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Plasma Distribution and Magnetic Field Orientation in the Venus Near Wake: Solar Wind Control of the Nightside Ionopause

H. PÉREZ-DE-TEJADA,[1] M. DRYER,[2] D. S. INTRILIGATOR,[3] C. T. RUSSELL,[4] AND L. H. BRACE[5]

A comparative study of the position of the Venus nightside ionopause and of the orientation of the magnetic field in the near Venus wake is presented. It is shown that when the ionopause is detected deep within the umbra the magnetic field vector above that boundary shows consistently a convergent orientation toward the sun-Venus axis. When the ionopause is encountered outside the umbra, the magnetic field may assume directions not necessarily indicative of closure. The overall configuration of the nightside ionopause seems, in addition, to be strongly controlled by the kinetic energy density of the solar wind. At high values of this quantity the ionopause tends to occur more often at low heights.

INTRODUCTION

One of the most remarkable results reported from the Pioneer Venus Orbiter (PVO) experience has been the observation that the Venus nightside ionosphere also terminates sharply at an outer boundary and that the well-defined sudden drop of ionospheric densities to solar wind values seen in the dayside is also present in the nightside. The compression of the dayside ionosphere by the ram pressure of the oncoming solar wind was expected ever since it was learned that Venus does not have an intrinsic magnetic field sufficiently strong to prevent the solar wind from impinging upon the upper layers of the ionosphere. The conditions in the nightside were unknown, however, as no clear information was available on the extension of the ionosphere downstream from the terminator. The low periapsis orbits of the Pioneer Venus spacecraft have now provided the opportunity to examine, in situ, the distribution of ionospheric plasma around the planet. This has been reported by *Brace et al.* [1979, 1980] who find that in addition to a clear orbit to orbit variability of the position of the nightside ionopause, there is a notable tendency for that boundary to extend to large distances downstream. This apparent bulged appearance of the Venus nightside ionosphere has no parallel in the ionospheres of the magnetic planets where a near-spherical symmetry is ensured by the protective action of the planetary magnetic field. In Venus, however, there appears to be a global deformation of the upper layers of the ionosphere due to a continuous exchange of mass, momentum, and energy with the shocked solar wind plasma [*Michel,* 1971; *Cloutier et al.,* 1974; *Perez-de-Tejada and Dryer,* 1976; *Gombosi et al.,* 1981; *Slavin et al.,* 1983]. The manner in which such an exchange operates is currently the subject of extensive examination in the experimental data. This should ultimately allow the identification of the relative role of the plasma and magnetic fluxes to produce the observed distortion of the ionosphere.

We note, for example, that the preferential downstream elongation of the nightside ionopause at low latitudes and the lower ionopause heights seen at high latitudes, as is shown in Figure 3 of *Brace et al.* [1979], suggests a phenomenon which originates from the polar terminator. This observation prompted those authors to propose that the slipping of the interplanetary magnetic field lines over the poles, as they are convected by the shocked solar wind streaming at lower latitudes, could explain the observed ionospheric geometry at high latitudes. They noted, however, that this concept possibly could not be applicable to the low height ionopause positions detected in the deep regions of the umbra.

An alternative interpretation was proposed by *Perez-de-Tejada* [1980, see Figure 1] in terms of a preferential deflection of the ionosheath flow into the wake behind the magnetic polar regions (defined with respect to the plane formed by the sun-Venus axis and the IMF direction). In this latter interpretation, dissipative effects associated with the onset of a viscouslike interaction between the shocked solar wind and the ionospheric material near the magnetic polar terminator should result in an enhanced expansion of the local plasma into the wake. Such an expansion should, in turn, modify the local magnetic geometry and produce a preferential orientation of the field lines from the magnetic polar terminator toward the magnetic equatorial plane.

In the present report we discuss the conditions associated with the plasma and magnetic fluxes seen across the nightside ionopause and present evidence indicating that the magnetic field vector in the near wake shows consistently a converging orientation when that boundary is crossed within the umbra. This result is in agreement with the notion that the magnetic field lines are preferentially oriented from the polar terminator toward the equatorial plane and, again, suggests a polar origin for the phenomenon producing the confinement of the nightside ionosphere. The position of the ionopause appears, at the same time, to be strongly controlled by the kinetic energy density of the solar wind, and the data examined reveal a clear correlation between this latter quantity and the ionopause height.

