

The solar wind in the Venus ionosheath: examination of mass loading and frictional phenomena

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RESUMEN

Los datos de plasma de los vehículos Mariner 5, Venera 9 y 10, y Pionero Venus, son utilizados en un estudio comparativo del viento solar en la región exterior a la ionosfera del planeta Venus. La evidencia experimental indica que atrás del frente de choque, en la vecindad del terminador, el viento solar experimenta una desaceleración repentina. Se discuten las implicaciones de este cambio de velocidad en relación con los efectos de procesos químicos (asimilación de masa y colisiones de intercambio de carga) y fenómenos de fricción. Se concluye que los primeros no son suficientes para explicar la manera en que el viento solar se desacelera en esa región, y que cerca del terminador existe un fuerte acoplamiento entre el viento solar y el plasma ionosférico.

PALABRAS CLAVE: Ionopausa de Venus, asimilación de masa, fricción en plasmas.

ABSTRACT

A comparative study of the solar wind in the Venus ionosheath, based on the Mariner 5, Venera 9 and 10, and Pioneer Venus spacecraft, is presented. It is shown that the available experimental evidence indicates that, downstream from the bow shock, the solar wind experiences a strong and sudden deceleration in the vicinity of the terminator. The implications of this velocity change are further discussed in connection with the effects of chemical processes (mass loading and charge exchange collisions), and frictional phenomena at the ionopause. It is concluded that the former processes are not sufficient to account for the manner in which the solar wind decelerates in that region, and that a strong coupling between that plasma and the topside ionosphere exists near the terminator.

KEY WORDS: Venus ionopause, mass loading, plasma friction.

INTRODUCTION

After over twenty years since the Venera 4 and the Mariner 5 spacecraft conducted the first *in situ* measurements of the Venus near-plasma environment, a significant amount of material has been acquired which substantiates much of the findings of those early experiences. A persistent feature of the data is the marked decrease of the velocity of the shocked solar wind in the inner ionosheath near and downstream from the terminator. This was first reported by Bridge *et al.* (1967) from the Mariner 5 fly-by, and later by Verigin *et al.* (1978) and by Romanov *et al.* (1979) from the Venera 9 and 10 plasma data. More recently Mihalov *et al.* (1980), Intriligator (1982), and Pérez-de-Tejada *et al.* (1985) examined the Pioneer Venus Orbiter (PVO) plasma data and obtained further evidence that substantiates the same overall behavior of the flow; namely, that the plasma fluxes detected in the inner ionosheath, downstream from the planet, have substantially lower velocities than those measured in the outer ionosheath. The identification of the manner in which the velocity varies along the direction of the flow has remained elusive, however, and thus it has not been possible to examine how the shocked solar wind loses momentum as it moves around the planet.

On the theoretical stand point there are various mechanisms which are currently thought to contribute to the re-

moval of the momentum flux of the shocked solar wind in the Venus plasma environment. Most notable is the mass loading of the incident flow with planetary ions picked up through the convective $V \times B$ electric field of the solar wind (V and B denoting, respectively, the velocity and magnetic field vectors of the solar wind). This process produces a gradual and accumulated erosion of the momentum flux of the solar wind as it moves toward and around the planet's ionosphere. An additional reduction of the incident momentum flux is produced by charge exchange collisions between the solar wind protons and hydrogen atoms of the Venus exosphere. In this case the momentum flux of the incident plasma is directly transferred to the neutral components of the planet's atmosphere. Independent of these processes it has also been suggested that the shocked solar wind suffers an additional deceleration through frictional effects at the Venus ionopause (Pérez-de-Tejada, 1982). The idea here is that some of the momentum of the solar wind is transferred to the ionospheric plasma through plasma turbulence at this latter boundary.

While all these processes are, in one way or another, undoubtedly active in removing momentum from the solar wind there is, as yet, much controversy regarding their quantitative participation. In particular, it has not been

possible to establish whether mass loading and charge exchange collisions are the dominant mechanisms which produce the deceleration of the solar wind that is implied by the observed velocity profiles within the Venus ionosheath. Important information on this matter has recently been obtained from measurements conducted with the Phobos spacecraft in the Mars plasma environment where the interaction with the solar wind is similar to that at Venus (Lundin *et al.*, 1990). In this case there is evidence that the contribution of mass loading and charge exchange collisions is indeed very small and insufficient to account for the severe deceleration that the solar wind exhibits in the vicinity of the Mars magnetopause.

This issue is further examined in the present report with particular emphasis on the properties of the velocity field in the Venus ionosheath. It will be shown that the available experimental evidence suggests that much of the deceleration of the shocked solar wind near the planet does not necessarily occur in a gradual accumulated manner, but that it takes place sharply across a layer which develops in the vicinity of the Venus ionopause near the terminator. The observed velocity variation is in accord with the effects of frictional phenomena at that boundary and suggests that, as in Mars, mass loading and charge exchange collisions may not be dominant in producing the bulk of the deceleration of the solar wind in that region of space.

