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Plasma Measurements of the Pioneer Venus Orbiter in the Venus Ionosheath: Evidence for Plasma Heating Near the Ionopause

H. PÉREZ-DE-TEJADA

Instituto de Geofisica, Universidad Nacional Autónoma de México, Ensenada, Baja California

D. S. INTRILIGATOR

Carmel Research Center, Santa Monica, California

F. L. SCARF

Applied Technology Division, Space and Technology Group, TRW, Redondo Beach, California

A study of the angular spread of plasma fluxes detected in the Venus ionosheath is presented. It is shown that in the inner regions of the ionosheath, where the flux intensity is severely decreased with respect to solar wind values, the width of the azimuthal distribution of the local plasma is comparable to, or even larger than, that of the stronger fluxes measured in the outer ionosheath. The observed variation of the angular width suggests the existence of a source of heating near the ionopause but is not consistent with the overall cooling that would be expected if mass loading and charge exchange collisions were solely responsible for the interaction process at that boundary. Dissipative phenomena associated with local plasma turbulent processes seem to be required to account for the broad angular distributions seen near the ionopause.

INTRODUCTION

The identity of the plasma fluxes that stream in the vicinity of the Venus ionopause remains one of the most important issues of the analysis of the interaction process that takes place between the solar wind and the ionospheric plasma. From the early observation of a gradual decrease of the flow velocity in the inner regions of the Venus ionosheath during the inbound leg of the Mariner 5 fly-by [*Bridge et al.*, 1967], a significant amount of experimental evidence has been accumulated which indicates that the shocked solar wind is severely modified by its interaction with the ionosphere/atmosphere of the planet. In that and more recent experiments conducted with the Venera [*Vaisberg et al.*, 1976; *Gringauz*, 1976] and the Pioneer Venus (PVO) [*Wolfe et al.*, 1979; *Intriligator et al.*, 1979; *Mihalov et al.*, 1982] orbiters it has been recognized that the plasma fluxes streaming near the Venus ionopause are significantly weaker than those seen in the outer ionosheath and that a certain loss of the incident momentum flux is implied by the observed velocity and density profiles.

Further measurements made with the PVO spacecraft have also revealed that the inner region of the ionosheath is contaminated with a population of ionospheric particles. *Spenner et al.* [1980] have reported, for example, that in a region about 1500 km thick above the ionopause near the terminator the measured electron spectra contain an appreciable component of low-energy electrons of ionospheric origin. These measurements were recently used by *Russell and Vaisberg* [1983] to propose that the decreased momentum flux seen in the inner ionosheath is mostly due to the mass loading of the incident solar wind plasma with cool ionospheric material and that the different composition of the plasma fluxes in that region is responsible for the observed changes in the flow.

Perez-de-Tejada [1982] has pointed out, on the other hand, that in addition to the decreased flow velocities seen near and downstream from the terminator, the observations show that the plasma temperature appears to be higher in that region [*Verigin et al.*, 1978 Figure 8; *Romanov et al.*, 1979, Figure 5]. The observed temperature enhancements are considerably larger than that predicted from the inviscid flow calculations of *Spreiter and Stahara* [1980, Figure 9], and suggest the existence of dissipative processes, as would be expected to result from a viscous interaction between the shocked solar wind and the ionospheric plasma. In this alternative interpretation [*Perez-de-Tejada and Dryer*, 1976] the loss of momentum flux of the shocked solar wind is due to viscous transfer processes which drive the upper ionospheric plasma toward the nightside. The observation of a general displacement of the ionospheric particles in that direction [*Knudsen et al.*, 1980] is in agreement with this view and accounts self-consistently for the momentum flux missing above the ionopause [see *Perez-de-Tejada*, 1982].

In the present report we provide evidence, based on the analysis of the PVO plasma data, which further supports the high plasma temperatures in the inner ionosheath reported from the Venera measurements. The inferred temperature values suggest that the streaming plasma population, even in the immediate vicinity of the ionopause, is formed mainly of shocked solar wind protons or heated ionospheric particles. In either case the high temperatures associated with such population are not consistent with the overall cooling that would be expected if mass loading and charge exchange collisions dominated the interaction process.

