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MOMENTUM FLUX OF THE SOLAR WIND NEAR PLANETARY MAGNETOSPHERES: A COMPARATIVE STUDY

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RESUMEN

Se presenta un estudio del perfil de velocidad del viento solar exterior a las magnetosferas de la Tierra, Marte y Venus. Existe una diferencia característica en las condiciones presentes en planetas con magnetización interna alta y débil. En el caso de un planeta fuertemente magnetizado, como lo es la Tierra, la velocidad del viento solar cerca de la magnetopausa se mantiene aproximadamente constante en la dirección normal a esa frontera. En planetas de baja magnetización (Venus, Marte) el perfil de velocidad muestra, cerca de la magnetoionopausa, un gradiente transversal el cual implica una reducción efectiva del flujo de momento del viento solar en esa región. El diferente comportamiento del viento solar en la vecindad de cada planeta es examinado en conexión con el proceso de interacción que opera en su frontera magnetosférica.

ABSTRACT

A study of the velocity profiles of the shocked solar wind exterior to the magnetospheres of the Earth, Mars and Venus is presented. A characteristic difference exists between the conditions present in planets with and without a strong intrinsic magnetic field. In a strongly magnetized planet (as it is the case in the earth), the velocity of the solar wind near the magnetopause remains nearly constant along directions normal to that boundary. In weakly magnetized planets (Venus, Mars), on the other hand, the velocity profile near the magnetopause/ionopause exhibits a transverse gradient which implies decreased values of the momentum flux of the solar wind in those regions. The implications of the different behavior of the shocked solar wind are discussed in connection with the nature of the interaction process that takes place in each case.

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INTRODUCTION

The different intrinsic magnetization of the planets of the solar system is responsible for the different character of the obstacle that each planet generates within the solar wind. In planets with a strong internal magnetization the solar wind is forced to flow around an obstacle whose dimensions are much larger than those of their atmospheres. In such planets the solar wind interacts with the magnetic field and does not reach directly the planetary atmosphere. A different situation is observed in weakly magnetized planets where the solar wind may compress the magnetic field down to a region whose dimensions are comparable to those of its atmosphere. In these cases the local ionospheric plasma may play a very important role in decelerating and deflecting the solar wind around the planet.

Table 1 summarizes the magnetization of planets where *in-situ* measurements have been conducted, together with the approximate dimensions of their effective obstacles in the solar wind flow. In Jupiter, Saturn and the Earth, the internal magnetic field produces an obstacle (magnetosphere) much larger than the planetary radius, and thus their atmospheres can only play a minor role in supporting the kinetic pressure of the solar wind. Additional effects can be produced, however, by contaminant plasma transported from the inner regions of the magnetosphere to its outer boundary, where it can generate local currents which have the effect of modulating the local magnetic pressure.

Table 1

Equivalent magnetic dipolar moment and normalized magnetospheric radius of planets where *in situ* measurements have been conducted.

	Dipolar moment	Rm/Rp
JUPITER	1.5×10^{30} Gauss cm^3	100
SATURN	2.2×10^{29} Gauss cm^3	25
EARTH	8.2×10^{25} Gauss cm^3	10
MERCURY	2.4×10^{22} Gauss cm^3	1.2
MARS	$\sim 10^{22}$ Gauss cm^3	~ 1.1
VENUS	$< 10^{21}$ Gauss cm^3	1.05

Rm = Magnetospheric radius

Rp = Planetary radius

In Mercury, Mars and Venus, on the other hand, the low intrinsic magnetization can produce, at most, obstacles whose dimensions are comparable to the planetary radius. It is in such planets where the local ionosphere is expected to participate significantly in the process of deceleration and deflection of the solar wind. This participation is less important in Mercury where the photoionization of the weak local exosphere produces only very low concentrations of ionospheric particles. In Mars, a well populated ionosphere appears to provide a very significant contribution to the local pressure required to divert the solar wind around the planet. Finally, Venus represents the extreme case of a very weakly magnetized planet in which the ionosphere controls almost completely the process of interaction with the solar wind. In this case the local ionosphere is compressed by the solar wind and confined below a sharp boundary which is usually located a few hundred kilometers above the surface of the planet.