VELOCITY AND TEMPERATURE MEASUREMENTS NEAR THE TERMINATOR

A particularly useful data of the flow conditions within the Venus ionosheath are the plasma measurements conducted during the Mariner 5 fly-by. Unlike the PVO and the Venera spacecraft the trajectory of the Mariner 5 was such that it kept a nearly constant distance to the Sun-planet line while the spacecraft moved across the terminator. Such a trajectory is useful because it allows to compare, in the same pass, the flow conditions in the dayside and in the nightside hemispheres. Figure 1 reproduces (from top to bottom) the magnetic field intensity, temperature, pressure and bulk speed profiles measured along the section of the Mariner 5 trajectory closest to the planet. (Sheffer *et al.*, 1979, see Figure 2). The flow properties reported by these authors are based on the re-examination of the Mariner 5 plasma data, and differ somewhat from those originally published by Bridge *et al.* (1967) and Bridge *et al.* (1976).

In addition to the bow shock crossing, identified by the foremost changes in the magnetic field intensity and in all the plasma parameters at $t = E + 20$ min (E being the time of closest approach), the most important feature of the data is that the bulk speed profile does not reveal a gradual deceleration of the shocked solar wind along the spacecraft trajectory. Instead, it shows that the deceleration occurs mostly across a second transition encountered between $t = E + 6$ min and $t = E + 8$ min, some 5 000 km behind the bow shock. The velocity decreases, at this location, by about 20% of the upstream value (from ~500 km/s to ~400

km/s, and does not experience a similar change until the plasma enters the wake (a transition detected at $t = E - 16$ min, when the Mariner 5 was some 7 000 km behind the terminator). The bulk speed signature across the section of the trajectory shown in Figure 1 reveals that the erosion of the momentum flux of the solar wind does not occur primarily in a gradually accumulated manner, as it would be expected to result from the sole action of mass loading processes and charge exchange collisions. The removal of the incident momentum flux through these processes is expected to occur in a continuous way and should be most severe along the streamlines which pass closest to the planet. The fact that this variation is not dominant, but that the flow slows down in a more abrupt manner suggests that other processes are actually required to account for the removal of the bulk of the momentum flux of the incident flow. Thus, the shape of the bulk speed profile shown in Figure 1 seems to imply that mass loading and charge exchange collisions may not be sufficient to account for the observations.

Together with the velocity jump detected between $t = E + 6$ min and $t = E + 8$ min, the data of Figure 1 shows that a strong pressure change was also measured at that time. The higher plasma pressure of the slower moving fluxes reveals that a compressional wave develops ahead of the planet. Such higher pressures result mostly from the enhanced plasma temperatures recorded throughout the transit of the spacecraft across the near nightside of the planet, and suggest the existence of local dissipative processes independent of those associated with the bow shock crossing. It is in fact notable that the temperature of the plasma near and downstream from the terminator is nearly twice as high as that of the plasma measured across the bow shock.

VELOCITY AND TEMPERATURE MEASUREMENTS IN THE NEAR WAKE

The sharp change of the flow parameters within the Venus ionosheath, revealed by the data shown in Figure 1, is also present in the near wake pass of the inbound leg of the Mariner 5 trajectory and even more clearly in the April 19, 1976 pass of the Venera 10 across that region (Romanov *et al.*, 1979). The plasma data of these two passes are reproduced in Figures 2 and 3 together with the section of the trajectories of both spacecraft where the measurements apply. As before, it is clear that in addition to the bow shock crossing (detected at $t = E - 160$ min in the Mariner 5 fly-by, see Figure 2, and at ~ 2400 MT in the Venera 10 pass, see Figure 3) there is evidence of a second (intermediate) transition embedded deep within the ionosheath (at $t = E - 100$ min in the Mariner 5 data, and at ~ 0200 MT in the Venera data). In both cases the plasma changes across this transition are equally strong and similar to those noted in the data shown in Figure 1. In particular, the velocity begins a steeper decrease, and the plasma temperature a notable increase, downstream from the intermediate transition. Both changes are again dominant over those observed upstream from this transition and, in