PVO OBSERVATIONS

The high temperatures of the plasma in the inner ionosheath reported from the Venera measurements have been inferred from calculations based on the shape of the energy spectra of the plasma fluxes detected in this region. Such estimates apply across distances traveled by the spacecraft during the time interval taken by the plasma instrument to complete

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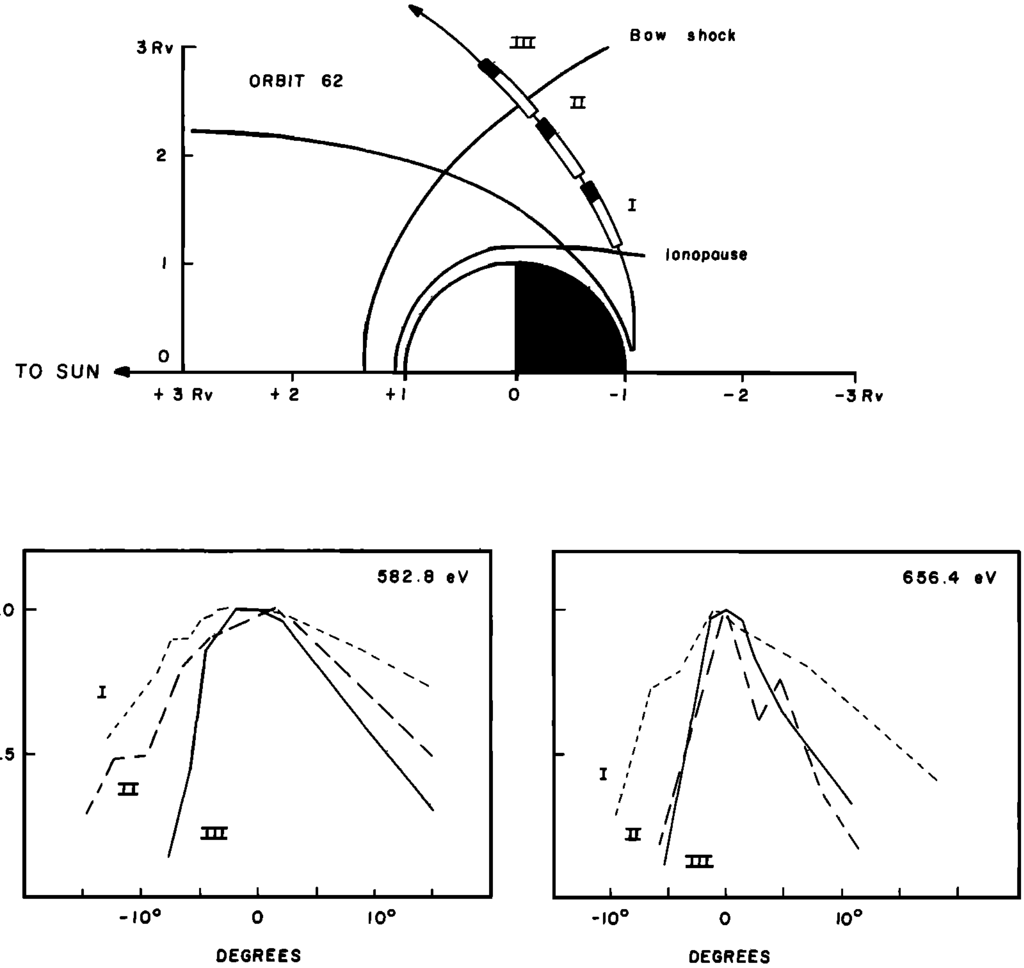

Fig. 1. Upper panel shows trajectory of the PVO during orbit 62 projected on a plane in which the vertical coordinate gives the distance from the spacecraft to the sun-venus axis. The black boxes indicate the position of the PVO at the time when the plasma instrument conducted angular scans within the region of rarified fluxes near the ionopause (I), in the outer ionosheath (II), and in the solar wind (III). The long white boxes indicate the position of the spacecraft when the plasma instrument carried out energy scans previous to the angular measurements. Lower panel shows azimuthal distribution of peak plasma fluxes measured in the 582.8- and 656.4-eV energy steps during the angular scans indicated in the upper panel.

