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Structure of the Venus ionosheath

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RESUMEN

Se presenta un resumen de observaciones experimentales realizadas en la región de interacción del viento solar con la ionosfera del planeta Venus. En particular, se discuten mediciones del flujo de viento solar entre la ionopausa (frontera exterior de la ionosfera) y el frente de choque que se forma al frente de ella. En esta región (llamada ionofunda) existe una transición intermedia que la divide en 2 estratos de características muy diferentes. En la parte interior el plasma se mueve más lentamente, es más caliente y menos denso que en la parte exterior. Esta transición se observa por los flancos de la ionofunda y se extiende hacia atrás del planeta por los lados de la cauda de plasma planetario.

PALABRAS CLAVE: Ionosfera de Venus, interacción con el viento solar.

ABSTRACT

A review of experimental observations of the region of interaction of the solar wind with the Venus ionosphere is presented. In particular we examine measurements of the solar wind flow between the ionopause (outer boundary of the ionosphere) and the bow shock that forms upstream from it. That region (the ionosheath) is divided by an intermediate plasma transition into 2 distinct layers. In the inner layer the plasma moves slower, is hotter, and less dense than in the external layer. Such plasma transition is detected along the flanks of the Venus ionosheath and downstream along the sides of the planet's plasma tail.

KEY WORDS: Venus ionosphere, Solar wind interactions.

INTRODUCTION

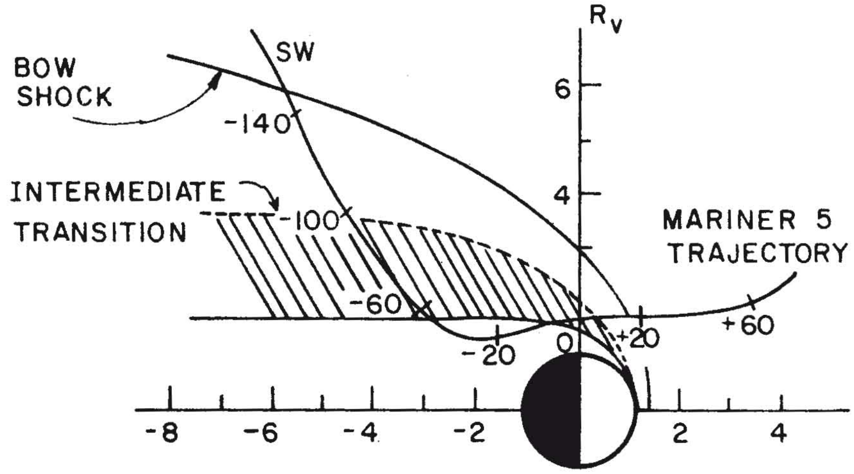
After nearly 25 years of *in situ* experimental research of the Venus plasma environment our understanding of the interaction of the solar wind with that planet's ionosphere is still far from adequate. This statement may appear to some as unfair, in view of the abundant experimental information now available. But important aspects of that information are yet to be incorporated into consistent theoretical interpretations. An example is the belated recognition of the existence of a well-defined plasma transition immersed in the Venus ionosheath (the region between the ionopause and the planet's bow shock). This transition divides that region of space into layers of different plasma properties and represents an important geometric property of the overall configuration of the Venus plasma environment. Very little attention has been given in the literature to this feature and, as a result, it has not been fashionable to incorporate it in theoretical models of the solar wind around Venus.

Much of the reluctance to accept the intermediate transition of the Venus ionosheath as an integral part of that planet's plasma environment is due to the difficulties associated with its identification in the Pioneer Venus Orbiter (PVO) data. This unfortunate circumstance has prevented us from having a more complete view of the configuration of that region of space and of the phenomena that occur in it. Nevertheless, there is clear and undeniable experimental evidence of the presence of that elusive feature whose origin, geometry and participation in the solar wind-Venus interaction process have yet to be properly accounted for.

We will review here some of the published experimental information on the intermediate transition of the Venus ionosheath. We will emphasize an important circumstance of that data; namely, the overall consistency regarding this matter in the results derived from experiments on different spacecraft. Thus, we will stress that the identification of the intermediate transition is supported by measurements made in experiments carried out with the Mariner 5, the Venera 9 and 10, and the PVO spacecraft. The first section provides the historical background of the problem with brief descriptions of measurements conducted with the Mariner 5 and the Venera 9 and 10. The second section describes some of the PVO data with which it has been possible to support the presence of the intermediate transition as a steady state feature of the Venus plasma environment. The third section describes some theoretical ideas that seem relevant to account for the formation of the intermediate transition of the Venus ionosheath. In particular, we will discuss a hydrodynamic analogue, based on friction processes, which is consistent with the flow properties seen across that feature. The nature of the phenomena that may be responsible for the onset of such processes will also be discussed together with an account of the limitations that this and alternative views encounter at the present time.