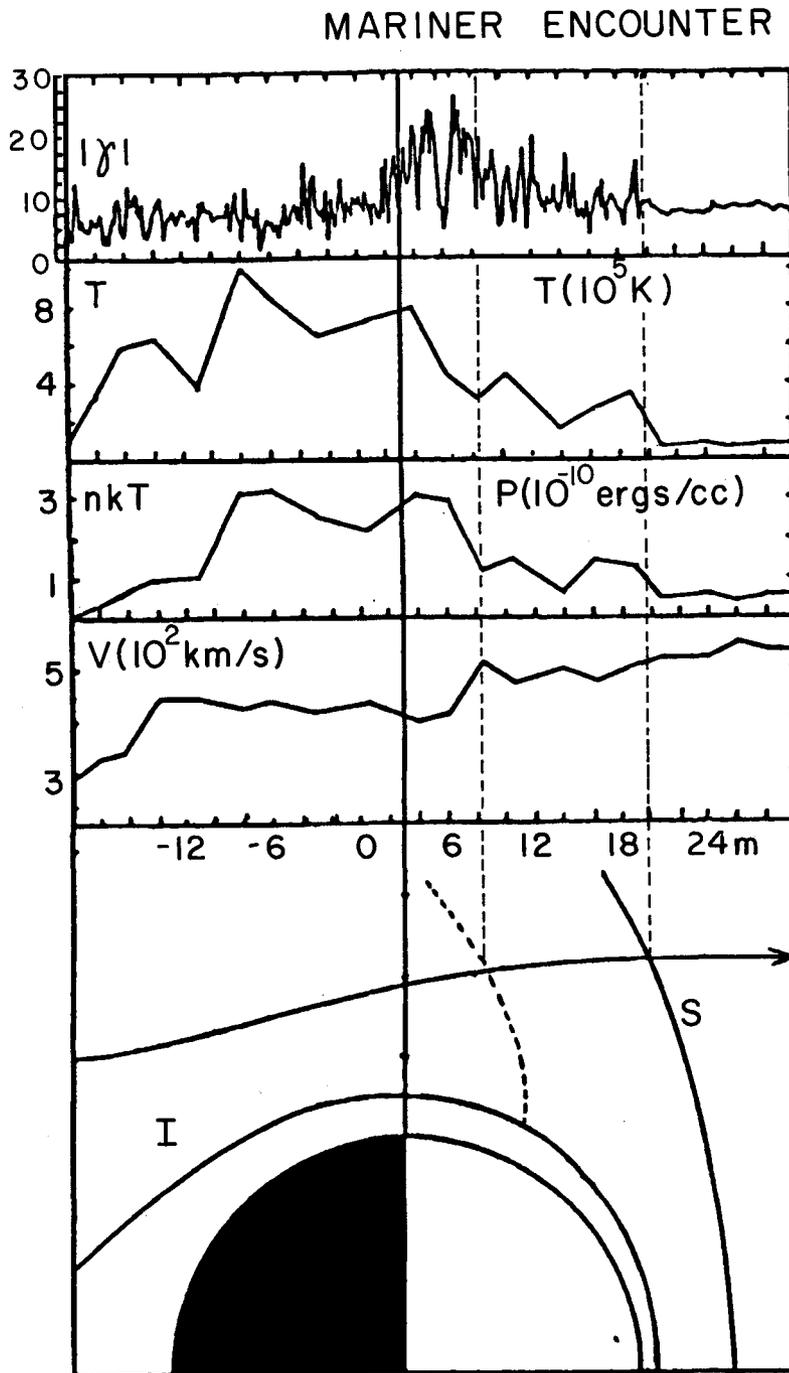


Fig. 1. Magnetic field intensity, ion temperature, thermal pressure, and bulk speed measured during the outbound pass (bottom panel) of the Mariner 5 spacecraft through the Venus plasma environment (from Sheffer *et al.*, 1979).

fact, there is little or no evidence, in the Venera 10 pass, of a significant deceleration or plasma heating in the outer ionosheath. The flow conditions downstream from the intermediate transition are clearly different from those upstream and, as in the Mariner 5 data, suggest the existence of a boundary layer in which the plasma moves with smaller velocities and exhibits higher temperatures. The later data (Fig. 2) also reveals that the intermediate transition marks as well a sudden decrease in the local plasma density and that the flow within the inner ionosheath is

significantly more rarefied than that outside.

Equally important to these results is the fact that in both, the Mariner 5 and in the Venera 10 data, the intermediate transition occurs roughly at the same spatial region within the near wake. Rizzi (1972) identified the intermediate transition as a rarefaction wave which marks the upstream extent of a region within the ionosheath flow affected by plasma disturbances generated at and downstream from the near-terminator ionopause. The approxi-