ORIENTATION OF THE MAGNETIC FIELD IN THE NEAR WAKE

Studies of the magnetic field configuration in the Venus wake have revealed the complexity and variability of the conditions present in that region. The distribution of magnetic field vectors measured with the Venera magnetometers was interpreted by *Dolginov et al.* [1980] as indicating a

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[1] Instituto de Geofisica, Universidad Nacional Autónoma de México, Baja California.
[2] Environmental Research Laboratory, National Oceanic and Atmospheric Administration.
[3] Carmel Research Center.
[4] Institute of Geophysics, University of California, Los Angeles.
[5] NASA Goddard Space Flight Center.

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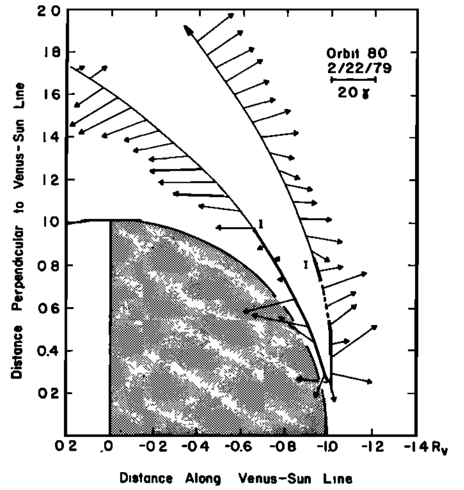

Fig. 1. Projection of the magnetic field vectors into the plane formed by Venus, the sun, and the PVO, as measured in orbit 80. The heavy trace along the trajectory indicates the transit of the spacecraft across the ionosphere.

geometry consistent with that expected from unipolar induction processes. These measurements reflect, however, the conditions expected at low magnetic latitudes which were more frequently probed by the low latitude trajectory of the Venera spacecraft.

The near-polar orientation of the PVO trajectory has provided, on the other hand, information which, as indicated above, may be related to phenomena taking place at and downstream from the magnetic polar terminator. Figure 1 shows a useful representation of the magnetic field vectors measured in orbit 80, projected on the plane formed by Venus, the sun, and the PVO. The presentation of the PVO magnetometer data in this plane was reported by *Russell et al.* [1980] for various orbits that probed the midnight region during the first year of operation of that spacecraft. The observed geometry illustrates the overall tendency of the projection of the magnetic field vector on the sun-Venus-PVO plane to change from a general divergent orientation in the outer ionosheath to directions nearly parallel to the sun-Venus line in the inner ionosheath. This is evident in the inbound and outbound legs with a consistent reversal in the direction of the magnetic field vector as the spacecraft moves across the midnight meridian. The gradual rotation of the magnetic field vector toward the sun-Venus line with decreasing distance from that axis along the PVO trajectory usually results in a component directed toward the interior of the wake. This latter behavior occurs generally in the outer regions of the umbra only and in many cases is abruptly replaced, close to the sun-Venus line, by a divergent orientation (as in the outbound leg of orbit 80) or by a near-zero magnetic field intensity in that plane.

The significance of the observed magnetic geometry in regard to the conditions present at the nightside ionopause can be investigated by identifying the position of that boundary, as inferred from the Orbiter Electron Temperature Probe (OETP) measurements. This is indicated by the symbol I at the end points of the heavy trace on the trajectory of the spacecraft in Figure 1. We note that the magnetic field is convergent above the outbound ionopause which lies well within the umbra. Conversely, on the inbound leg, where the ionopause occurs near the boundary of the optical umbra, the magnetic field is parallel to that boundary only in the region exterior to the ionopause.