EARLY MEASUREMENTS

The initial report of the plasma measurements conducted during the Mariner 5 fly-by near Venus (Bridge *et al.*, 1967) contains an extensive discussion of a plasma fea-



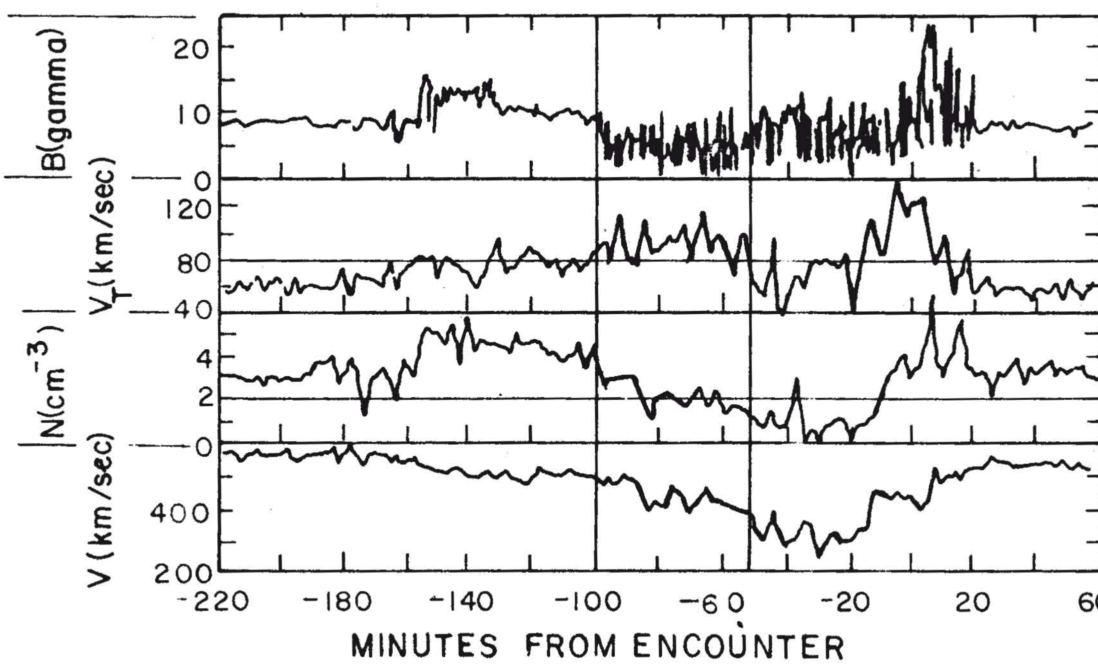


Fig. 1. (top panel) Trajectory of the Mariner 5 spacecraft during its Venus fly-by. The curves labeled BS, IT, and I indicate, respectively, the bow shock, the intermediate transition, and the ionopause. (lower panel) Magnetic field intensity, thermal speed, ion density, and bulk speed measured in the Venus plasma environment during the Mariner 5 fly-by (from Sheffer *et al.*, 1979).

ture detected in the region downstream from that planet's bow shock. As told by these authors, the shocked solar wind exhibits a sudden change of properties in the inner ionosheath where a well-defined transition marks the outer extent of a region with different plasma conditions.

Figure 1 reproduces the plasma properties reported by Sheffer *et al.* (1979) from the re-examination of the Mariner 5 data. The upper panel of that figure shows the approximate position of both the bow shock (labeled BS) and the (intermediate) plasma transition (labeled IT) detected downstream from it (the trajectory is shown on a plane in which the ordinate is the distance to the Sun-Venus line). The changes observed at both transitions can be identified from the various profiles shown in the lower panel of Figure 1. Note, in particular, that at the inbound crossing of the bow shock (at t = E - 160 min, E being the time of closest approach) the magnetic field intensity, the thermal speed (proportional to the plasma temperature), and the flow density, increase downstream, while the bulk speed (bottom panel) decreases in that direction. Similar variations are present at the outbound crossing of the bow shock (at t = E + 20 min) though they are superimposed on changes produced by multiple traversals of that boundary.

The (intermediate) transition marked in the lower panels by the vertical lines at t = E - 100 min (inbound), and at t = E + 8 min (outbound) is characterized, on the other hand, by different conditions. While the bulk speed is lower, and the thermal speed is higher downstream (as is the case across the bow shock), the plasma density and the magnetic field intensity are lower downstream. The changes in the latter parameters are opposite to that seen across a bow shock and indicate that the flow experiences locally an expansion rather than a compression. The strong velocity decrease seen in the outbound crossing of the intermediate transition (at t = E + 8 min) is important not only because the implied deceleration of the shocked solar wind is larger than that seen at the bow shock, but also because it occurs deep within the ionosheath (at a location much closer to the planet than those resulting from time variations of the position of the bow shock).

The peculiar changes experienced by the shocked solar wind at the intermediate transition led to arguments regarding the possibility that this feature may, in fact, reflect time variations of the solar wind rather than an intrinsic property of its interaction with the Venus ionosphere. In the early Mariner 5 report (Bridge *et al.*, 1967) and in the literature derived from it (e.g. Rizzi, 1972), emphasis was placed in the marked decrease of the density and magnetic field intensity seen at the intermediate transition; a variation that was believed resulted from the entry of the solar wind flow into the planet's wake. For this reason that feature was addressed as a strong "rarefaction wave" which marked the outer extent of the flow perturbed by that process. However, in a later publication (Sheffer *et al.*, 1979) it was pointed out that the higher plasma temperatures that characterize the plasma downstream from such a rarefaction wave hinder that interpretation; namely a gas filling in the wake behind a body is expected to cool off rather than to exhibit higher temperatures.