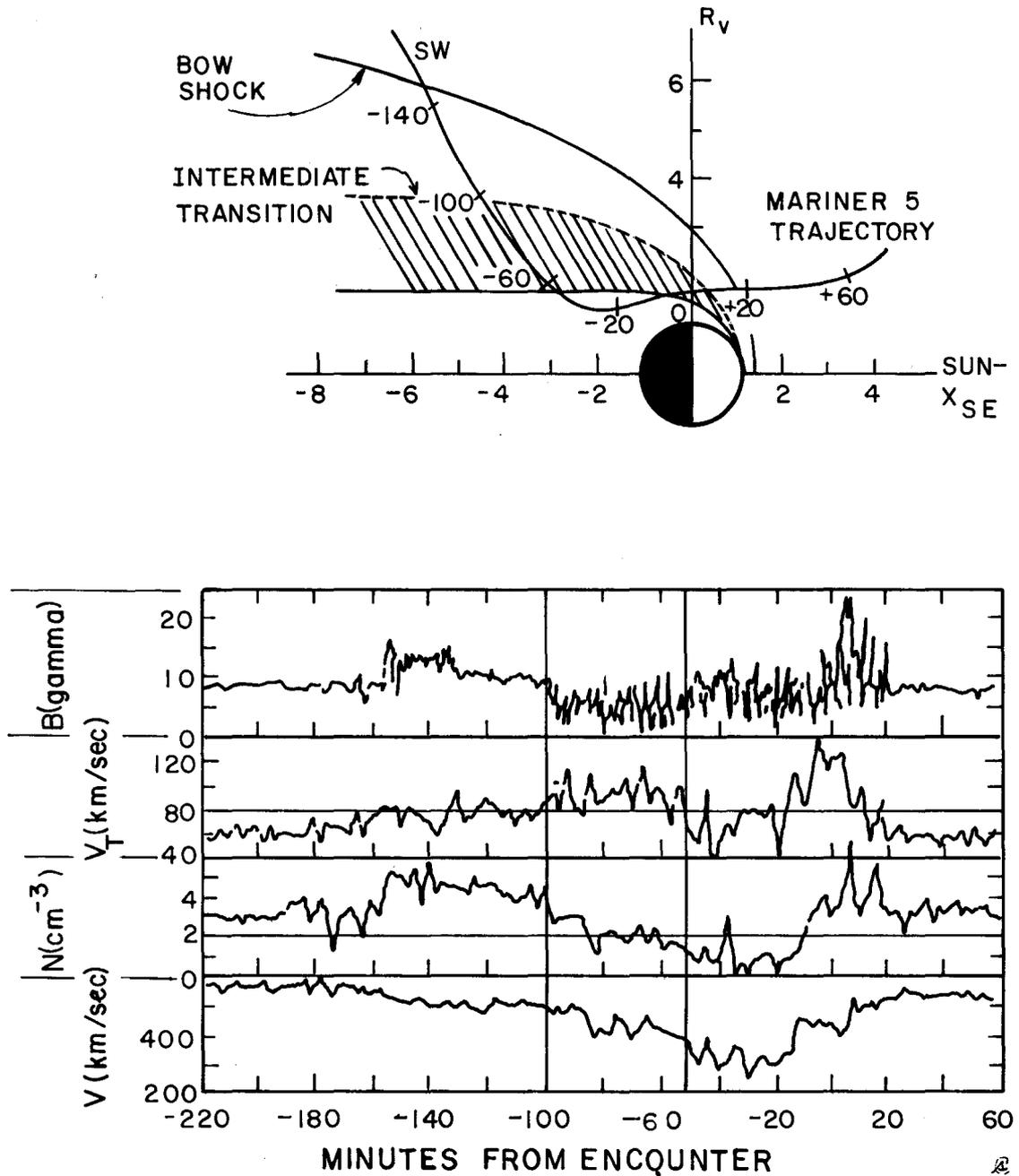


Fig. 2. (top panel) Geometry of the Mariner 5 trajectory during its Venus fly-by projected on a plane in which the vertical coordinate is the distance to the Sun-Venus axis. (lower panel) Magnetic field intensity, thermal speed, ion density and bulk speed measured across the entire fly-by of the Mariner 5 spacecraft (from Sheffer *et al.*, 1979).

mate shape of that characteristic line is indicated in Figures 2 and 3 by the dashed curve that runs from the ionopause across the ionosheath, and roughly fits with that of the curve that intersects, in Figure 1, the outbound leg of the Mariner 5 trajectory at the transition seen between $t = E + 6$ min and $t = E + 8$ min. The identification of this common property in all these data suggests that the intermediate transition is, most likely, a steady state feature of the Venus ionosheath, and that it represents the effects of the same phenomenon.

This issue was further investigated by Pérez-de-Tejada *et al.* (1984) in the plasma and electric field data of the Pioneer Venus spacecraft. In these data it is possible to identify the intermediate transition as a distinguishable feature in the 30 kHz noise of the electric field detector. The signatures recorded by that instrument across the near wake in orbit 80, together with the ion energy distributions measured in that orbit with the plasma probe, are reproduced in Figure 4. Upstream from the bow shock the

