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ON THE SOURCES OF THE NIGHT SIDE IONOSPHERE OF VENUS

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RESUMEN

Se presenta una descripción general de las características de la ionosfera nocturna en Venus y del medio magnético y plasmático en su estela. Se sugiere que el carácter variable de la ionosfera nocturna es debido, en parte, a condiciones de asimetría y variaciones temporales de la penetración viscosa del viento solar a la región de la umbra óptica atrás del terminador planetario. Además de los efectos de inducción, la presencia de flujos magnéticos asociados con el plasma solar debe contribuir a explicar la dependencia que ejerce el campo magnético interplanetario sobre la geometría magnética dentro de la umbra óptica.

ABSTRACT

A general description of the characteristics of the night side ionosphere of Venus and of the plasma and magnetic environment in the near wake is presented. It is suggested that the variable character of the night side ionosphere should result, in part, from asymmetric conditions and time-dependent variations of the viscous penetration of the ionosheath flow into, the umbra, downstream from the planetary terminator. In addition to induction effects, the presence of magnetic fluxes associated with the intruding solar wind plasma should also contribute to explain the observed dependence of the magnetic geometry of the near wake on the interplanetary magnetic field.

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I. OBSERVATIONS OF THE NIGHT SIDE IONOSPHERE AND PLASMA WAKE

One of the outstanding results obtained from the Mariner 5 encounter with Venus was the detection of a significant ionospheric concentration above the night side hemisphere. The results of the radio occultation experiment showed, in fact, the existence of a well defined ionospheric layer situated at about 140 km above the planet with a maximum electron concentration of $\sim 10^4$ cm^{-3} (Mariner Stanford group, 1967). Further observation carried out during the Mariner 10 encounter revealed the existence of two night side layers at ~ 120 km and 140 km above the planet with maximun electron concentrations of 7×10^3 cm^{-3} and 9×10^3 cm^{-3} respectively (Fjeldbo *et al.*, 1975). The more recent radio occultation experiments of the Venera 9 and 10 orbiters have confirmed the presence of both layers and the (usually) smaller peak intensity of the lower one which in some occasions is not present. A summary of the Venera observations is reproduced in Figure 1 (from Keldysh, 1977).

The most peculiar characteristic of the geometry of both ionospheric layers is their variability as the maximun electron density is seen to fluctuate up to a factor of five. Also significant is their persistent sharpness which indicates that the ions in the region are heavy and cold. At the same time, the measured topside plasma scale height is only of the order of ~ 5 km so that the local electron density is seen to decrease to solar wind values a few tens of kilometers above the peak of the upper layer.

The basic difficulty encountered when interpreting the high electron densities observed in the night side ionosphere lies in the fact that the characteristic recombination time of the ions in the region is of the order of $T_R \sim 5 \times 10^2$ sec (for the dissociative recombination of CO_2^+) and hence much smaller than the 4 day period characteristic of the rotation of the upper atmosphere of Venus (Boyer, 1973). Consequently, the supply of ionized material to the night side hemisphere should be mainly provided by local sources rather than by the lateral transport of day side ionization across the terminator. In this regard, McElroy and Strobel (1969) have pointed out that horizontal motions in the vicinity of

The day side ionospheric peak (~ 140 km) cannot transport charged particles very far past the terminator. Further penetration into the night side could only proceed at higher altitudes provided diffusion processes could then bring the ions downward to lower altitudes.

In the early interpretation of the night side ionospheric profiles, it was recognized that the solar wind represents a potentially adequate source of energy and particle fluxes to sustain the observed electron densities. McElroy and Strobel (1969) estimated, in fact, that a (reverse) planetward flux of approximately 10% of the undisturbed solar wind flux could be sufficient to account for the measured night side peak concentrations. At the same time, the effects of a small leakage of solar wind particles across the optical umbra to the night side planetary atmosphere were examined by Hartle and Herman (see Bauer, 1973) who concluded that about 1-2% of the solar wind energy would be required to produce the observed electron density profiles. The reality of the assumed transport of solar wind particles to the vicinity of the night side atmosphere depends fundametally on the structure and dynamics of the planetary wake which were, at that time, unknown. Recent theoretical and experimental studies of the plasma and magnetic environment in this region have now revealed that such a transport can in fact proceed and that it is intimately connected with the overall configuration of the wake.

The presence of an appreciable component of solar wind particles within the planetary umbra can be theoretically predicted as a consequence of the viscous-like interaction of the solar wind with the ionospheric plasma at the planetary terminator (Pérez de Tejada and Dryer, 1976). Considerations of conservation of mass flux within the ionosheath flow suggest that about 10% of the solar wind flux must be forced into the wake from all around the planetary terminator (Pérez de Tejada, 1979). Plasma probe measurements carried out with the Venera 9 and 10 orbiters indicate that a plasma population with such characteristics is in fact present across a large section of the planetary umbra (Vaisberg *et al.*, 1976; Romanov *et al.*, 1978), and that particle fluxes are seen to converge to the inner regions of the wake at locations about 3 planetary radii downstream from the terminator (Gringauz *et al.*, 1976a; Verigin *et al.*, 1978).