Independent information which agreed with the unexpected presence of the intermediate transition reported from the Mariner 5 measurements was presented years later by Vaisberg (1976) and by Romanov *et al.* (1979) using Venera 9 and 10 plasma data. In this case the measurements showed that the inner region of the flank ionosheath seems indeed to be dominated by plasma with properties different from those present further outside. In particular the flow speed is significantly lower, and the plasma temperature higher, in the inner ionosheath. However, the outer boundary of this later region could not always be identified and, as a result, only circumstantial evidence of its existence persisted.

A useful example which contains information consistent with the Mariner 5 results is reproduced in Figure 2 from the April 19, 1976 pass of the Venera 10 reported by Romanov *et al.* (1979). As that spacecraft approached the planet from the wake (see inset) there is clear evidence of a bow shock crossing (at 2400 MT, Moscow Time), in the ion temperature and speed profiles. As in the Mariner 5 encounter, a second (intermediate) plasma transition can be identified deep within the ionosheath (at 0145 MT). The anticorrelation between the sudden increase of the plasma temperature and the decrease of flow speed seen at this transition is the same as that observed in both, the inbound and the outbound passes of the Mariner 5 fly-by and again reveal that the local change of the plasma properties can be very substantial. Equally important is the fact that the region where the second transition is located along the trajectory of Venera 10 is equivalent to that in the Mariner 5 trajectory where the intermediate transition was observed. We argue that this apparent agreement is not coincidental but reflects the persistent presence of a steady state feature in the same general region of the flanks of the Venus ionosheath.

A third plasma boundary can also be identified in the temperature profile shown in Figure 2 (at 0240 MT). Romanov *et al.* argued that this additional boundary may simply reflect the different composition of the plasma streaming along both sides of that boundary and that cool material of planetary origin may be dominant downstream from it. The position of this transition is in general agreement with that view if the shocked solar wind is forced to stream outside the Venus plasma tail (in this case that boundary marks the outer extent of such a plasma tail whose material also shares a certain bulk speed in the downstream direction). Unlike this boundary, however, the second (intermediate) transition does not seem to have a simple interpretation particularly since, as is the case in the Mariner 5 plasma data, it displays a marked outward flaring with the downstream distance.

PIONEER VENUS ORBITER MEASUREMENTS

Despite the substantial amount of information acquired with the many experiments conducted since 1978 with the Pioneer Venus Orbiter (PVO), there are various important issues which have not been poperly examined. A good example is the presence of the intermediate transition of the Venus ionosheath which, as discussed above, was only supported by circumstantial evidence from earlier spacecraft data.

In retrospect one can identify at least 2 different factors which, in the end, have discouraged further examination of that feature. On the one hand it is now clear that the peculiar conditions present in the inner ionosheath (low flow speeds and plasma densities) are not suitable for the