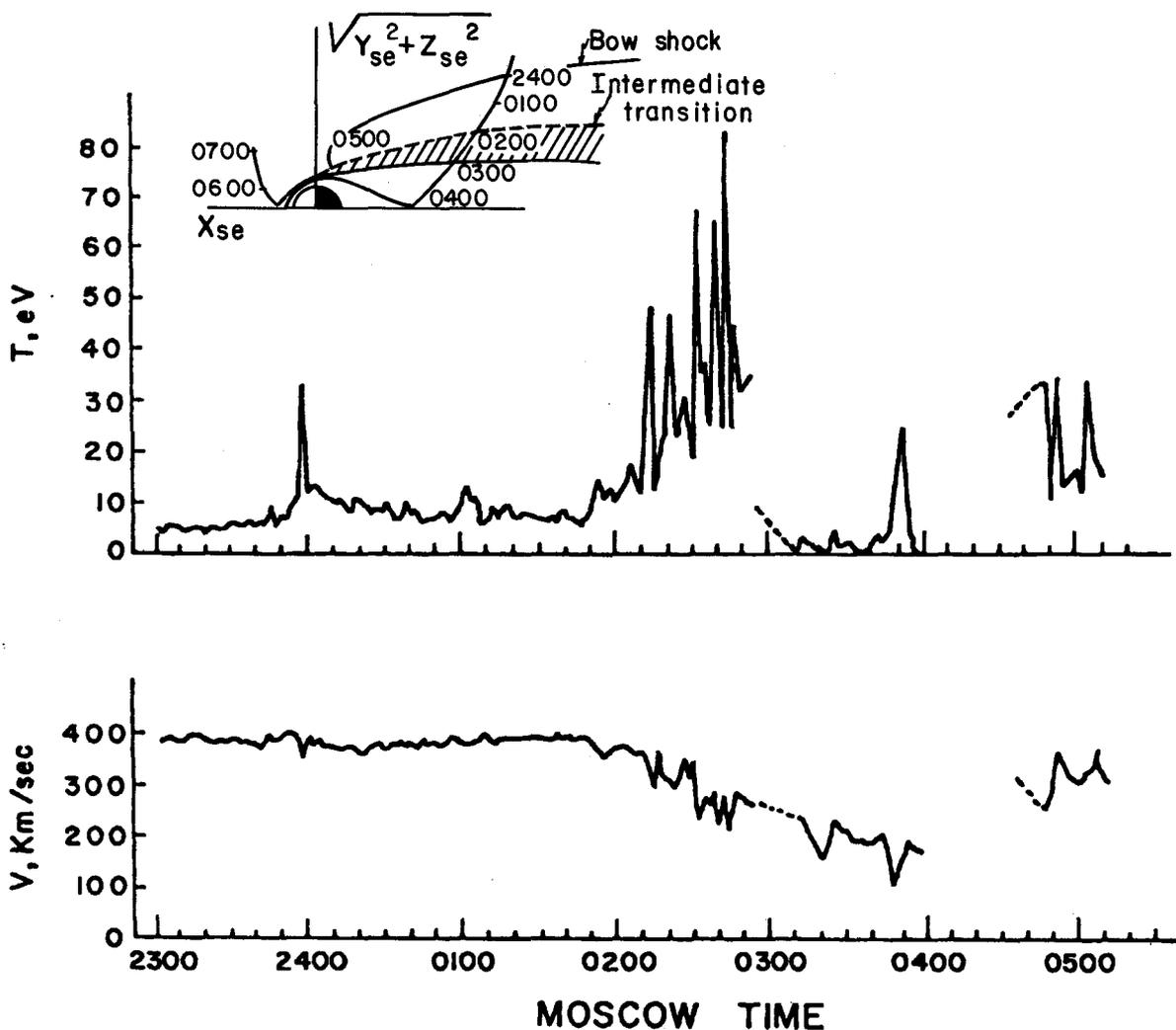


Fig. 3. Ion temperature and bulk speed measured during the April 19, 1976 pass of the Venera 10 orbiter through the Venus near wake (from Romanov *et al.*, 1978)

30 kHz noise (middle panel) reflects electric field activity at the plasma frequency for standard ($n \sim 10 \text{ cm}^{-3}$) density values of the solar wind. Across this transition the plasma becomes compressed and thus the plasma frequency occurs above the response range of the 30 kHz channel. As a result few or no signals are recorded in that channel across most of the cross section of the ionosheath traversed by the spacecraft. In many orbits, however, there is evidence of additional short-lived 30 kHz signals nearly halfway between the bow shock and the ionopause. These occur roughly at the expected position of the characteristic line shown in Figures 2 and 3 and indicate that the local plasma experiences a sudden expansion. In fact, as the density drops from its high postshock levels to values smaller than $n \sim 10 \text{ cm}^{-3}$, it should trigger a brief response in the 30 kHz channel. This response is observed at 1938-1939 UT in the data of orbit 80 shown in Figure 4, and reveals that,

in a stationary situation, the front wave of the expansion region may be, only a few hundred kilometers thick (this estimate is derived from the fact that the PVO travels $\sim 7 \text{ km/s}$ with respect to Venus, see, for example, Colin, 1980).