The observation of significant electron fluxes moving planetward in the optical umbra was used by Gringauz *et al.* (1976b, 1977) to examine the formation of the night side ionospheric layers through direct electron bombardment of the local atmosphere. By modeling the ion production rate in a planar atmosphere consisting of CO_2^+ molecules, these authors concluded that the measured electron fluxes in the umbra ($\sim 10^8$ cm^{-2} sec^{-1} with energies $\in \lesssim$ 300 eV) can adequately account for the accumulation of densities up to 10^4 cm^{-3} at the observed position of the upper ionospheric layer ($\sim$ 140 km).

The effects of cosmic rays, meteoric bombardment, and scattered Lα radiation have also been examined to model the generation of the observed night side ionospheric layers. In particular, Butler and Chamberlain (1976) noted that meteor ionization could also account for the peak ionospheric concentations provided the local density of neutral particles is $n_0 \sim 10^{12}$ - 10^{13} cm^{-3}. Since such values occur at lower altitudes than those required by the electron bombardment ($n_0 \sim 10^9$ cm^{-3}) it is possible that meteoric ionization could contribute to the production of the lower night side ionospheric layer (Gringauz *et al.*, 1977). It should be noted, however that the contribution of (yet undetected) more energetic electrons ($\in >$ 300 eV) was not included in the calculations of the collisional ionization processes, and that they could also affect sensibly the population and dynamics of both ionospheric layers. In this respect, Chen and Nagy (1978) have presented the results of independent calculations of night side ionospheric densities produced by more energetic electron fluxes. They conclude that the observed plasma densities at an altitude of $\sim$ 140 km can also be obtained by assuming a total downward flux of $\sim 10^6$ cm^{-2} sec^{-1} at an energy of 700 ev.

II. WAKE DYNAMICS AND ITS EFFECTS ON THE NIGHT SIDE IONOSPHERE

a) Magnetic Fields in the Wake

Even though it is fairly clear that the particle fluxes detected in the plantetary umbra can account for the observed ionization of the night side atmosphere, the overall description of how such fluxes are generated and directed towards the planet awaits intense theoretical and experimental examination. Thus, studies of the origin, acceleration, and spatial location of these fluxes will prove essential to the understanding of the detailed dynamics of the night side ionosphere. The present view of the geometry and structure of the plasma wake, assembled from current theoretical and experimental research, appears to be consistent enough to permit a preliminary qualitative description of correlated events which could result in the formation of the night side ionosphere. First of all, it is necessary to point out that the planetary umbra is not devoid of magnetic fluxes, but that an appreciable magnetic field intensity exists throughout the wake. Early estimates of the planetary magnetic moment indicated that the magnetic field intensity in the vicinity of the planet would not be much higher than that of the solar wind in freestream conditions (Dolginov *et al.*, 1969). The re-examination of such calculations proved, however, that the magnetic field at the planetary surface could be as high as 30γ (Russell, 1976a).

Recent experimental observations carried out with the Venera 9 and 10 orbiters revealed that the magnetic field in the wake is, in fact, of the order of 10-20 γ (Dolginov *et al.*, 1977). The origin of this field has not been established even though its configutarion in the far wake resembles that of the geomagnetic tail field: i.e. the magnetic field vector is essentially parallel to the Sun-Venus axis and exhibits a well-defined reversal in its direction (from anti-sunward in the northern hemisphere to sunward in the southern hemisphere). Dolginov *et al.* (1977) report, in addition, that the magnetic field configuration in the near-wake does not conform with that expected for a planet-rooted field, but appears to be controlled (in sign and direction) by the interplanetary magnetic field. Current interpretation of this dependence has been directed to the evaluation of the magnetic field associated with the electric currents induced in the ionosphere by the solar wind (Eroshenko, 1978). The apparent irregular and variable geometry of the magnetic field in the near wake appears to be most suitable to the development of electron bonbardment events in the night side atmosphere. As pointed out by Gringauz *et al.* (1977), it is desirable that the magnetic field above the night side ionosphere not maintain a stable orientation parallel to the surface, as this would prevent the incidence of low energy electrons to the upper atmospheric layers.