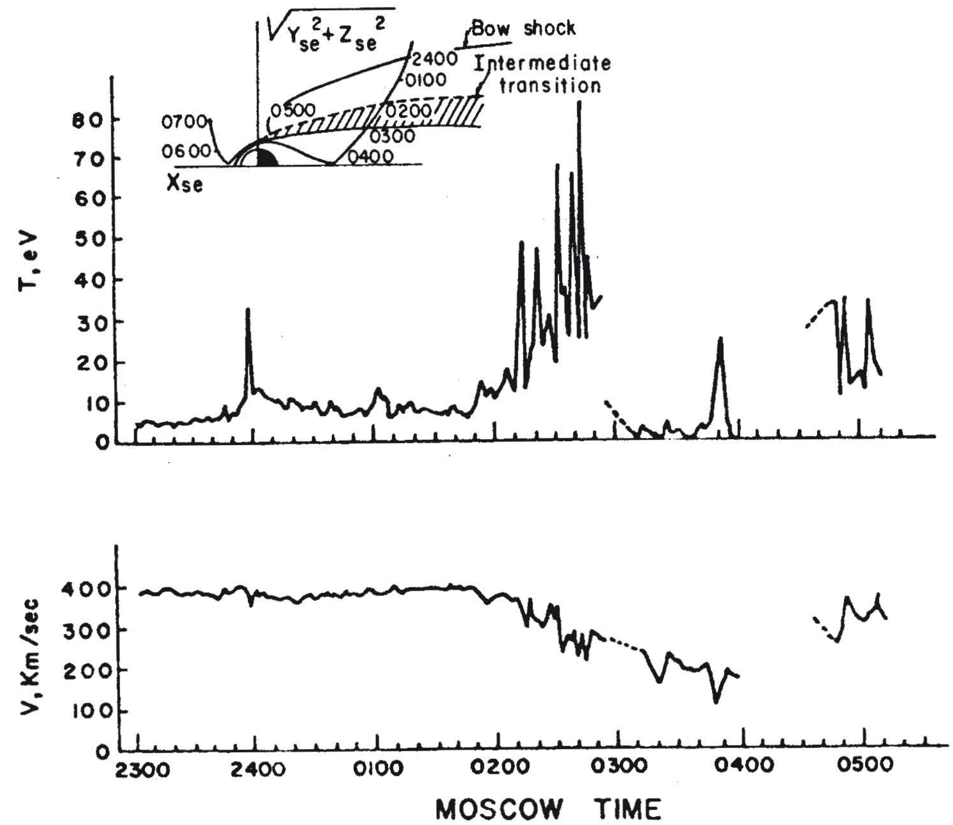


Fig. 2. Ion temperature and bulk speed measured during the April 19, 1976 pass of the Venera 10 orbiter through the Venus near wake (from Romanov *et al.*, 1979).

operation range of the plasma instrument of the PVO. In most cases the threshold of that instrument is far too high to enable the identification of plasma fluxes downstream from the intermediate transition and, as a result, it is not possible to determine the plasma properties of the flow within that region. Equally restrictive is the fact that within the ionosheath such plasma properties may change substantially across distances shorter than those traveled by the spacecraft during each scan of measurements (the instrument operates in a cyclic manner scanning particles of different energy and angle of arrival). As a result of these complications the PVO plasma data has been insufficient to provide information which, by itself, could have been used to identify the intermediate transition.

Independent of these limitations there is the complicating factor that the intermediate transition does not appear to produce a persistent signature in the magnetic field data. Problems related to the limited spatial extent of the region around Venus where the intermediate transition is present, and/or a possible axial asymmetry of its geometry, result in the absence of consistent magnetic signatures across the ionosheath. Under these conditions, the magnetic field data gives unclear information on the intermediate transition and cannot be used as a sole indicator of its presence.

While neither the plasma probe data nor the magnetic field data of the PVO can independently be used to identify the intermediate transition it is possible to use them both in combination with additional data. A useful piece of information that serves this purpose is available from measurements conducted with the electric field instrument of the PVO (Scarf *et al.*, 1980). In this experiment there are 4 different channels that register local electric noise. The channel centered around 30 kHz is suitable for measuring plasma (Langmuir) oscillations at the local plasma frequency when the density is ~ $10 cm^{-3}$ (as is usually the case in the freestream solar wind). The incorporation of the electric field data to study the intermediate transition is illustrated in the analysis of the conditions observed in the inbound pass of the PVO across the Venus ionosheath in orbit 80, which are reproduced in Figure 3 (Pérez-de-Tejada *et al.*, 1984). The top panel shows the PVO trajectory on a plane similar to that of Figure 1, except that both the inbound and the outbound passes are shown in the same quadrant.

The electric field signature recorded with the 30 kHz channel (middle panel) shows high activity upstream from the bow shock (indicated by the vertical line at 1925 UT). This response is consistent with the detection of plasma oscillations at that frequency under typical ~ $10 cm^{-3}$ solar wind density values. Downstream from that transition the flow becomes compressed and the local plasma frequency