The sudden change of plasma conditions that takes place at this transition is further evidenced by the dramatic drop of the particle flux intensity measured in the ion energy distribution labeled II in the bottom panel of Figure 4. In fact, unlike the energy distribution measured in the outer ionosheath (labeled I) there is, in the second energy distribution, a sharp cut-off at the 1122 eV energy step. This latter measurement was made precisely at the same time the brief 30 kHz ionosheath signals of the middle panel of Figure 4 were recorded, and agrees with the presence of a strong and sudden expansion of the flow in

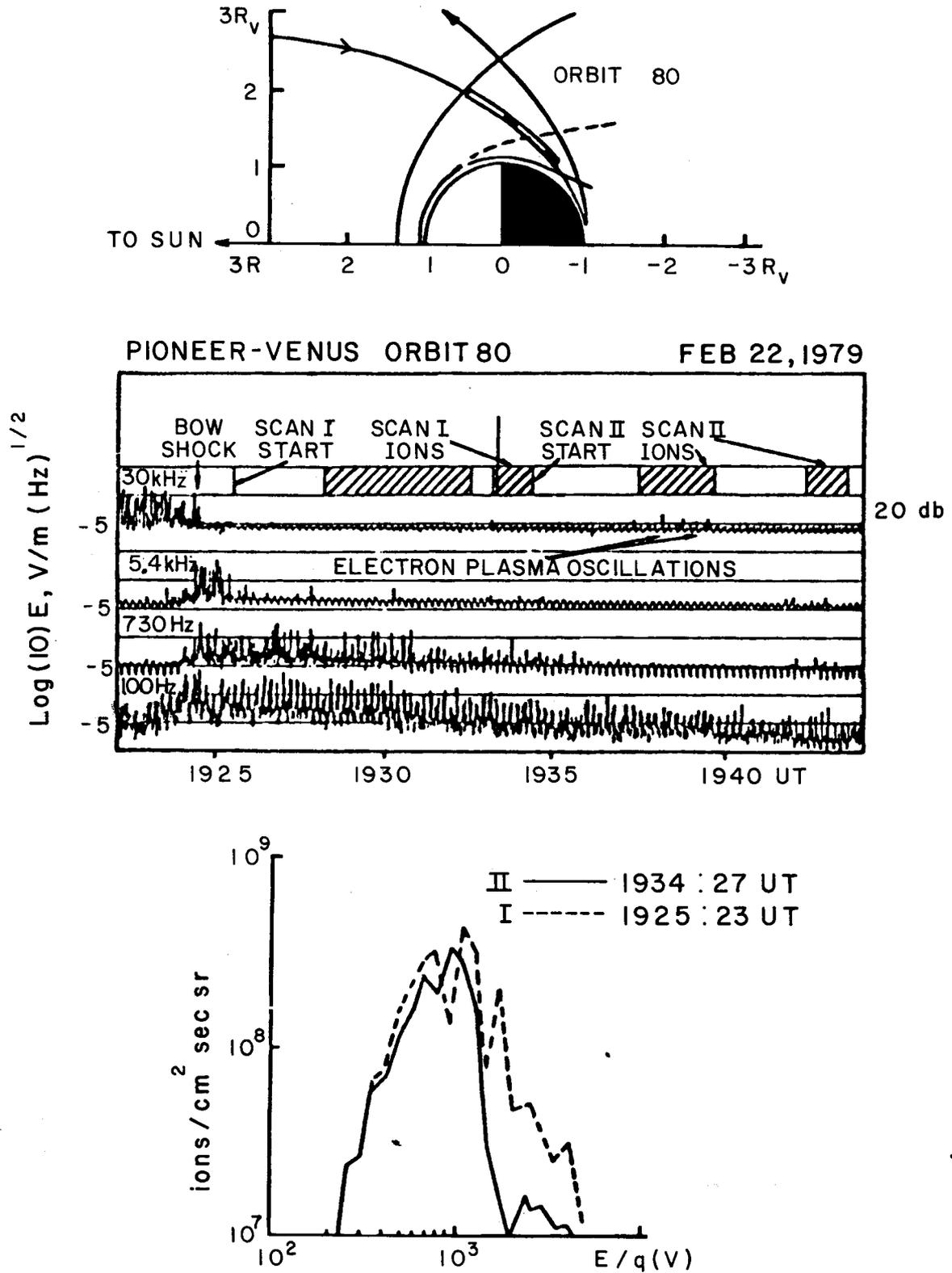


Fig. 4. (top panel) Geometry of the trajectory of the Pioneer Venus Orbiter (PVO) projected on one quadrant of a plane in which the vertical coordinate is the distance to the Sun-Venus axis. (middle panel) Electric field signals in the 30 kHz, 5.4 kHz, 730 Hz, and 100 Hz channels of the electric field detector of the PVO during the inbound pass of orbit 80. (lower panel) Ion energy spectra measured during the same pass with the plasma instrument of the PVO (from Pérez-de-Tejada *et al.*, 1984).

that region of space. Even though the geometry of the transition where this expansion occurs cannot yet be fully established the arguments given below support the view that it originates, most likely, from a position in the ionopause located not too far ahead from the terminator.

EFFECTS OF FRICTION AT THE IONOPAUSE

While it is clear that chemical processes (mass loading and charge exchange collisions) should contribute to the removal of the momentum flux of the solar wind, their role in producing the velocity profiles shown in Figures 1 - 3 remains to be clarified. In particular, it is not evident that these processes should result in the development of the sharp intermediate transition that is observed by the mid section of the ionosheath, nor the plasma changes that characterize that transition. Thus, independent of the gradual accumulated erosion that they produce on the velocity of the oncoming solar plasma (Phillips *et al.*, 1987; Belotserkovskii *et al.*, 1987), it is also necessary to explain the sudden deceleration that is observed at that transition.