each energy scan. In the Soviet experiments [*Vaisberg et al.*, 1976; *Gringauz et al.*, 1976] the distances involved are comparable or even smaller than the thickness of the region of rarified fluxes adjacent to the ionopause near the terminator. In the PVO data, however, each energy scan may be obtained across significantly larger distances, and thus it is difficult, in general, to estimate adequately the temperature of the plasma from energy measurements taken in that region.

Data which are not restricted by this limitation are provided by the angular scan measurements that the PVO plasma instrument performs after each energy scan. In its angular mode [*Intriligator et al.*, 1980] the plasma instrument analyzes the azimuthal and latitudinal distribution of the plasma fluxes detected in four adjacent energy steps at and near the peak of the energy spectrum. Since each angular scan takes approximately 12 s (while the PVO travels distances of the order of 100 km), the information obtained from these measurements is more adequate for examining locally the properties of the plasma in the ionosheath.

The study presented in this report is based on the examination of about 20 orbits which probed the near-wake region during the first year of operation of the PVO. The low height periapsis of those early orbits is, in fact, most suitable to examine the conditions in the vicinity of the terminator, downstream from the planet. The availability of adequate angular measurements in the inner ionosheath is limited, however, by the short operation time of the plasma analyzer in its angular mode. Thus, in most orbits the spacecraft moves across that region while the plasma instrument performs energy measurements and only occasionally while it conducts an angular scan. An example in which these latter observations were made is presented in Figure 1. The lower panels in Figure 1 show the normalized azimuthal distribution of plasma fluxes in the 582.8- and 656.4-eV energy steps in which peak intensities were measured in the inner regions of the ionosheath (I), in the outer ionosheath (II), and in the free stream solar wind (III) during the outbound leg of orbit 62. The position of the spacecraft at the time in which such measurements were made is indicated schematically by the black boxes along the trajectory shown in the upper panel of Figure 1. The long white boxes indicate, on the other hand, the position of the spacecraft at the time when energy scans were conducted (the vertical coordinate in this plot represents the distance from the spacecraft to the sun-Venus axis). The data of orbit 62 are particularly useful because clearly distinct flux levels were measured in the inner and outer regions of the

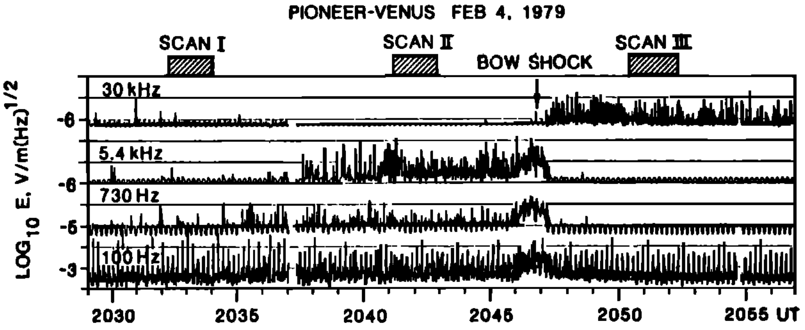

Fig. 2. Electric field signature recorded with the electric field detector of the PVO during its outbound pass through the Venus ionosheath on orbit 62 The time intervals during which the angular scan measurements of Figure 1 were conducted are indicated at the top of the figure.