The distribution of plasma and magnetic fluxes at the boundary of the obstacles of magnetized and non-magnetized planets is sensibly different. At the Earth, Jupiter, and Saturn the solar wind particles interact directly with the planetary magnetic field and produce a current layer whose end effect is to compress and terminate the planetary field. At Venus, on the other hand, the outer boundary of the ionosphere is the site of an electrodynamic interaction in which the incident solar wind flow builds up a layer of enhanced magnetic fluxes. The development of such a layer, or barrier, of magnetic fluxes can be viewed as resulting from the accumulation of interplanetary magnetic field lines around the Venus ionosphere. Thus, the conditions at the boundary of Venus ionosphere (or ionopause), are in a sense opposite to those at the boundary of a planetary magnetosphere (or magnetopause), with a strong magnetic field present outside, and a weakly magnetized plasma inside the obstacle.

In the present report we will examine the implications that this different configuration has on the behavior of the solar wind outside magnetized and non-magnetized planets. We will show that the temperature and velocity profiles of the plasma streaming around their effective obstacles reflect the character of the interaction process that takes place in each case.

OBSERVATIONS

Even though the amount of experimental information which is currently available on the behavior of the solar wind near the planetary bodies of the solar system is still very limited, it is possible to prepare a fairly complete account of the plasma environments observed in magnetized and non-magnetized planets. In particular, we will examine measurements conducted in the Earth, Venus and Mars and, at the end, discuss their interpretation in an inter-comparative manner.

THE EARTH

Over the years it has been recognized that one of the most dominant features of the Earth's magnetosphere is the presence of an internal plasma flow, or mantle, in the vicinity of the high latitude regions of the magnetopause. The origin of the motion of the plasma in that region has been traced to phenomena associated with magnetic reconnection processes (Dungey, 1961), with a viscous transfer of momentum across the magnetopause (Axford and Hines, 1961); Faye, Petersen and Heckman, 1968; Cassen, 1970), and with the turbulent diffusion of solar wind particles entering through the cusps of the magnetosphere (Haerendel *et al.*, 1978; Johnson, 1978). In these and other studies it has been apparent that the flow within the magnetosphere is generally less dense and slower than that measured in the solar wind.

Figure 1 (left panel) shows the velocity, density, and temperature of the plasma across the Earth's magnetopause together with the intensity and the azimuthal ϕ_B and latitudinal Λ_B orientation of the magnetic field measured with instruments onboard the HEOS-2 spacecraft on June 4, 1972 (Rosenbauer *et al.*, 1975). The region of the magnetosphere traversed by the spacecraft when these measurements were conducted is illustrated schematically in the right hand side panel. In the outbound leg, the magnetopause is identified by the drastic change in the latitudinal orientation of the magnetic field, which is evident at 1100 UT. Prior to this time, while the vehicle was within the magnetosphere, the velocity values detected are significantly smaller than those measured in the magnetosheath. In this latter region, the velocity profiles seem to be rather uniform with no apparent overshootings near the magnetopause. The fact that the initial decrease of the velocity coincides with the position of the magnetopause reflects little or no changes in the momentum flux of the shocked solar wind exterior to that boundary.

The signatures reproduced in Figure 1 are representative of the conditions at high and medium latitudes where the mantle particles cover almost entirely the Earth's magnetopause. At low latitudes, on the other