Similar conditions are present in the magnetic field data of other orbits even though the properties of the magnetic field below the nightside ionopause may be completely different. Thus, there appears to exist a consistent identification of the observed magnetic field geometry exterior to the nightside ionopause, namely, that the projection of the magnetic field vector on the sun-Venus-PVO plane shows a convergent orientation immediately above that boundary. A divergent geometry occurs only far away from this boundary or when the ionopause is detected outside of the umbra. Composites based on selected passes of the PVO during orbits 62–80, in which the PVO probed the midnight region of the near wake

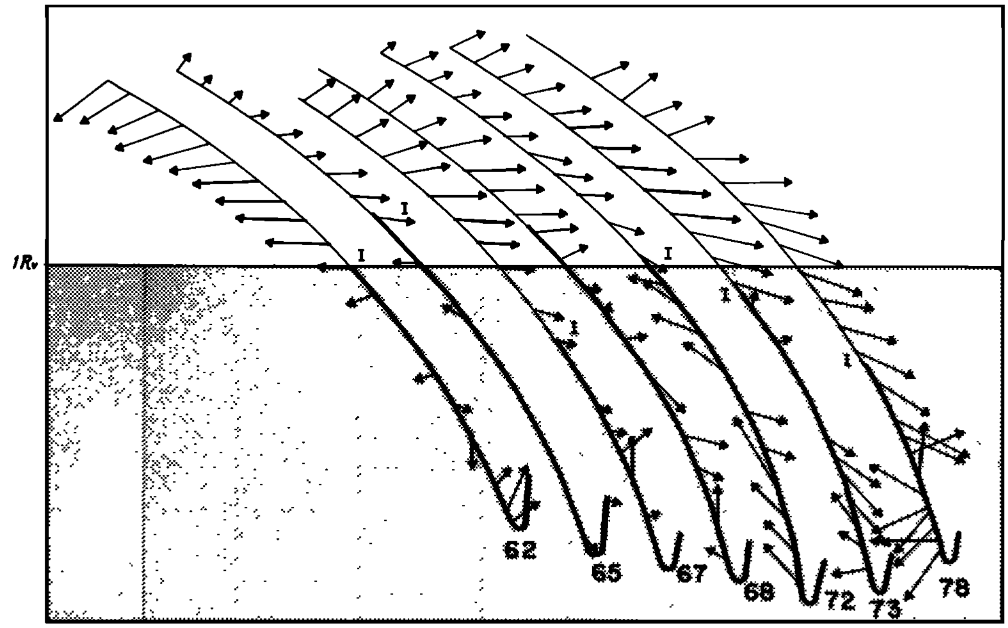

Fig. 2. Composite formed by the magnetic measurements during the inbound leg of various PVO orbits in the same plane as Figure 1.

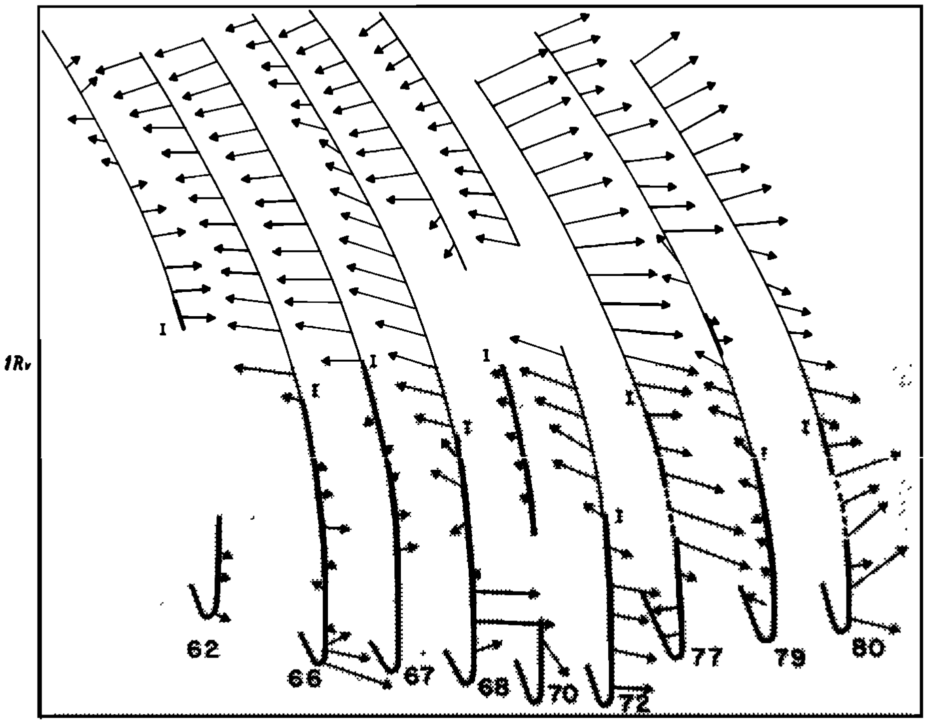

Fig. 3. Composite formed by the magnetic measurements during the outbound leg of various PVO orbits in the same plane as Figure 1.