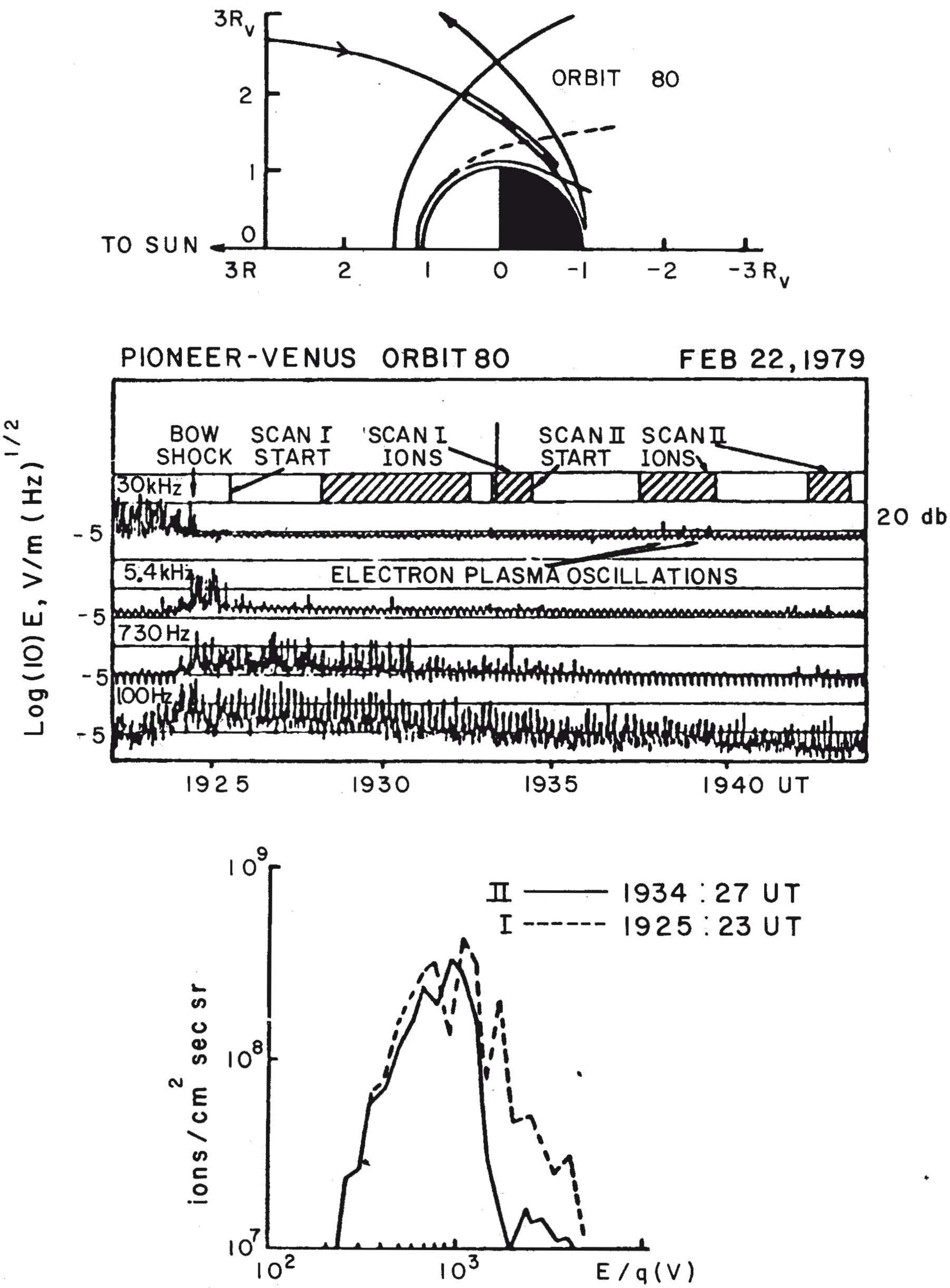


Fig. 3. (top panel) Trajectory of the Pioneer Venus Orbiter (PVO) projected on a plane similar to that on Figure 1. (middle panel) Electric field signals in the 30 kHz, 5.4 kHz, 730 Hz, and 100 Hz, channels of the PVO electric field detector during the inbound pass of orbit 80. (lower panel) Ion energy spectra measured with the PVO plasma instrument during the same pass (from Pérez-de-Tejada *et al.*,1984).

occurs outside the response range of the 30 kHz channel. As a result, no electric noise is observed in that region. It turns out, however, that deep within the ionosheath (at ~ 1938 UT in the pass shown in Figure 3) there is evidence of a brief burst of additional electric field noise in that channel. These electric signals, which are detected upstream from the ionopause (vertical line at 1945 UT), imply that the local plasma density may have again become suitable for the generation of plasma waves near 30 kHz. Thus, it is possible that these signals represent oscillations at the plasma frequency which were produced by the sudden decrease of the plasma density from > $10 cm^{-3}$ to < $10 cm^{-3}$ values.

The sudden expansion of plasma in the inner ionosheath, suggested by these concepts, is consistent with the traversal of the intermediate transition inferred from the Mariner 5 plasma data. In fact, this feature is characterized by a sudden decrease of the local plasma density, a variation that was used in the Mariner 5 literature to adopt the term "rarefaction wave" to identify that transition. In the present case we can further test this claim by examining the PVO plasma probe data obtained during orbit 80. This is reproduced in the bottom panel of Figure 3 which shows the 2 ion energy spectra recorded as the PVO traversed the ionosheath in its inbound pass. The ion spectrum labeled I (initiated at 1925:23 UT) was recorded while the PVO was in the outer ionosheath and shows an energy particle distribution typical of those seen in many orbits. The second ion spectrum (initiated at 1934:27 UT) began as the PVO moved to the inner region of the ionosheath and shows a noticeably atypical shape. Most notable is the fact that, despite having a very similar buildup at low energies the second ion spectrum displays a strong sudden drop of the particle flux intensity (involving nearly a one order of magnitude difference in the values recorded) between 2 neighboring energy steps. Very low intensity plasma fluxes are measured at higher energies, thereby resulting in a very unusual particle flux distribution with a strongly depressed high energy tail.

The most important aspect of these measurements is the fact that the severe drop of the particle flux intensity took place very nearly at the same time the brief 30 kHz electric field bursts were recorded. Consequently, the data of both the plasma probe and the electric field instrument, show consistent evidence indicating that a dramatic change in the plasma properties did take place as the PVO moved into the inner ionosheath. The suggested change, namely, the sudden drop of the particle flux intensity, agrees with the crossing of a plasma transition whose signature is compatible with that inferred from the early Mariner 5 measurements (in both cases there is evidence of the sudden expansion of the local plasma).

The identification of the brief 30 kHz electric field bursts of the Venus ionosheath, as markers of the intermediate transition, has been extensively applied to other PVO orbits (Pérez-de-Tejada *et al.*, 1991). From the examination of nearly 200 ionosheath passes it has been found that electric field signatures like that shown in Figure 3 are not unusual but occur in a significant number of cases. In many instances strong and well-defined bursts appear unmistakably between the bow shock and the ionopause. In others the signals are weak and cannot be adequately defined from the background intensity level. A sample of passes with some of the most distinguishable ionosheath bursts is reproduced in Figure 4. In all cases shown the signals occur well within the ionosheath and thus it can be safely assumed that they are not related to ionopause phenomena. However, in some orbits the electric field bursts are located very close to this later boundary and thus it is difficult to discriminate the origin of the feature.