Another important aspect of the dynamics of the plasma wake which must be considered in connection with its magnetic configuration concerns the very presence of interplanetary magnetic fluxes associated with the ionosheath flow forced into the planetary umbra. Within the framework of the predicted viscous deflection of the solar wind flow behind the terminator, it is also contemplated that the magnetic field in the umbra must accomodate the magnetic flux of the intruding plasma (Pérez de Tejada *et al.*, 1977). This concept provides a natural explanation for the observed dependence of the magnetic field in the planetary umbra on the interplanetary magnetic field, and exposes its predicted complexity. Thus, in addition to a stable planetary component, the presence of the interplanetary magnetic field together with the ionosphere-induced magnetic field will render a highly variable magnetic configuration which will exhibit marked temporal and spatial changes in intensity and vector orientation. An order-of-magnitude estimate of the total magnetic flux forced into the umbra by the viscous interaction at the flank regions of the ionosphere can be derived by following the calculations of Pérez de Tejada (1979) on the total mass flux defect exhibited by the Mariner 5 plasma probe measurements. The comparison of this data with the inviscid flow calculations of Spreiter *et al.* (1970) indicates, in fact, that the measured velocity values in the ionosheath are deficient on the average by about 10% with respect to the predicted values. This amount, which implies a total mass flux of $\sim 10^{26}$ sec^{-1}, can satisfactorily account for the observed velocity and density values of the plasma in the umbra and thus provides a simple interpretation of the origin of this plasma.

Since the total amount of mass flux forced into the umbra is equivalent to that present in an annulus of undisturbed ionosheath flow

($n=4\ cm^{-3}$, $U_i=500$ km/sec) with external and internal radii $R_e=10\,000$ km and $R_i=9\,000$ km, respectively, we can estimate the total magnetic flux expected in the umbra by calculating that associated with such an annulus of material. The total amount of magnetic flux in the annulus is

$$F_B=\pi\ (R_e^2 - R_i^2)\ B_i=7.1 \times 10^{13} \text{ Gauss cm}^2$$

where $B_i=12\gamma$ in the magnetic field in the ionosheath. Since this magnetic flux should be equivalent to that associated with the ionosheath plasma forced into the umbra, the magnetic field in the umbra produced by this effect should be given by:

$$B_u = \frac{F_B}{\pi R_i^2} \approx 3\ \gamma .$$

Even though a slightly larger value ($\sim$5-6γ) would also be predicted by assuming that the intruding ionosheath flow occupies only the outer region of the wake, it is evident that such a component cannot account for the totality of the magnetic field intensity detected in the umbra. Its presence, however, may be essential to understand the spatial and time-dependent behavior of the magnetic geometry of the wake.

Before discussing the possible consequences of this geometry on the local particle population, it is first necessary to note that across a large section of the planetary umbra (particularly in its outer region) the local flow conditions of the solar wind mixed with planetary ions remain super alfvenic. Throughout this region, the plasma should behave no differently than in the ionosheath even though its velocity and density may be significantly reduced. In the inner region of the wake, on the other hand, the kinetic energy density should become smaller than the magnetic energy density so that the plasma and magnetic environment may resemble that of the earth's magnetosphere. It is in this region of the wake where the complexity of the magnetic geometry may prove essential to the acceleration of the local plasma.

b) Effects on the Local Plasma

In analogy with the magnetic and plasma dynamics of the earth's magnetic tail, we should expect that processes similar to plasma sheet expansions and substorm events be present as well in the inner regions of the Venusian wake. Russell (1976b) has, in fact, interpreted certain fluctuations of the magnetic field measured by the Venera 9 as indicative of field-aligned currents associated with a plasma sheet expansion within the wake. It is most important to realize, however, that the location of the regions where these events take place will be far more variable on Venus than in the earth's magnetotail. In fact, the continuous distortion of the planetary field by ionospheric currents and by the intruding interplanetary magnetic field should result in a time-dependent asymmetric orientation of the local magnetic field vector. Breus (1978) reports, in this regard, that the Venera 9 and 10 observations indicate that no single polarity holds steadily in the southern hemisphere of the wake, but that the component directed along the Sun-Venus axis is seen to exhibit different directions as a function of time. These observations seem to indicate that the region of magnetic reversal in the near wake may execute continuous spatial displacements across the umbra and that the magnetic field orientation in the inner regions of the wake simply reflects this displacement. A direct consequence of this behavior is the conclusion that the position of the region where reconnection of magnetic field lines may occur will also be affected by continuous spatial displacements across the umbra. This could affect, in an asymmetric manner, the entire cross sectional area of the near-wake as represented schematically in Figure 2: Note that the suggested geometry differs from that usually associated with the earth's magnetosphere in that magnetic reconnection processes may not be operative in the dayside hemisphere. In Venus, the planetary magnetic field present in the ionosphere should be partially shielded from the interplanetary magnetic field by the ionopause and by electric currents induced in the ionosphere by the solar wind. Thus, we can picture the interplanetary magnetic field lines as being effectively draped around the ionospheric obstacle and at the same time distorted as the ionosheath flow is laterally forced into the umbra. The variable character of the magnetic geometry in the near-wake should result from the combined action of the following factors. i) asymmetries associated with the orientation of the planetary dipole field; ii) asymmetries due to the time-dependent electric currents induced in the ionosphere by the solar wind; iii) a dawn-dusk asymmetry of the efficiency of the viscous interaction between the solar wind and the ionospheric plasma, caused by differences in the thermal and dynamic state of the ionosheath flow around the planetary terminator. This latter condition will also be complicated by the presence of an induced magnetic field as noted in ii above. Pérez de Tejada (1979) argued, in this regard, that the viscous mixing between the solar wind and the ionospheric plasma can be significantly reduced if a strong local magnetic field exists in the ionosphere at the terminator. The possible generation of a magnetic barrier in front of the dayside ionopause, as suggested by Dessler (1968), could have important consequences on the latitudinal geometry of the viscous boundary layer at and behind the terminator. This could explain the occasional absence of the mixing region in the wake as reported by Romanov *et al.* (1977).