In previous studies (Pérez-de-Tejada *et al.*, 1984, 1985) it has been argued that the intermediate transition, and the plasma changes across it, are consistent with the effects of a viscous-like interaction at the ionopause. In this interpretation that transition can be accounted for as the outer boundary of the region adjacent to the ionopause that is affected by the distribution of friction-induced perturbations produced at the ionopause. The origin of the viscous process has been traced to momentum scattering interactions that both the solar wind and the contaminating planetary pickup ions experience with local magnetic turbulent fields in the presence of a velocity shear (Pérez-de-Tejada, 1990). Much of the argument behind this concept is based on the results of modelling studies of the behavior of the pickup ions in the presence of strong magnetic turbulence (Wu *et al.*, 1986; Gaffey *et al.*, 1988); these indicate that the scattering of momentum can be as efficient as the pitch angle scattering and proceed in time-scales comparable to the ions' gyration period. Under these conditions the particles should readily exchange any momentum excess that they may have with respect to the local flow when moving across a region dominated by a velocity shear.

Figure 5 illustrates schematically the trajectory of a pickup ion subject to such interactions. As the particle is first accelerated through the convective $V \times B$ electric field of the solar wind it will execute a Larmor gyration whose radius is determined, to first approximation, by the local flow speed. As the particle moves into a region where the flow speed is smaller it will necessarily lose some of its momentum to the local flow upon experiencing a momentum scattering interaction with the turbulent wave field. As a result, its gyration radius will be smaller and the particle will be impeded to reach back to regions of the flow where it was first accelerated. The latter could be achieved only

through selective interactions in which the particle is further deviated in that direction. However, as a whole, the pickup ions will be forced to remain within the velocity shear and to transfer some of their momentum to the local flow. What this means is that the effect of the momentum scattering interactions is to gradually but inexorably trap the particles within the velocity shear and to extract from them kinetic momentum which was initially obtained from the solar wind through their convective $V \times B$ acceleration.

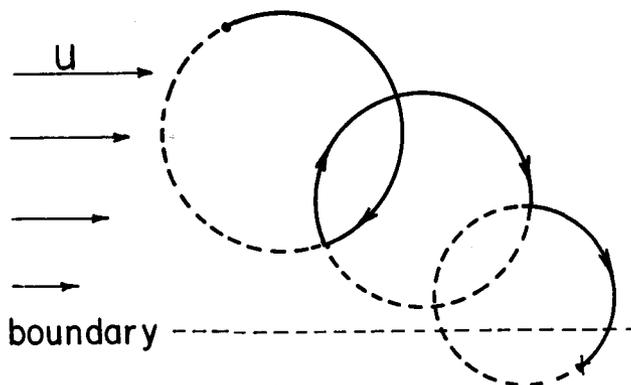


Fig. 5. Schematic diagram of the trajectory of a pickup ion in a velocity shear as it experiences momentum scattering interactions with a local turbulent wave field.

The net effect of this process is a cross-flow transport of momentum which is eventually delivered to the plasma below the ionopause. The latter occurs as the pickup ions move across that boundary and interact collisionally with the local particles where the density is substantially higher than in the solar wind. These various concepts have been quantified in a separate report (Pérez-de-Tejada, 1990) where it was further shown that the development of the friction process requires that the effective mean free path of the momentum scattering interactions be comparable to the gyration radii of the pickup ions. In other words, these particles experience on the average one such interaction every time they move about their Larmor gyration.

Independent of the physical mechanism responsible for the transfer of solar wind momentum to the Venus ionosphere it should be emphasized that the observed stratification of the Venus ionosheath is entirely compatible with the effects of that process. In particular, the finite width of the region affected by the phenomenon is due to the supersonic character of the reexpanded shocked solar wind that streams around the flanks of the Venus ionosphere. No flow disturbances produced by the viscous process can be propagated upstream of this region because they are washed out by the motion of the plasma.

Equally important are the lower velocities seen at and downstream from the intermediate transition within the Venus ionosheath. These are due to the loss of some of the momentum of the streaming shocked solar wind to the ionospheric plasma below the ionopause. The momentum flux involved in this process appears within the ionosphere

itself and, in fact, was used by Pérez-de-Tejada (1986) to explain the trans-terminator flow of the Venus upper ionosphere reported by Knudsen *et al.* (1980, 1981) from the Retarding Potential Analyzer measurements of the PVO. The latter flow is seen to develop at large ($>70^\circ$) solar zenith angles and involves ionospheric flow velocities of up to 4 km/s near the terminator. The important result here is that the height integrated momentum flux of this flow is very nearly equal to the height integrated deficiency of momentum flux within the shocked solar wind adjacent to the ionopause that is implied by the velocity profiles shown in Figures 1 - 3. Consequently, the bulk of the erosion of the velocity field in the inner ionosheath can be accounted for as due to the drag exerted by the ionospheric plasma on the shocked solar wind.