ionosheath. Thus the peak intensity of the plasma fluxes detected in cycle I (in the 656.4-eV energy step) is $\sim 2.6 \times 10^8$ cm^{-2} s^{-1} sr^{-1} and is about one order of magnitude smaller than the $\sim 2.1 \times 10^9$ cm^2 s^{-1} sr^{-1} peak flux of cycle II, and the 4.4×10^9 cm^{-2} s^{-1} sr^{-1} peak flux of cycle III. An indication that weak fluxes are also present at locations closer to the ionopause is provided by the measurements conducted in the energy scan previous to the angular measurements of cycle I. The peak fluxes of the energy spectrum of these previous measurements were only $\sim 9 \times 10^7$ cm^{-2} s^{-1} sr^{-1} (also detected in the 656.4-eV energy step) and thus are a factor of 3 smaller than those measured in angular scan I. The different flux intensity measured in the inner and outer regions of the ionosheath implies density values which range from about $N = 3$ cm^{-3} to $N = 15$ cm^{-3} (calculated from the measurements conducted in the first and second energy scans, respectively). These values are consistent with the concept that the plasma density decreases in the inner ionosheath as reported previously from the Mariner 5 [*Bridge et al.*, 1967, Figure 2], Venera [*Verigin et al.*, 1978, Figure 7], and PVO [*Spenner et al.*, 1980, Figure 4] measurements.

The variation of the plasma density with distance from the ionopause is also compatible with the measurements of the electric noise level recorded with the orbiter electric field detector (OEFD) of the PVO [*Scarf et al.*, 1980]. This is illustrated in Figure 2 on a plot of the electric signatures measured in the 100-Hz, 730-Hz, 5.4-kHz, and 30-kHz channels of the OEFD. The time intervals in which the angular scans were conducted are indicated by the cross-hatched areas at the top of Figure 2. In this plot it can be appreciated that a notable increase of the electric signals in the 5.4-kHz and 730-Hz channels occurred between the first and the second angular scans. We note, in addition, that the distinct enhancements seen in the 30-kHz channel in the inner ionosheath (between 2029:20 UT and 2035:30 UT) indicate that the density in that region occurred in the 8 $cm^{-3} < N < 15$ cm^{-3} range (in which the plasma frequency falls within the reponse range of that channel). The detection of such signals, at and near the time when the angular scan I were conducted, thus fits adequately with the concept that the plasma density increased from low values (<8 cm^{-3}) in the inner ionosheath to high values (>15 cm^{-3}) beyond angular scan I.

There is experimental evidence which indicates that the decrease of the plasma density in the inner ionosheath downstream from the terminator may occur as a sudden transition across a strong rarefaction wave and that it is not necessarily accompanied by a commensurate increase of the magnetic field intensity [*Perez-de-Tejada et al.*, 1984]. Such conditions differ from those contemplated in the compression of interplanetary magnetic fluxes against a planetary obstacle [*Ioffe*, 1968; *Zwan and Wolf*, 1976] but seem to indicate that the plasma simply expands behind the planet.

In addition to the different flux intensities seen in the inner and outer ionosheath, the data of Figure 1 show that the angular spread of the plasma fluxes in the inner ionosheath (curves I) is larger than in the outer ionosheath (curves II). This variation is clear in both lower panels of Figure 1 despite the fact that the angular width of the distribution of plasma fluxes of different energy is not the same. The overall evolution of their angular spread, between the outer and the inner ionosheath, can be interpreted as indicating that hydromagnetic waves, plasma turbulence, and/or the thermal motion of the plasma produces a higher angular dispersion in the inner ionosheath. In the case shown in Figure 1 the angular distribution of the plasma in this region (curves I) appears to be broader than that detected in the outer ionosheath and in the free stream solar wind. This result is also evident in Figure 3, where the angular width of the distributions measured in all four energy steps are given. The angular width plotted in Figure 3 is that across which the normalized flux intensity is $>80\%$ of the peak value (this width can be readily estimated even in cases in which the data are restricted to small angles around the preferential direction of motion). The symbols used in Figure 3 are coded according to the energies sampled in each angular scan. Thus we see that the angular width of plasma fluxes with the same energy can be compared in three different energy steps common to all measurements. The slightly lower energy range probed in the inner ionosheath is due to a small shift of the peak of the local energy spectrum and reflects the lower velocities that the plasma has in that region. The solid symbols refer, in addition, to cases in which the peak flux intensity is at least 40% of the maximum value measured in each angular scan. The fact that all four readings in the inner ionosheath satisfy this condition is indicative of a more even distribution of the flux intensity with energy and is again consistent with the contention that the plasma fluxes in that region may have high temperatures.