The abundance of cases in which the 30 kHz electric field bursts appear as a separate and well developed structure of the Venus ionosheath provide, perhaps, the best evidence available of the presence of the intermediate transition as a steady state feature of that region of space. This conclusion is further supported by the observed position of the PVO where such bursts are detected. A summary of the recorded crossings of the 30 kHz bursts in the Venus ionosheath is reproduced in Figure 5. Despite a certain dispersion, there are many cases which cluster in a fairly small region of the ionosheath. That region extends downstream from the vicinity of the terminator along the flanks and covers an area consistent with that where the "rarefaction wave" of the Mariner 5 data is located.

While the data set represented in Figure 5 defines the general region of the ionosheath where the intermediate transition is more favorably detected, it is not sufficient to determine its geometry. In particular, it does not provide information to establish the spatial origin of the transition upstream from the terminator. In the modeling studies of the Mariner 5 plasma data Rizzi (1972) suggested that the "rarefaction wave" could originate from a position on the ionopause not too far upstream from the terminator (in his interpretation that position defined the most upstream extent of the region influenced by the expansion of the flow into the wake). That view appears to be consistent with the overall distribution of PVO crossings of the intermediate transition shown in Figure 5, but it does not rule out the possibility that the foot of that transition may occur much further upstream near the nose region. Unfortunately the identification of crossings of that feature upstream from the terminator is masked by the superposition, in the 30 kHz electric field signature, of noise associated with the neighboring ionopause. It is difficult, under such conditions, to distinguish that boundary from the intermediate transition.

In addition to studies of the PVO electric field data there have been efforts directed to examine the structure of the Venus ionosheath from the combined analysis of the magnetic and the plasma data (Feodorov *et al.*, 1991). In this case, evidence has been found of a rotational magnetic field wave associated with changes in the velocity field (steeper velocity gradients are measured downstream from that wave). Since a rotation of the magnetic field is sometimes present when the brief 30 kHz electric field signals are de-