The onset of friction phenomena at the ionopause can account as well for the enhanced temperatures and the lower densities that are seen at and downstream from the intermediate transition. The dissipation associated with viscosity should in fact produce an effective plasma heating which in turn leads to the expansion of the local plasma in order to maintain pressure balance with the external inviscid flow.

CONCLUSIONS

What has been written here stresses the view that the plasma changes that characterize the intermediate transition of the Venus ionosheath are in the same sense than those expected from the distribution of flow properties that would result from a viscous interaction at the ionopause. The presence of that boundary, together with the lower speeds and densities and higher temperatures of the local plasma, are properties compatible with the development of friction phenomena at the ionopause. While some general ideas have already been advanced in regard to the origin of the process it is clear that much work is still necessary to fully substantiate the viscous concept. Among the various questions which await examination is the undefined interdependence between the velocity and temperature fields of the particle populations involved. Thus, while it is possible to qualitatively explain the manner in which the momentum of the solar wind can be transferred to the ionospheric plasma via the momentum scattering interactions experienced by the pickup ions, it is still necessary to, at least, provide a phenomenological description of the manner in which a fraction of the momentum involved in the process is converted into thermal energy of the participating particles. The energy dissipation that this concept implies was calculated by Pérez-de-Tejada (1982) in a comparative study of the Venera 10 velocity and temperature profiles. The results of that study gave a reasonable energy budget of the flow adjacent to the ionopause, but more formal and extensive work is still required.

An equally important question which awaits examination is the location of the position on the dayside ionopause where the intermediate transition originates. We

indicated earlier that the Mariner 5 data suggests that the characteristic line that connects the inbound and the outbound crossings of the intermediate transition seems to emerge from a location at the ionopause not too far ahead of the terminator. While the available data are not sufficient to fully examine this claim there are independent arguments which give credence to that possibility. First, within the context of the viscous origin given to the disturbances that are distributed at and downstream from the intermediate transition it is necessary to assume that a plasma-plasma interaction takes place at the ionopause; that is, that the shocked solar wind is effectively slowed down by the ionospheric plasma below that boundary. In general, however, this action will be inhibited by the interplanetary magnetic field fluxes that accumulate around the dayside ionopause. These fluxes represent in fact a buffer zone which has the effect of reducing the direct contact between both plasmas. While this restriction may severely prevent the development of friction forces across most of the dayside ionopause, the conditions seen near the terminator suggest a different scenario. In this region the accumulation of interplanetary magnetic fluxes around the ionopause is much weaker, and the resulting local magnetic field intensities do not exceed significantly the values measured in the freestream solar wind (Luhmann *et al.*, 1980). Consequently, one should expect the shocked solar wind to interact more directly with the ionospheric plasma as it gradually moves toward the terminator. It is even possible that the development of friction forces occurs only when the local flow conditions at the ionopause change from subalfvenic to superalfvenic with increasing solar zenith angle (it is known, for example, that in a subalfvenic flow, the magnetic fluxes prevent the formation of friction layers around an obstacle, see Greenspan and Carrier, 1959).

An independent reasoning which also gives support to the view that the intermediate transition originates from a region on the ionopause located not too far ahead from the terminator can be prepared by pointing out the peculiar circumstance that the topside ionospheric flow develops at large solar zenith angles only. According to Whitten *et al.* (1982) the flow velocities measured across the upper ionosphere are large (>2 km/s) in the $70^\circ < \text{SZA} < 120^\circ$ range and the velocity field, as a whole, exhibits a sharp change of conditions at the lower end of this range; that is, much smaller (< 0.5 km/s) flow velocities are measured at $\text{SZA} < 70^\circ$. The fact that the SZA value where the ionospheric flow develops coincides with the general region where the intermediate transition outside is expected to emerge from the ionopause may suggest that both phenomena are not unrelated but reflect a strong coupling between them. Thus, the claim made earlier in the sense that the momentum flux of the topside ionospheric flow derives from that of the shocked solar wind streaming in the vicinity of the ionopause explains selfconsistently its height-integrated value and the overall region where it is observed. This result can, in turn, be used to substantiate the view that the viscous layer, which is bounded by the intermediate transition, develops from the vicinity of the

terminator and not from the subsolar region of the Venus ionosheath.

The arguments presented here should not be interpreted as suggesting that chemical processes (mass loading and charge exchange collisions) are not important contributors to the removal of the momentum of the incident plasma. Instead, we can only conclude that their role in producing the overall deceleration of the shock solar wind may vary strongly according to position throughout the ionosheath. Near the subsolar region, where weak or no friction processes are expected, most of the local loss of momentum flux could occur through mass loading and charge exchange collisions. Near the terminator region, on the other hand, the development of the viscous layer appears to result in a deceleration process stronger than that produced through chemical phenomena.

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