Data which are particularly useful for examining the angular distribution of plasma fluxes in the immediate vicinity of the ionopause, downstream from the terminator, are provided by the measurements conducted in orbit 82. These are shown in Figure 4 with the same format used in Figure 1. In this case a cycle of observations ended soon after the spacecraft exited the ionosphere, and two more before the PVO left the ionosheath. The profiles shown in the two lower panels of Figure 4 are those of the strongest fluxes detected during the angular

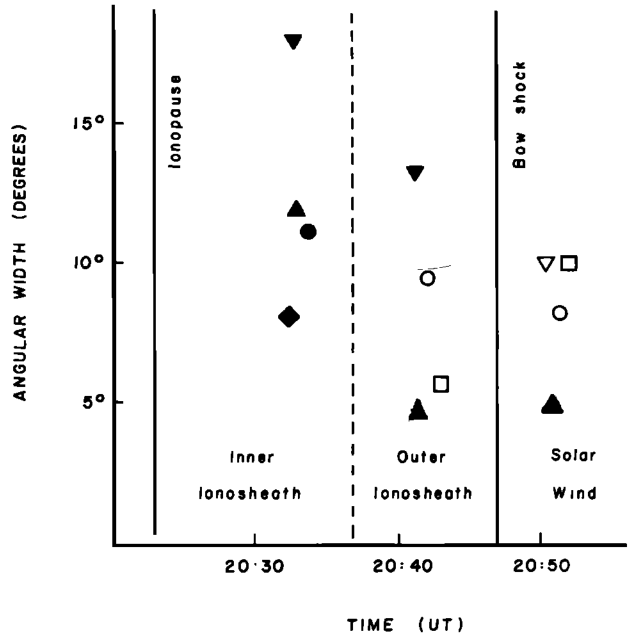

Fig. 3. Comparison of the width of the azimuthal distribution of plasma fluxes recorded in all four energy steps in which the three angular scan measurements shown in Figure 1 were conducted. The angular width is that across which the normalized flux remains above 80% of the peak value. The various symbols used correspond to the following energies: diamonds, 494.7 eV; inverted triangles, 582.8 eV; triangles, 656.4 eV; circles, 808.5 eV; squares, 953.3 eV. The solid symbols indicate that the flux intensity is at least 40% of the maximum value measured in each angular scan.

measurements of cycles I and II (in the 1.3- and 1.5-keV energy steps) and in the free stream solar wind, where the strongest fluxes were measured in the 1.1- and 1.3-keV energy steps (the angular measurements of cycle III are not suitable for comparison because of fluctuations in the flux intensity caused by the crossing of the spacecraft through the bow shock). As in orbit 62 (Figure 1), a gradual increase in the strength of the plasma fluxes with distance from the ionopause is also evident in this case. Thus we find that in the (dominant) 1.5-keV energy step the peak intensity changed from 1.38×10^8 cm^{-2} s^{-1} sr^{-1} in cycle I to 3.23×10^8 cm^{-2} s^{-1} sr^{-1} in cycle II and to $>6 \times 10^8$ cm^{-2} s^{-1} sr^{-1} during the energy scan of cycle III before the PVO approached the bow shock.

The importance of the data of orbit 82 derives from the fact that it reveals that angular widths comparable to, or even larger than, that of the free stream solar wind can be present even in the immediate vicinity of the ionopause. This is evident in both lower panels of Figure 4 despite the fact that the angular width of the 1.3-keV fluxes in cycle I is slightly smaller than that of cycle II. Thus, while evidence for a wider angular distribution in the inner ionosheath is available only from the (dominant) 1.5-keV fluxes, we find no indications in this, or in any of the other orbits examined, of significantly narrower profiles in that region. This latter behavior would be expected to occur if mass loading and/or charge exchange collisions dominated the interaction process and the plasma in the inner ionosheath consisted mostly of planetary particles at ionospheric temperatures. The observation of wide angular distributions in that region suggests, therefore, that in addition to such processes the plasma may be subject to dissipative phenomena which have the effect of increasing the local temperature.