during its first year of operation, are shown in Figures 2 and 3 for the inbound and outbound crossings, respectively. A list of all the cases examined is also presented in Table 1, which separately contains passes with a convergent, an undeflected, and a divergent magnetic orientation just above the nightside ionopause. The detection of this boundary outside or within the umbra is indicated by "A" and "W," respectively. The data presented in Table 1 clearly show that in all cases examined the projection of the magnetic field vector on the sun-Venus-PVO plane keeps a convergent orientation whenever the ionopause is detected within the umbra. When the ionopause is crossed outside the umbra, the magnetic field may assume various directions, including a divergent geometry as is the case in the outbound leg of orbit 62. It is also of interest to note that there does not seem to exist one same consistent change in the magnitude and/or direction of the magnetic field across the ionopause, but that the magnetic field below may assume a wide variety of values and directions. Finally, we point out that the correlation between the orientation of the magnetic field and the position of the ionopause, as suggested here, can be used as a criterion to identify the latter when there is evidence of multiple crossings in the electron density signature. Such is the case in the outbound leg of orbit 79, where a plasma cloud [*Brace et al.*, 1982*a*] was detected far above the actual ionopause, and also in the outbound leg of orbits 77 and 80, where the (dashed) sections of the trajectory, with a significantly larger magnetic field intensity below the ionopause, coincide with the location of well-defined ionospheric holes [*Brace et al.*, 1982*b*].

TABLE 1. Magnetic Field Orientation Above the Nightside Ionopause During Selected Passes of the PVO

	Magnetic Orientation (Inbound)			Magnetic Orientation (Outbound)				
Orbit	Convergent	Parallel to Sun-Venus Axis	Divergent	Convergent	Parallel to Sun-Venus Axis	Divergent	$D(R_v)$	ρV^2, 10^{-8} erg/cm^3
62	A				A		1.15	3.5
65	A					A	1.28	3.1
66		A		W			0.90	5.3
67	W				A		1.00	4.2
68		A		W			0.80	5.2
70	A					A	1.00	3.4
72	A			W			0.60	7.5
73	W			A*				
77			A	W			0.90	6.5
78	W			A*				
79		A		W			0.70	7.2
80		A		W			0.80	8.0
				W				

A and W indicate ionopause locations within and outside the umbra and $D(R_v)$ its distance to the sun-Venus axis.
*Ionopause not known.

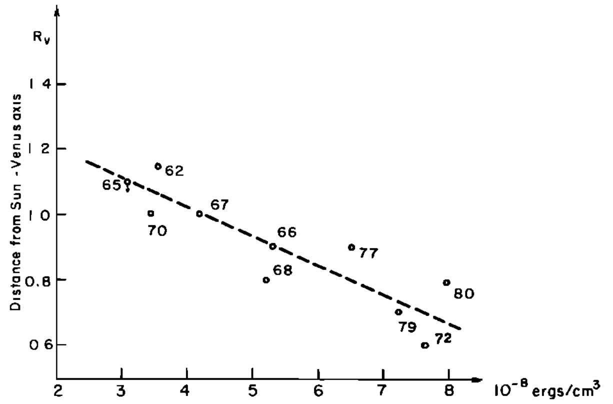

Fig. 4. Ionopause position with respect to the sun-Venus axis as a function of ρv^2 in the outbound leg of the orbits given in Table 1. The dashed line indicates the least square fit to the data.