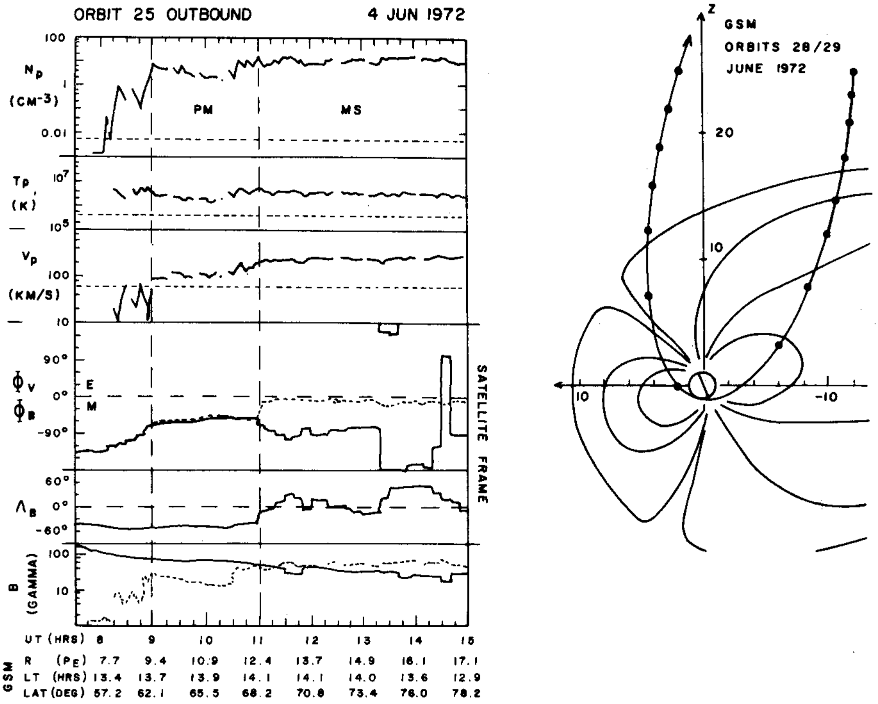

Fig. 1. Density, temperature, velocity and magnetic field profiles measured within and outside the Earth's magnetosphere during the outbound leg of the HEOS-2 satellite on June 4, 1972. The trajectory of the spacecraft is indicated in the right hand side panel, on a plane perpendicular to the magnetic equator (from Rosenbauer *et al.*, 1975).

hand, no mantle particles seem to populate the outer regions of the magnetosphere. In this case the plasma within the magnetosphere (entry layer) show a drastic decrease in the velocity and density in the immediate vicinity of the magnetopause (see, for example, Crooker, 1977) but, as at high latitudes, the profiles remain fairly uniform outside this boundary.

VENUS

From the early experimental reconnaissance of the Venus plasma environment (Bridge *et al.*, 1967; Spreiter *et al.*, 1970) it was evident that the flow of solar wind that streams around the effective obstacle of that planet exhibits a behavior radically different from that observed at the Earth. Most notable was the detection of a region, exterior to the Venusian ionosphere, where the flow velocity exhibits a severe decrease with respect to the values seen further away from the planet (Bridge *et al.,* 1967; Spreiter *et al.,* 1970; Pérez de Tejada and Dryer, 1976; Verigin *et al.,* 1978) Figure 2 illustrates the velocity and temperature profiles reported by Romanov *et al.* (1979) from measurements conducted along the trajectory of the Venera 10 orbiter in the region exterior to the near wake of the planet, on April 19, 1976. The trajectory of the spacecraft is indicated in the upper panel of Figure 2 on a plane in which the vertical coordinate gives the distance to the Sun-Venus axis.

The velocity decrease initiated at 0200 UT is reminiscent of that seen in the plasma mantle of the high latitude regions of the Earth's magnetosphere. Between both cases there is, however, a basic difference which reveals the different character of the effective obstacle that each planet produces in the solar wind. At Venus, the velocity decrease begins well outside of the downstream extension of the boundary of the obstacle (indicated by the dashed line in the upper panel of Figure 2). At the Earth, on the other hand, the velocity decrease occurs exclusively within the magnetosphere, and a uniform profile is observed beyond the magnetopause.

In addition to the different location of the velocity profile, the data of Figure 2 shows that, at Venus, the temperature of the plasma exterior to the obstacle is significantly enhanced. This is not the case outside the Earth's magnetosphere where, as shown in Figure 1, the temperature remains fairly uniform throughout the region exterior to that boundary downstream from the planet. As suggested before, this observation indicates a different type of response of the shocked solar wind as it interacts with a planetary ionosphere.