DISCUSSION

Adequate estimates of the temperature of the plasma fluxes, based on the width of their azimuthal distribution, require of the detailed examination of the effects that hydromagnetic waves and plasma turbulence may produce on the observed angular broadening. Because of the short (< 12 s) scale time of the azimuthal scans it is possible to consider that long-period waves and large-scale turbulent eddies may not be effective in significantly aliasing the broadening produced by the thermal motion of the plasma. On the other hand, it is clear that the effects of short-period waves as well as that of any intrinsic spatial irregularities of the solar wind flow cannot be disregarded.

It appears pertinent to point out, however, that large angular widths in the inner ionosheath are observed even when the fluctuation level of the magnetic field intensity is not very significant nor different from that detected during the angular observations conducted in the outer ionosheath. On the basis of this latter circumstance we can make a comparative calculation of the equivalent plasma temperature implied by the width of the angular distributions in the inner and outer ionosheath. Such a calculation will enable us to reach some significant conclusions regarding the composition and acceleration of the local plasma.

From the data shown in Figure 1 we can estimate that the half width of the azimuthal distribution of the plasma fluxes measured in the inner ionosheath in orbit 62 is between $\phi = 10°$ and $\phi = 15°$. These values imply that the ratio of their thermal velocity V to the kinetic velocity U, which can be estimated from $V/U = \tan \phi$, is in the 0.15–0.25 range. Since, in addition, such plasma fluxes are detected in the 500–600 eV energy range, we can further calculate their thermal velocity by assuming that they are either protons or planetary O^+ ions. In the first case the kinetic velocity is $U_p = 350$ km/s and the thermal speed is, therefore, between $V_p \sim 50$ km/s and $V_p \sim 100$ km/s. For such values the temperature of the plasma should be between $T = 10^5$ °K and $T = 3 \times 10^5$ °K which is of the order of standard ionosheath temperatures (see, for example, *Mihalov et al.* [1982, Table 3]). At the same time we can also infer that the larger width of the azimuthal distribution of the plasma fluxes in the inner ionosheath, shown in both lower panels of Figure 1, implies a temperature increase of up to a factor of 3 with respect to the temperature of plasma fluxes of similar energy in the outer ionosheath. Such an increase is comparable to those reported from the energy spectra analysis of the Venera plasma measurements [see *Verigin et al.*, 1978; *Romanov et al.*, 1979].

The identification of the plasma fluxes in the inner ionosheath as material of exospheric/ionospheric origin, on the other hand, presents some difficulties in regard to their observed behavior. For example, if such fluxes represent a population of O^+ ions scavenged directly from the ionosphere, their streaming velocity would be $U_{O^+} = U_p(m_p/m_{O^+})^{1/2} = 90$ km/s, and their thermal speed would be between $V_{O^+} \sim 15$ km/s and $V_{O^+} \sim 25$ km/s. Since these lower velocities are commensurate with the larger mass of the O^+ ions in the calculation of the thermal energy ($2\,kT = m_{O^+} V_{O^+}{}^2$) the same temperature values derived above must also be expected in this case. It is clear, however, that ionosheath temperatures of the order of 10^5 °K are much higher than the temperatures measured in the Venus upper ionosphere, and thus it is necessary, in this interpretation, that the O^+ ions be strongly heated as they leave the ionosphere.