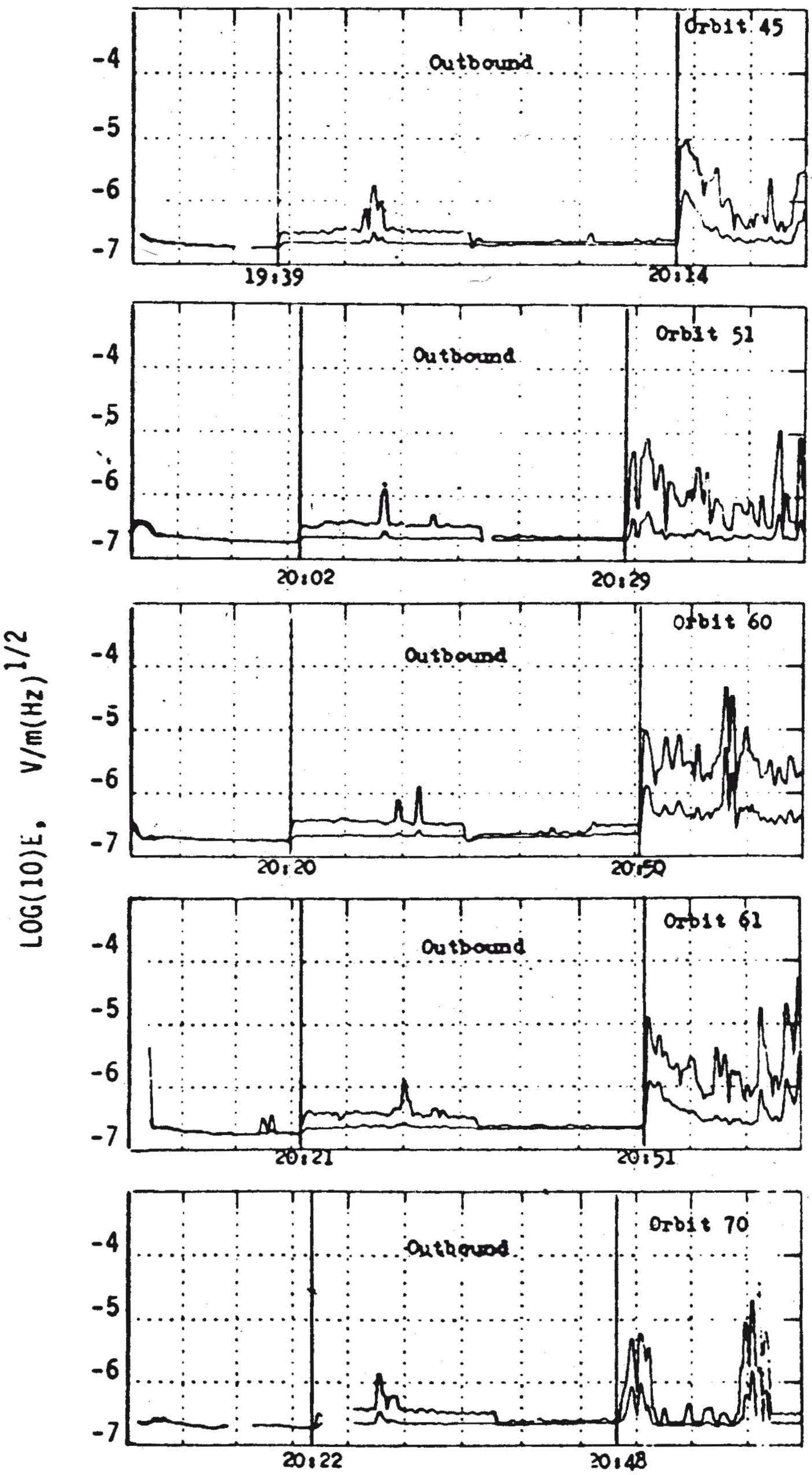


Fig. 4. Examples of PVO electric field data with strong 30 kHz bursts detected in the ionosheath (the vertical lines indicate the bow shock (BS) and ionopause (I) crossings).

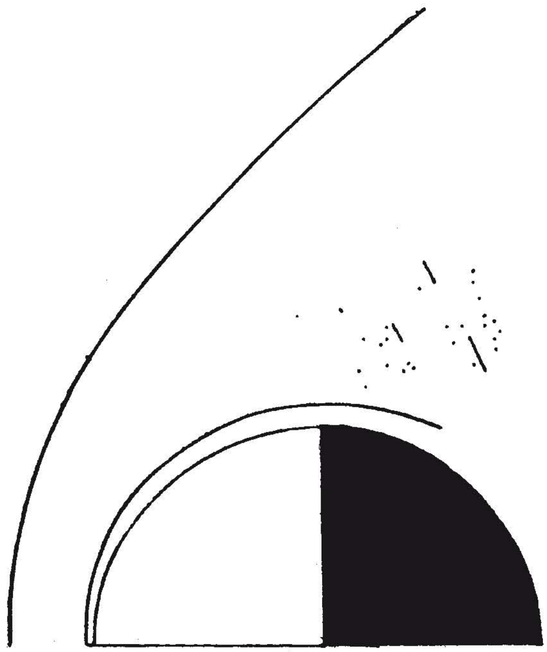


Fig. 5. PVO position (projected on a similar plane as Figure 1) at the time when strong 30 kHz electric bursts were detected in the Venus ionosheath. The bow shock and ionopause curves are assumed shapes for their average locations.

tected (e.g. the pass of orbit 80 shown in Figure 3) it is possible that the feature identified by Feodorov *et al.* (1991), and that inferred from the electric field data, is one and the same.

A HYDRODYNAMIC ANALOGUE

Unlike the ionopause and the bow shock that forms in front of the Venus ionosphere there is no precedent, in the solar wind interaction with other planets, of a plasma transition located in the region between a bow shock and the planet's effective obstacle. No such transition has ever been recorded in the magnetosheaths of the Earth or of other planets with a strong intrinsic magnetic field. However, as discussed above, there is a substantial amount of data which strongly supports the presence of the (intermediate) steady state transition of the Venus ionosheath. Perhaps the absence of a similar feature in the magnetosheaths of other planets, reinforced by its difficult identification in the plasma and magnetic field data of the PVO, has been partially responsible for the fact that little if any attention has been given in recent years to that important component of the Venus plasma environment.

There is no reason at the present time to continue ignoring the presence of the intermediate transition of the Venus ionosheath and, on the contrary, it is essential to consider viable explanations for its existence. We noted earlier that in the initial Mariner 5 report (Bridge *et al.*, 1967) it was suggested that the "rarefaction wave" marks the outer extent of that part of the ionosheath flow which is influenced by the entry of the shocked solar wind into the Venus wake. However, the difficulties raised by the fact that the enhanced plasma temperatures measured in the inner ionosheath are contrary to this interpretation (the entry of the flow into the planet's wake should result in the overall cooling of the plasma) have not been addressed.

It has also been argued that the properties of the shocked solar wind in the inner ionosheath are consistent with an assumed viscous interaction of the incident flow with the planet's upper ionosphere (e.g. Pérez-de-Tejada, 1982). In this case, the deceleration of the shocked solar wind in the vicinity of the ionopause should be produced through a drag force exerted by the ionospheric obstacle. The basic concept here is that a fraction of the momentum of the solar wind is transferred through friction to the ionosphere. At the same time, enhanced plasma temperatures should be produced within that region by the energy dissipated in the momentum transfer process. The latter should also result from the expansion of the local plasma so that its pressure matches that of the flow outside the friction layer. While the observed behavior of the shocked solar wind in the inner ionosheath agrees with this qualitative description there is, in principle, no clear physical basis to substantiate the validity of that comparison. In fact, the collisionless character of the solar wind rules out the possibility that a direct transfer of momentum may proceed through Coulomb collisions across the ionopause. Recently, however, it has become apparent that there exist non-collisional processes in the solar wind which can produce an effective transfer of momentum within the flow. Central to this contention is the role of turbulent electric and magnetic fluctuations which under certain conditions can interact strongly with the solar wind particle populations. From measurements conducted in cometary plasma environments where, as in Venus, the presence of contaminant particles in the solar wind results in the generation of strong turbulent plasma conditions (Scarf *et al.*, Coates *et al.*, 1989), it has been learned that the plasma particles experience efficient pitch angle and momentum scattering interactions. In these processes (modeled theoretically by Wu *et al.*, 1986 and Gaffey *et al.*, 1988) the bulk energy of the particles may be severely modified by the turbulent fields and, as a result, be collectively shared by the plasma as a whole. These concepts may provide the basis for understanding the manner in which the momentum of the solar wind could be successfully transferred to a planetary ionosphere (an extended discussion of this issue has been presented by Pérez-de-Tejada, 1991).