The discontinuity seen at ~ 0250 MT in the temperature profile of Figure 2 represents the downstream extension of the effective obstacle of the planet, and may reflect a drastic change in the composition of the local plasma population (from hot solar wind plasma outside, to cool ionospheric particles inside). Such a transition may also coincide with the outer boundary of the Venus magnetotail, which is formed by the interplanetary magnetic field lines draped around the dayside iono-

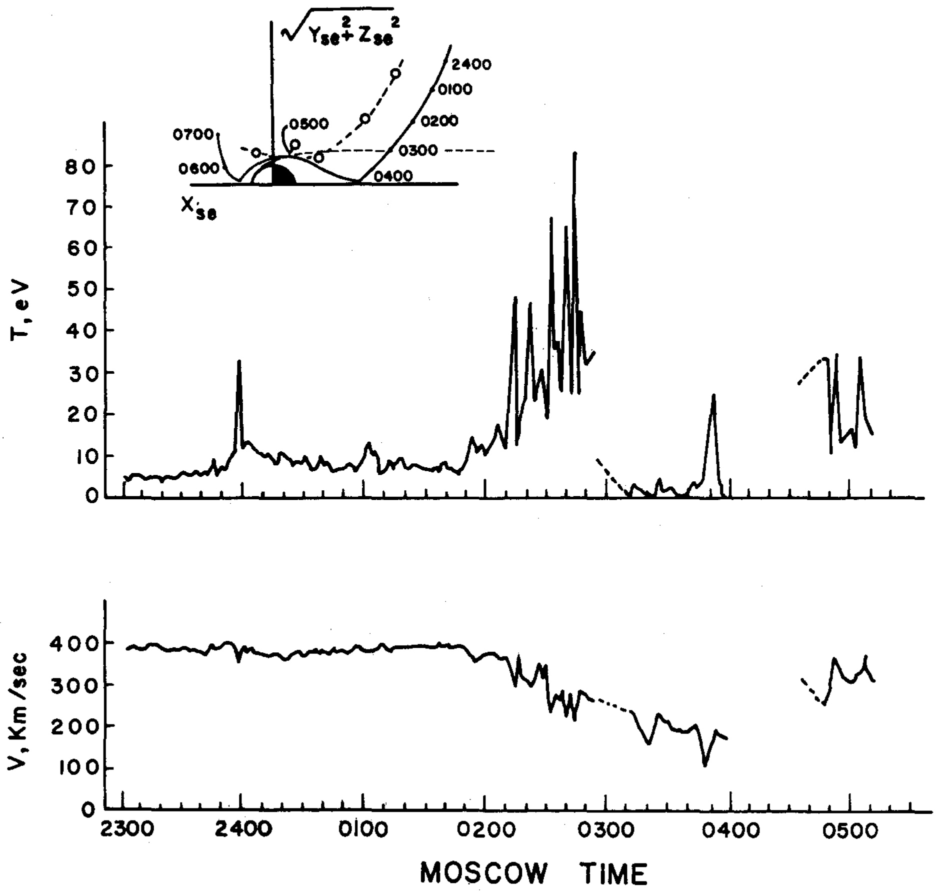

Fig. 2. Velocity and temperature profiles measured in the Venus near wake with instruments onboard the Venera 10 orbiter on April 19, 1976. The trajectory of the spacecraft is indicated in the upper panel on a plane in which the vertical axis gives the distance to the Sun-Venus axis (from Romanov *et al.*, 1975).

pause (see Russell and Vaisberg, 1983, for a review of the processes involved), we should note, however, that the magnetic data does not appear to identify consistently, in this case, the location of that boundary. In fact, Dolginov (1978) indicates that the entry into the magnetotail, in that orbit, occurred until 0324 MT when a significant jump in the B_x component took place. Despite this difference it is clear that there exists (at least in the temperature field) a sharp discontinuity which marks the existence of different plasma conditions within and outside the plasma wake.