An alternative option is to assume that the plasma fluxes

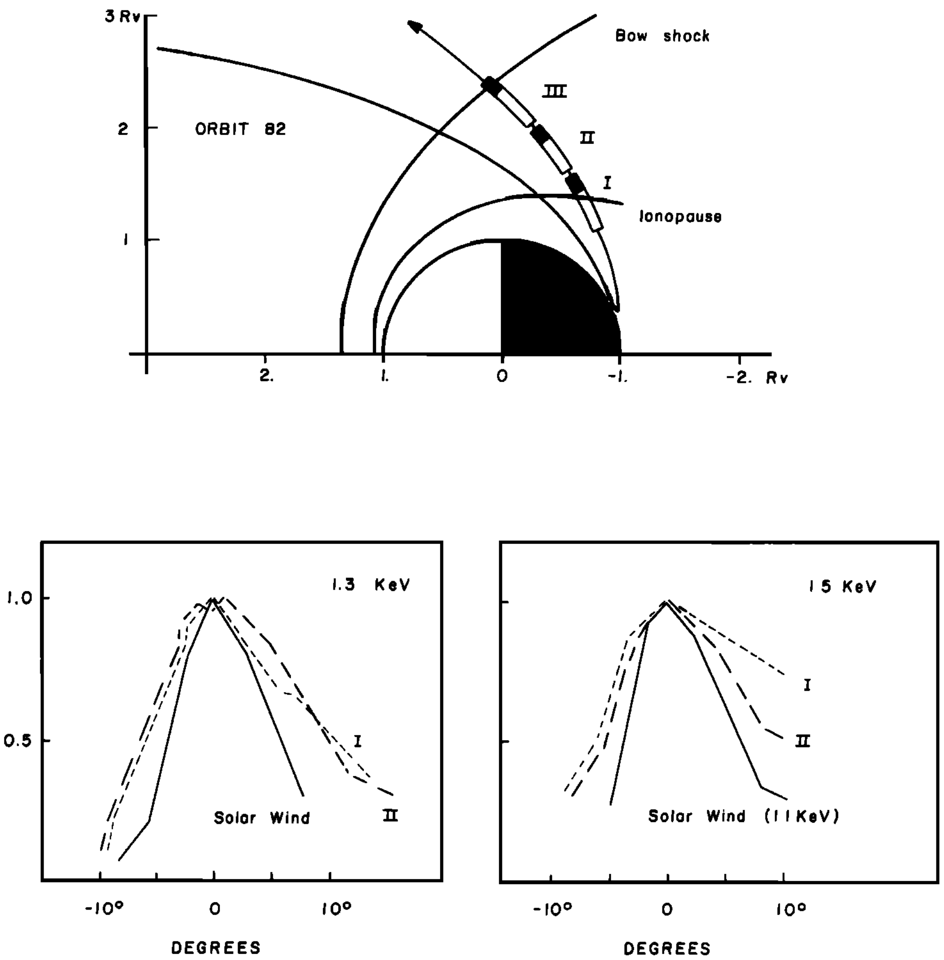

Fig. 4. Same as Figure 1 for measurements conducted in orbit 82. The angular distributions shown in both lower panels are those of the strongest fluxes measured in cycles I and II (in the 1.3- and 1.5-keV energy steps) and in the free stream solar wind (in the 1.3- and 1.1-keV energy steps).

present in the inner ionosheath result from photoionization processes taking place above the ionopause. The mass loading of the oncoming flow through the convective $V \times B$ electric field requires, in this case, that the thermal and the kinetic speeds of the planetary ions be of the same order of magnitude. Since this condition is not consistent with the numbers given above, it is necessary to assume further that the fluxes undergo an additional expansion which has the effect of reducing their thermal velocity. *Mihalov and Barnes* [1982] noted a similar discrepancy in the thermal and kinetic speeds of O^+ fluxes detected in the far wake. These authors estimate that a 10^3-fold expansion of the volume occupied by the O^+ fluxes would be sufficient to decrease the thermal velocity to the observed values. Even though the large dimensions of the wake seem to be adequate to account for such an expansion, it is not evident that the same argument can also be applied to the much smaller region near the terminator which was probed during orbit 62.