Friction phenomena describing the interaction of the solar wind with the Venus ionosphere may be relevant to provide an interpretation of the origin of the intermediate transition which is consistent with that view. The description is based on the conventional configuration of a viscous hypersonic flow past an obstacle, as is generally known in standard hydrodynamic theory. The diagram in Figure 6 illustrates the flow structure around a flat plate which provides the simplest possible obstacle geometry for that problem. In addition to the (attached) bow shock that originates from the nose of the plate, a second (intermediate)

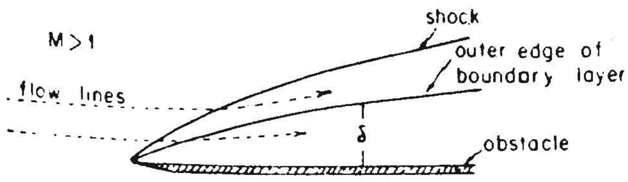


Fig. 6. Schematic view of flow structure in conventional supersonic flows past an obstacle (from Mikhailov *et al.*, 1971).

transition forms downstream from it. This transition marks the outer edge of the friction layer that develops around the obstacle as a result of the drag exerted on the flow. Downstream from that transition the flow speed exhibits a sharp decrease with decreasing distance from the obstacle, the local temperature is higher as a result of viscous dissipation, and the density is low. All these variations are due to the effect of fluid disturbances generated at the obstacle by the friction process and distributed downstream within the flow. However, the distribution of disturbances can modify only the region adjacent to the obstacle. Further outside they are washed out by the local re-expanded shocked flow that streams again with supersonic speeds. Thus no disturbance produced at the obstacle can reach the flow beyond the outer edge of the friction layer. Such an edge marks a sharp transition of properties within the flow and appears as a distinguishable feature downstream from the bow shock. No such transition is expected to develop in subsonic flow past an obstacle because, in this case, the disturbances generated at the obstacle are not restricted from perturbing the entire flow field.

Even though similar concepts could, in principle, be also applicable to account for the intermediate transition of the Venus ionosheath, it is necessary to clarify firstly to what extent the fluid description of flow disturbances is valid in the solar wind. The suggested participation of turbulent electric and magnetic field fluctuations to the momentum transport process seems essential to produce this effect but detailed explanations of how they affect the particles' properties are necessary. In particular, a consideration of the manner in which the plasma-wave interactions result in the effective heating of the plasma deserve special and exhaustive attention.

Despite the as yet unresolved identification of the basic physics that is required to validate the viscous fluid concepts there is, in the viscous flow interpretation, a general consistency with the observed behavior of the solar wind in the Venus ionosheath. In addition to prescribing changes of the plasma properties in the right sense, the viscous flow interpretation provides a simple and natural explanation for the presence of the intermediate transition. No alternative explanation has been advanced even though other processes may also produce effects compatible with the properties of the solar wind in the inner ionosheath. The most important of these is the very presence of the population of particles of planetary origin which are incorporated to the solar wind. This population of mass loaded material has the effect of removing some of the momentum of the oncoming flow and thus contributes to produce its deceleration. There is clear evidence in the data available about the presence of that component in the solar wind near Venus (Intriligator, 1982); but it is by no means evident that such a component is sufficient to account for the observed deceleration, nor that it produces an effective heating of the local plasma. Calculations based on the observed density of contaminant planetary ions near Venus and Mars suggest that the fraction of the momentum flux of the incident solar wind assimilated by that component is only minor (Breus, 1989; Pérez-de-Tejada, 1991).

Despite these arguments there is still a widespread opinion in the literature in the sense that chemical processes (mass loading and charge exchange collisions) are sufficient to account for the complex dynamics of the solar wind as it streams around Venus. A more stringent test of the sufficiency of these processes should aim at reproducing the intermediate transition, including the peculiar change of plasma properties that occurs across it. This requirement seems to be particularly critical because there is no apparent reason why chemical phenomena should result in the formation of a sharp boundary within the solar wind, irrespective of the local density of neutral particles (note that the intermediate transition is observed both near and far downstream from the planet). Whether no major difficulties are encountered in resolving this problem, and whether chemical processes can in fact account for the conditions observed across the intermediate transition, remains to be demonstrated.

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