SOLAR WIND CONTROL OF THE NIGHTSIDE IONOPAUSE

The different extent of the section of the PVO trajectory located within the ionosphere (heavy traces in Figures 2 and 3) illustrates graphically the variability of the position of the nightside ionopause. For example, that boundary was detected at fairly close distances from the sun-Venus axis in the outbound leg of orbit 72 but nearly outside the umbra in orbit 70, despite the fact that similar spatial regions of the wake were probed in both orbits. The variability of the position of the ionopause in the set of orbits included in Figures 2 and 3 appears to follow; however, a consistent trend when plotted against the ram pressure ρv^2 of the solar wind (ρ denotes the mass density and v the flow speed). This is shown in Figure 4 for the outbound crossings which occurred deeper within the umbra in the set of orbits examined. The distance from the ionopause to the sun-Venus axis is given, in that figure, as a function of ρv^2 calculated when the spacecraft was in the freestream solar wind in each orbit. A notable ordering of ionopause crossings is readily apparent with the innermost positions seen at high ρv^2 values. On the other hand, ionopause crossings detected in the outer regions of the umbra, or even exterior to it occur consistently at low ρv^2 values. A best fit linear dependence is included in Figure 4 to exhibit better the suggested behavior of the nightside ionopause position with ρv^2.

Since the height of the PVO above the planet increases with the distance from the sun-Venus axis (except within the ionosphere in the region where the spacecraft crosses the equator), the overall decrease of the distance from such an axis to the ionopause with ρv^2 should also be reflected in the height of that boundary above the planet. Such a dependence should, therefore, also become apparent when directly plotting the ionopause height versus ρv^2. Thus, we can conduct a more general analysis by examining the ionopause altitude as a function of the dynamic pressure of the freestream solar wind (even if we include orbits which did not probe specifically the near-midnight region). The position of 40 nightside outbound ionopause crossings for which ρv^2 is available is shown in Figure 5. These indicate again a marked control of ρv^2 on the ionopause height, which occurs more favorably at low altitudes when the ram pressure of the solar wind is high. The more general data base used here shows, in addition, that at low values of ρv^2 the scatter of ionopause heights is much larger than that obtained in Figure 4. This spread of values is consistent with the large variability of the nightside ionopause position reported by *Brace et al.* [1979, 1980] and may reflect its distribution with solar zenith angle SZA. Aside from the fact that the detection of the ionopause at large SZA values is restricted to low altitudes by the position of the PVO orbit in space [*Brace et al.*, 1980], the data of Figure 5 suggest that the dependence of ionopause heights with SZA reported by *Brace et al.* [1979, see Figure 2] may occur more favorably when ρv^2 is low. This result indicates, in turn, that the response of the nightside ionosphere to different solar wind conditions is not necessarily the same and that the location and magnitude of the nightside ionospheric bulge can be strongly dependent on the ρv^2 value present at the time of the observation. In fact, the smaller variation of the nightside ionopause height with SZA at high ρv^2 values should result in a less notable ionospheric bulge shape.

THERMAL AND MAGNETIC PRESSURE ACROSS THE NIGHTSIDE IONOPAUSE

Even though the analysis of the conditions present across the nightside ionopause may require a greater data base than that used here, it is of interest to examine, in the orbits available, the role of the magnetic and ionospheric thermal pressures to determine the position of that boundary. Studies of the magnetometer, plasma probe, and electron temperature data in the dayside have revealed the way in which the ram pressure of the solar wind is transferred to the magnetic field to compress the topside ionospheric plasma. The position and overall intensity of the piled up magnetic field above the dayside ionopause are, in most cases, clearly correlated with the topside ionospheric pressure [*Vaisberg et al.*, 1980; *Brace et al.*, 1980; *Elphic et al.*, 1980].

Examination of the electron density data in the nightside crossings indicates that, in general, the conditions present there are somewhat different, and that there appears to be a lack of correlation between the ionopause height and the topside thermal pressure below that boundary. This is illustrated in Figure 6, where various density profiles near the ionopause have been plotted. These show that even though the topside ionospheric density is very nearly the same in all the cases examined, the location of this boundary can occur at very different altitudes. Since, in addition, the plasma temperature in the upper ionosphere (near the terminator region) remains fairly constant from orbit to orbit [*Miller et*

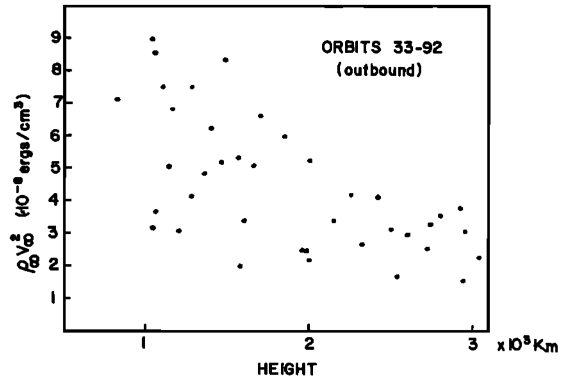

Fig. 5. Ionopause height measured in 40 outbound crossings of the PVO throughout the nightside hemisphere as a function of ρv^2.