MARS

Experimental information on the distribution of plasma and magnetic fluxes near Mars is still scarce and circumstancial. Almost all of the data available have been obtained from soviet spacecraft (Mars 2, 3 and 5) which orbited the planet but did not penetrate into the optical umbra. As a result, there are no magnetic field measurements in the inner regions of the wake, and it has not been possible to determine the actual strength of the Martian magnetic field. The data available apply only to the region exterior to the optical umbra and has led to controversial interpretations of the relative role that the planetary magnetic field and the local ionosphere have in producing the deflection of the solar wind around the planet.

The observation of a noticeable increase of the magnetic intensity in the near plasma environment of Mars (Dolginov *et al.*, 1973) has been the basis for suggesting that its effective obstacle is produced primarily by an appreciable internal magnetization. The position of such an obstacle has been estimated to be ~800 km near the subsolar point (Gringauz, 1976) and thus at a much higher altitude than that of the planetary ionosphere. The existence of a magnetopause at Mars, rather than of an ionopause as boundary of the effective obstacle, has also been suggested by the apparent absence of an abrupt decrease of the ionospheric density with height as observed in Venus. In fact, most of the results of the radio-occultation experiments of the soviet spacecraft indicate an electron profile which decreases gradually with height. Evidence for a sharp discontinuity is present only in the profiles derived from the Mars 6 (Vasiliev *et al.*, 1975), and Viking 2 (Hanson *et al.*, 1977) measurements. Finally, it has been pointed out by Dolginov *et al.* (1976) that the magnetic measurements conducted with the Mars 5 spacecraft in the outer regions of the Martian tail reveal, in most orbits, a B_x component (directed along the Sun-Mars axis) which is independent of the IMF direction. This result is also compatible with the view that the magnetic field in that region is of planetary origin and indicates that, at least under certain circumstances, such planetary field can be detected in the region exterior to the umbra (see also Dubinin *et al.*, 1981).

This interpretation has been contested by Russell (1979) who noted that in the region where the enhanced magnetic fluxes are measured,

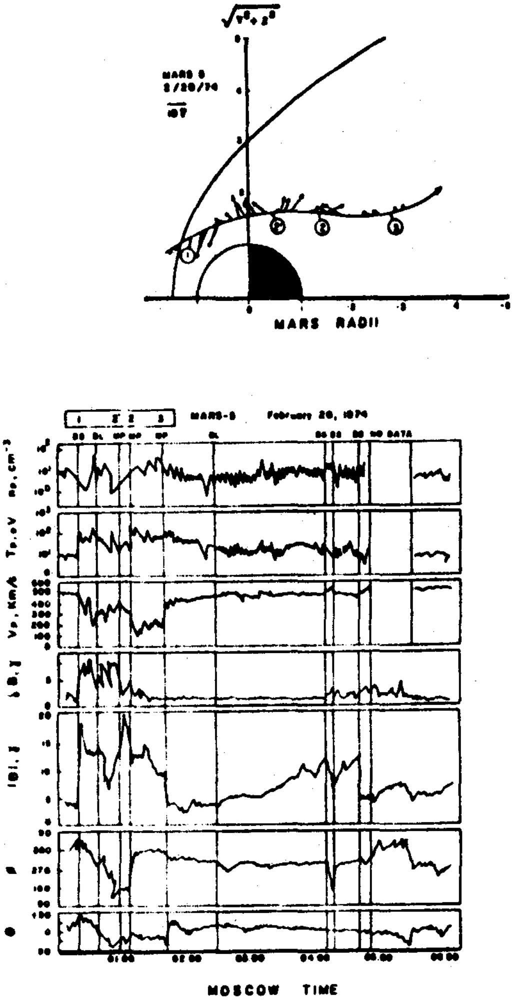

Fig. 3. Density, temperature, velocity and magnetic field profiles measured in the near Mars wake with instruments onboard the Mars 5 space probe on Feb. 20, 1974. The trajectory of the spacecraft is indicated in the upper panel on a plane in which the vertical axis gives the distance to the Sun-Mars axis (from Vaisberg *et al.*, 1976 and Russell, 1979).

