAPIRO, V., K. SZEGO, S. RIDE and V. SHEVCHENKO, 1995. On the interaction between the shocked solar wind and the planetary ions on the dayside of Venus. *J. Geophys. Res., 100*, 21289.

SHEFER, R., A. LAZARUS and H. BRIDGE, 1979. A reexamination of plasma measurements from the Mariner 5 Venus encounter. *J. Geophys. Res., 84*, 2109.

THEIS, R., L. BRACE and H. MAYR, 1980. Empirical models of the electron temperature and density in the Venus ionosphere. *J. Geophys. Res., 85*, 7787.

H. Pérez de Tejada
Instituto de Geofísica, UNAM,
Cd. Universitaria 04510 México, D.F.
México