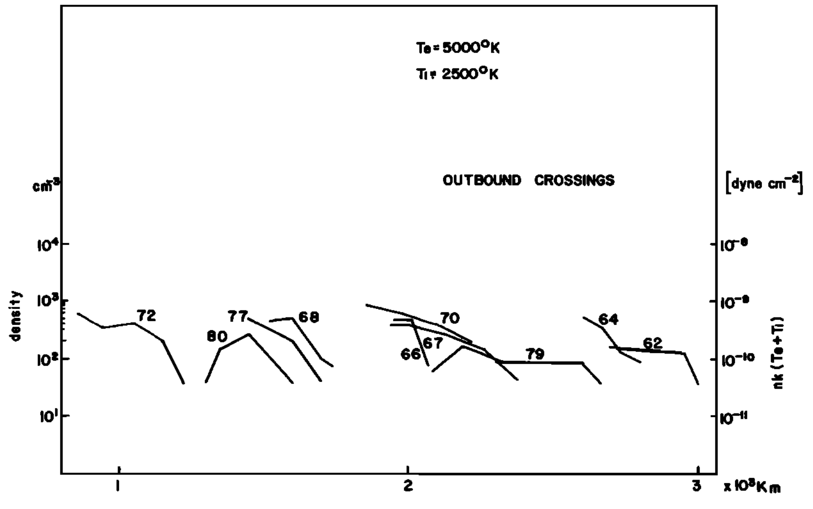

Fig. 6. Ionopause height versus electron density (and thermal pressure) of the topside nighttime ionosphere.

al., 1980], the above result implies that the position of the ionopause in that region can be uncorrelated with the topside ionospheric pressure. Thus, similar values of the thermal pressure may be present in cases where the ionopause is detected at both low and high altitudes. This behavior suggests that the topside ionospheric plasma does not respond necessarily like the dayside ionospheric material to external solar wind conditions. In fact, unlike the nightside ionopause position, the "back up" ionospheric thermal pressure apparently did not change significantly when ρv^2 increased by at least a factor of 2 between orbits 70 and 72.

It also should be pointed out that the correlation between the kinetic energy density of the solar wind and the position of the nightside ionopause, shown in Figures 4 and 5, does not necessarily indicate that the local magnetic field is ineffective in controlling the conditions present at this boundary. In fact it is found that, as in the dayside hemisphere [*Elphic et al.*, 1980; *Vaisberg et al.*, 1980], the magnetic field above the nightside ionopause may provide the necessary pressure to balance the topside thermal ionospheric pressure. An example of the magnetic field and electron density profiles seen across the ionopause is shown in Figure 7. These profiles correspond to the outbound leg of orbit 66, in which a very well defined ionopause crossing was detected. With the observed $B = 18\gamma$ magnetic field intensity outside the ionopause, $n = 400$ cm^{-3} for the electron density below that boundary, and an assumed (electron plus ion) temperature of $T = 7\,500$°K (consistent with the values used in Figure 6), we find that the external magnetic pressure could be more than adequate to balance the topside thermal pressure. Thus, the magnetic fluxes above the nightside ionopause are clearly an important factor in providing the necessary pressure to contain the ionospheric plasma below.