the component of the magnetic field vector perpendicular to the Sun-Mars axis reverses direction. In this region the observed geometry appears, in fact, to be similar to that detected outside the Venus ionosphere. Further arguments in favor of a Venus-type of interaction, have also been presented by Vaisberg *et al.* (1976) from measurements conducted with the Mars 5 spacecraft. Figure 3 shows (lower panel) density, velocity, temperature and magnetic field profiles measured along the spacecraft trajectory on 20/II/1974. From the values of the velocity of the plasma it is apparent that the local flow exhibits a behavior similar to that seen near Venus. We note, in particular, the steady increase of the velocity between 01 40 MT (at position labeled MP) and 02 30 MT (at position labeled BL). As shown at the bottom of the lower panel of Figure 3, these measurements were made outside of the region of enhanced magnetic field intensities (which fall between positions 2 and 3), and thus again differ from those made near the Earth where decreased flow velocities are detected exclusively within the magnetosphere. From Figure 3 we also note that the temperature of the slower moving plasma seen near and within the Martian obstacle is higher than that of the faster moving plasma detected further outside. The inferred temperature profile is similar to that measured in the Venus plasma environment even though it does not seem to extend so far away from the obstacle. This latter characteristic may simply reflect the different width of the boundary layers of both planets (according to Vaisberg *et al.*, 1976, the boundary layer in Mars is only about 500 km thick near the terminator, while Spenner *et al.*, 1980, estimate that the boundary layer in Venus is about 1500 km in that region).

DISCUSSION

The different location of the velocity boundary layer formed in the vicinity of the effective obstacles of the Earth, Venus and Mars reveals the different nature of the process of interaction that takes place in each planet. The strong reduction of the flow velocity seen outside of the Venus ionosphere indicates a severe loss of momentum flux of the incident solar wind. A significant loss of momentum is also present outside the Martian effective obstacle but, as pointed out before, it does not seem to occur outside the Earth's magnetosphere, where a uniform velocity profile is observed. In this latter case the solar wind appears to move without an appreciable deceleration even in the close vicinity of the obstacle.

Various processes have been suggested to explain the loss of momentum of the solar wind as it streams around the Venus ionosphere. On the one hand, charge exchange collisions (Gombosi *et al.*, 1980) and the mass loading of the incident plasma with planetary ions (Cloutier *et al.*, 1974) represent mechanisms which result in the continuous removal of momentum flux of the incident plasma. The first process occurs when an oncoming solar wind proton captures the electron of a planetary hydrogen atom and becomes a fast moving hydrogen atom. In such a collision a planetary hydrogen ion is also formed but it carries only a very small momentum flux. The second process deals with ion-electron pairs resulting from the photoionization of the neutral exosphere. These particles become accelerated by the convective V x B electric field of the solar wind and thus gain momentum at the expense of the latter.

Even though it is clear that both mechanisms do contribute to the removal of some of the momentum of the solar wind there are reasons to believe that they are not sufficient to account for the observations Pérez-de-Tejada (1982) has shown, in this regard, that the low (~1%) concentration of planetary O^+ ions measured in the downstream wake of Venus (Mihalov *et al.*, 1980; Intriligator, 1982) imply a momentum flux about one order of magnitude smaller than that required to produce the observed velocity profile. This result can be readily demonstrated from the relation:

$$m_p n_p (U_p^2 - U_p'^2) = m_{O^+} n_{O^+} U_{O^+}^2 \qquad (1)$$

where the left hand side gives the amount of momentum flux lost by the solar wind, and the right hand side the momentum flux carried by the planetary O^+ ions (n_p, m_p and n_{O^+}, m_{O^+} indicate, respectively, the number density and the mass of the solar wind proton, and of the planetary O^+ populations. U_p and U_p' are, in turn, the velocity of the solar wind protons outside and within the Venus wake; and U_{O^+} the velocity of the O^+ ions). The most favorable conditions are attained when the O^+ ions have achieved solar wind velocity. In this case $U_{O^+} = U_p''$, and equation (1) reduces to:

$$\frac{U_p}{U_p'} = \left(1 + 16 \frac{n_{O^+}}{n_p}\right)^{1/2} \qquad (2)$$

where we have taken $m_{O^+} = 16 m_p$ (suitable for an O^+population characteristic of the upper layers of the Venus ionosphere). With the measured $n_{O^+}/n_p = 0.01$ density ratio, we obtain $U_p' = 0.93\, U_p$ which implies a very small reduction of the solar wind velocity within the wake. From the observed velocity profile we can, in fact, estimate that a more realistic value is $U_p' = 0.50\, U_p$. Such small velocities within the wake can be derived from equation (1) only with a relative concentration of O^+ ions to solar wind protons of ~15%. As indicated before, however, this concentration is far larger than that measured in the Venus plasma environment.