A further complication encountered in this latter interpretation is the fact that the direction of motion of a planetary particle population accelerated through a convective $V \times B$ electric field is expected to be dependent on the local orientation of the magnetic field vector. The plasma fluxes detected in the inner ionosheath in orbit 62 are seen to mantain, however, a similar direction of motion (nearly coincident with the antisolar direction) despite continuous changes of the magnetic field orientation. This question is examined more fully in Figure 5 where the azimuthal direction of the particle fluxes of the first angular scan (cycle I) of Figure 1 is plotted together with the local magnetic field orientation obtained from the OMAG data of the PVO (C. T. Russell, personal communication, 1983). The apparent lack of correlation between both directions that is evident in Figure 5 is entirely analogous to that reported by *Perez-de-Tejada et al.* [1982] from PVO measurements conducted in the Venus distant ionosheath ($\sim 12\ R_V$). In that study it was concluded that the persistent motion of the planetary ions along the shocked solar wind direction is not consistent with the behavior expected if the convective $V \times B$ electric field was solely responsible for their acceleration. Instead, it was necessary to assume that wave-particle interactions control their assimilation into the shocked solar wind flow. The conditions which may lead to such a response have been examined by *Brinca* [1984], and it is clear that similar considerations would be required in orbit 62 if the plasma fluxes in the inner ionosheath were assumed to be of planetary origin.

The description of the behavior of the plasma fluxes of the inner ionosheath presented here appears also to be applicable to plasma fluxes measured in other orbits. As noted before, the observations conducted in the outbound leg of orbit 82 provide evidence which indicates that rarified fluxes with angular width comparable to, or even larger than, that of the free

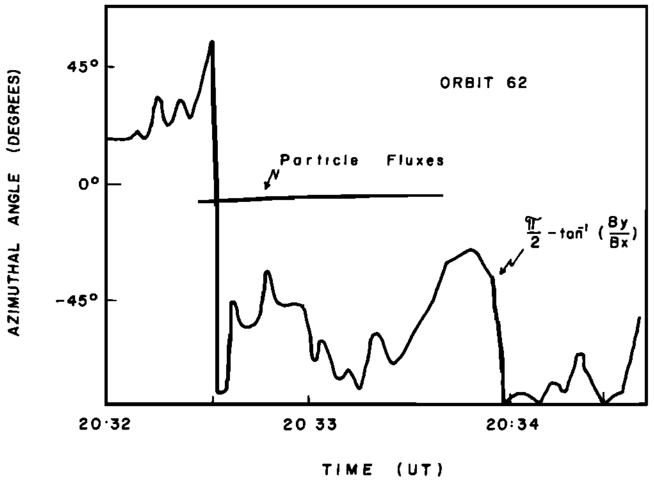

Fig. 5. Azimuthal angle of the direction of motion of the plasma fluxes detected in the first angular scan of Figure 1, together with the magnetic field orientation on the ecliptic plane measured during the same time interval (angles are measured with respect to the antisolar direction and become positive for field vectors with a component opposite to the orbital motion of the planet).

stream solar wind can be detected in the immediate vicinity of the ionopause. The identification of such fluxes as a population of photoionized material which has been incorporated into the solar wind through $V \times B$ effects is even more conflicting than in orbit 62. In fact, in order to account for their different thermal and kinetic velocities it would be necessary to assume that even in the immediate vicinity of the ionopause the O^+ ions undergo a very substantial expansion. If such particles are of planetary origin, it is more likely that their assimilation into the solar wind proceeds through thermalizing processes which bring their temperature to ionosheath values. Alternatively, a locally heated (and rarified) solar wind proton population could also account for the large widths of the angular distributions and the depressed flux intensities measured in that region. In either case it is necessary to assume the existence of a heating source at and near the ionopause, as would be expected to occur from the onset of viscous processes at that boundary. These views are not meant to imply that mass loading and charge exchange collisions are not effective in modifying the composition of the shocked solar wind streaming near the Venus ionopause (as described, for example, by *Slavin et al.* [1983]). Instead, the conclusion of our study is that despite the operation of these processes the plasma in that region appears to be dominated by dissipative phenomena which produce a net increase of the local temperature.

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

H. Pérez-de-Tejada, Instituto de Geofísica, Universidad Nacional Autónoma de México, Ensenada, Baja California, México.

F. L. Scarf, Applied Technology Divison, Space and Technology Group, TRW, Redondo Beach, CA 90278.

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