Discussion

The distribution of plasma and magnetic fields described in Figures 1–7 illustrate the conditions which appear to characterize the high latitude nightside ionopause. Because of the preferential orientation of the IMF near the ecliptic plane it is at high latitudes where the magnetic field geometry should reflect more frequently the slipping of the magnetic field lines over the planet. The persistent convergence of the magnetic field into the umbra, as shown in Figures 1–3, is consistent with that configuration even though it is not possible to identify, in the PVO data, the precise position of the magnetic polar terminator. Experimental data in which this verification can be conducted is provided, however, by the magnetic field measurements of the Venera 9 and 10 orbiters reported by *Dolginov et al.* [1980]. Figures 8 and 9 reproduce, in a plane similar to that of Figure 1, the magnetic field measurements recorded by the Venera 9 on October 30, 1975, and on November 17, 1975, respectively. In both cases the orientation of the IMF is known from the simultaneous measurements carried out with the Venera 10 which remained in the freestream solar wind when the first spacecraft probed the wake. With this latter information it is possible to identify, for each pass, the position of the magnetic polar regions with respect to the plane formed by the sun-Venus axis and the IMF vector. In the October 30, 1975, orbit the position of the Venera 9 within the umbra occurs at locations far away from such a plane and thus corresponds to a high latitude pass. The magnetic field orientation in that orbit shows a well defined convergent geometry and is consistent with that expected downstream from the magnetic polar regions. Such a geometry is compatible with those of the PVO crossings, which generally correspond to high magnetic latitudes. Conversely, in the orbit of November 17, 1975, the position of the Venera 9 in the outbound leg (at $t \approx 1000$

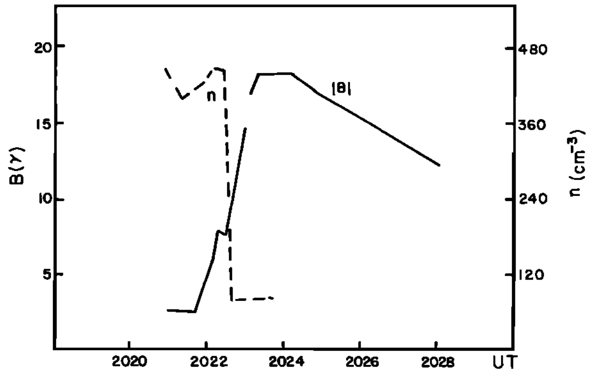

Fig. 7. Magnetic field intensity and electron density profiles measured in the outbound leg of orbit 66.

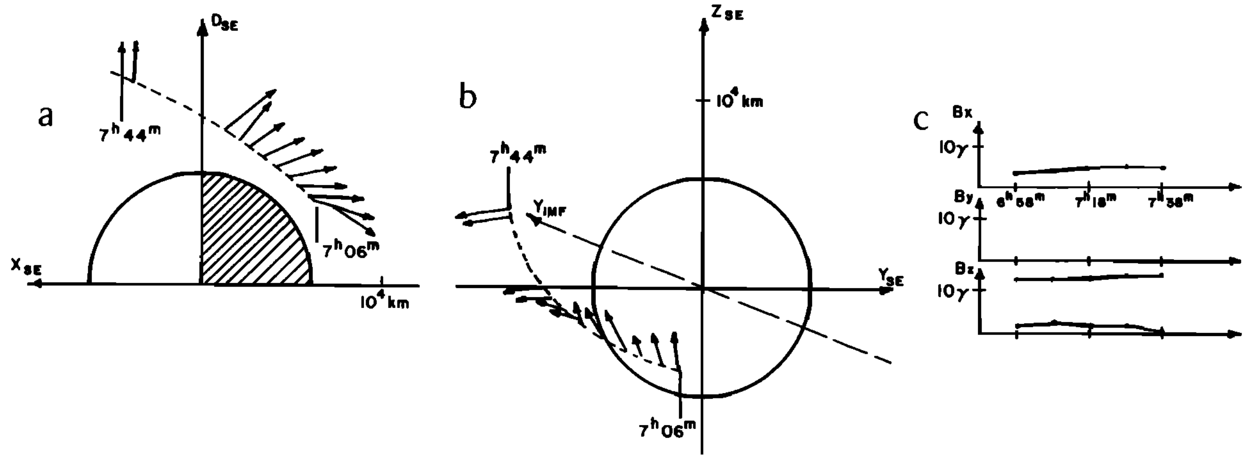

Fig. 8. (*a*) Magnetic field vectors projected in the same plane as Figure 1, as reported by *Dolginov et al.* [1980] from the Venera 9 measurements on October 30, 1975. (*b*) Projection of the same magnetic field vectors on the plane formed by the solar ecliptic coordinates *Y-Z* (perpendicular to the sun-Venus axis). (*c*) Simultaneous measurements of the IMF by the Venera 10 in the free stream solar wind (its direction on the *Y-Z* plane is indicated in Figure 8*b* by the dashed line).