An alternative interpretation of the velocity reduction of the solar wind plasma in the Venus near wake has been proposed by Pérez-de-Tejada (1982) in terms of viscous effects at the ionopause itself. In this view the solar wind transfers viscously some of its momentum to the upper layers of the Venus ionosphere, and gives place to a general displacement of the ionospheric plasma toward the nightside hemisphere. Measurements conducted with instruments onboard the Pioneer Venus orbiter (Knudsen *et al.*, 1980) have revealed that an ionospheric flow does exist in the Venus upper ionosphere, and that it is particularly strong near the terminator region. An important property of this flow is that its momentum flux is comparable to the momentum flux missing within the velocity boundary layer exterior to the ionosphere (Pérez-de-Tejada, 1982). This result is consistent with the concept that the latter quantity is primarily delivered to the upper ionospheric plasma, rather than to the planetary photoions carried off by the solar wind through mass loading processes.

The onset of viscous processes at the Venus ionopause is also supported by the observation of enhanced plasma temperatures in that region. As shown in Figure 2, the decelerated plasma is significantly hotter than that measured outside the velocity boundary layer. This variation cannot be explained in terms of charge-exchange collisions and mass loading processes (which are expected to produce a significant cooling of the incident flow). Instead, it appears necessary to assume that dissipative phenomena, such as those produced through viscous action, dominate the interaction between the solar wind and the ionospheric plasma.

Similar arguments seem to be also applicable to the data of Figure 3 for the Mars plasma environment. The observation of decelerated plasma fluxes outside the Martian magnetosphere (exterior to the region of enhanced magnetic field) implies a certain deficit of momentum flux within the shocked solar wind. As noted earlier, however, the velocity boundary layer in that planet does not appear to be as extended as that present outside the Venus ionosphere. Thus, even though the data of Figure 3 suggests an interaction similar to that seen at Venus, there is evidence that the conditions present at the boundary of the Martian obstacle are somewhat different. As suggested by various authors (Breus, 1980; Slavin and Holzer, 1982, Intriligator and Smith, 1979) it is possible that the manner in which the solar wind is deflected around

Mars depends on the dynamic pressure of the incident plasma and that a Venus-type interaction occurs more favorably at high values of this quantity. In this case the Martian magnetic field cannot deflect by itself the oncoming solar wind and thus allows the upper layers of the ionosphere to be eroded by the incident plasma. Under such conditions it is likely that a viscous-like interaction takes place, and that an ionospheric flow be generated through the transfer of momentum across the ionopause.

These concepts are also important to point out that the slowly moving plasma seen within the Earth's magnetosphere (Figure 1) should have a different origin than that of the velocity boundary layers in Venus and Mars; and that most likely do not result from the onset of viscous processes at the magnetopause. In the Earth there is, in fact, no clear evidence that the loss of momentum flux of the solar wind is comparable to that seen outside the effective obstacles of Venus and Mars. Current views based on the observation of electric fields smaller than that expected within the context of a viscous interaction, also indicate that it is unlikely that viscous processes be primarily responsible for the transfer of momentum and energy of the solar wind to the Earth's magnetosphere (Mozer, 1984). It is thus possible that the interaction between the solar wind and the geomagnetic field is not strong enough to produce an important retardation of the incident plasma. The observation of a distinct velocity signature, as well as of increased plasma temperatures in the immediate vicinity of the boundary of the obstacles of the non-magnetic planets (Venus and Mars) seems to indicate, therefore, that the plasma-plasma interaction processes may indeed modify more severely the solar wind than those associated with a plasma-magnetic field interaction.

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