hours) remained in the vicinity of the magnetic equatorial plane and thus reflects conditions for which there should be little deflection into the wake. We note that in this case there is no evidence of a convergent orientation within the umbra. These two examples clearly illustrate the different magnetic geometry present at low and high magnetic latitudes and, at the same time, expose the axial asymmetry which appears to characterize the near wake. The preferential downstream elongation of the nightside ionopause at low latitudes, and the observation of low ionopause altitudes at high latitudes [*Brace et al.*, 1979, 1980], also indicate the absence of axial symmetry in that region. As noted earlier, it is the onset of different conditions at the region where the field lines slip over the planet that should disrupt the development of an axially symmetric wake.

We should also note that the peculiarities of the magnetic field geometry downstream from the terminator should affect the distribution of plasma above the nightside ionopause. We can mention, in this regard, the existence of a clearly defined boundary separating plasmas with different spectral characteristics along the downstream extension of the low latitude dayside ionopause, as reported by *Romanov et al.* [1979, see Figure 5]. The observed change in the thermal and kinetic energies of the particles across that boundary is most likely associated with the draped IMF lines which apparently preserve that geometry many Venus radii downstream from the planet [*Russell et al.*, 1981]. At high magnetic latitudes, on the other hand, a different plasma distribution appears to be present with particle fluxes moving with a component directed toward the interior of the umbra [*Intriligator et al.*, 1979]. The different behavior of the high latitude plasma could be due to the smaller accumulation of interplanetary magnetic fluxes above the magnetic polar regions, which will allow a more direct interaction between the shocked solar wind and the ionospheric material. The correlation between the nightside ionopause height and ρv^2, as shown in Figures 4 and 5, is consistent with this suggestion and, at the same time, exposes the important role of the kinetic energy of the solar wind to determine the plasma configuration in the near wake. This circumstance points out, in turn, that the interaction between the shocked solar wind and the ionospheric material near the terminator should be determined, to some extent, by the plasma-plasma contact that takes place in that region. Thus, we can advance the idea that when the dynamic pressure of the solar wind is high, the conditions present at high magnetic latitudes may extend to lower latitudes, thus producing a stronger distortion of the nightside ionosphere. The noticeably reduced scattering of points shown in Figure 5 for high ρv^2 values may express this different configuration. The understanding of how this feature is precisely controlled by the solar wind and the IMF will be ultimately acquired from the continued and combined analysis of the magnetometer and the plasma probe data of the Pioneer Venus and Venera orbiters.

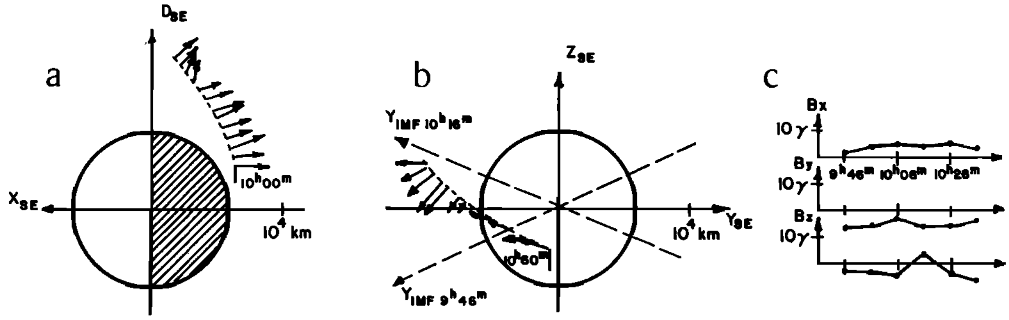

Fig. 9. Same as Figure 8 for the Venera observations of November 17, 1975.

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L. H. Brace, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

M. Dryer, National Oceanic and Atmospheric Administration, Environmental Research Laboratory, Boulder, CO 80302.

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

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

C. T. Russell, Institute of Geophysics, University of California, Los Angeles, CA 90024.

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