The overall implication of these concepts, insofar as the formation of the night side ionosphere is concerned, is that the access of energetic particle fluxes to the upper atmospheric layers will be, to a large extent, controlled by the geometry and dynamics of the plasma wake and the ionosheath flow. Thus, the precipitation of particle fluxes to the night side hemisphere along magnetic field lines should proceed under conditions similar to those encountered in the auroral zones of the earth, except that in the present case it may affect even the equatorial regions of the planet.

Experimental evidence in support of the sporadic occurrence of peculiar conditions in the wake is available from the magnetic and plasma data analysis of the Mariner 10 measurements. Yeates *et al.* (1978) report, in fact, the detection of two different plasma regimes in the optical umbra. One is characterized by high bulk speeds and high densities, and has been associated with the behavior of the predicted viscous plasma wake. Alternating with this regime, periods of lower bulk speeds, lower densities and high values of magnetic variance are also detected. The intermittent character of these latter conditions has made difficult their interpretation even though a tentative identification in terms of an inner plasma bounded by a tangential discontinuity has been suggested. Yeates *et al.* (1978) conclude that these periods of disturbed conditions appear to be correlated with specific orientations of the local magnetic field and that they may result from the acceleration of electrons close to where they are detected. The local acceleration of particles in the wake has also been inferred from the observation of sporadic energetic ion fluxes ($\in > 2$ kev) deep within the umbra (Gringauz *et al.*, 1976a). These particles are not observed in the ionosheath or in the penumbral regions of the wake and thus reflect conditions peculiar to processes operating only in the deep umbra. Also significant are the results of the magnetic data analysis of the Mariner 10 measurements carried out by Lepping and Behannon (1978). According to these authors, he periods of disturbed plasma conditions resported by Yeates *et al.* (1978) are coincident with the detection of quasiturbulent magnetic conditions in the wake. They suggest that these observations correspond to a region in the deep umbra where the magnetic geometry changes configuration in response to changes in the interplanetary magnetic field and solar wind.

These various observations provide strong evidence that peculiar time-dependent processes take place deep within the optical umbra. The variable character of the viscous-flow behavior of the ionosheath plasma as it penetrates into the umbra represents, as noted above, a mechanism which should regulate the control that the solar wind exerts on the local plasma and magnetic field. The in-situ measurements to be made with the Pioneer Venus spacecrafts will provide a more comprehensive knowledge of the correlation existing between the magnetic geometry in the umbra and the plasma and magnetic conditions in the ionosheath flow.

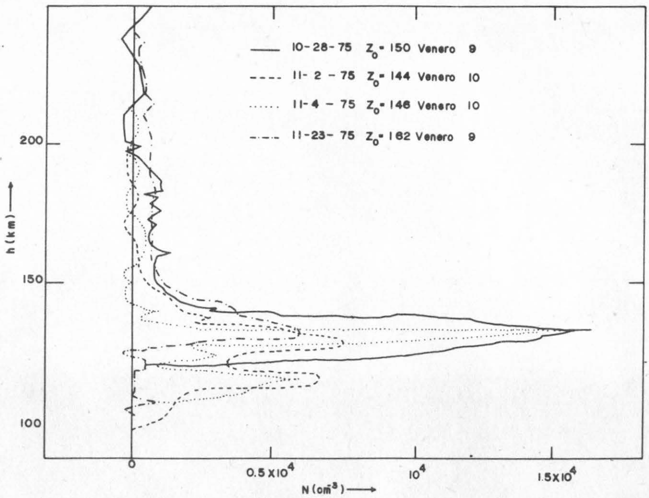

Fig. 1. Night side ionospheric electron concentration variations from the radio occultation measurements for different solar zenith angles Z_0 (from Keldysh, 1977).

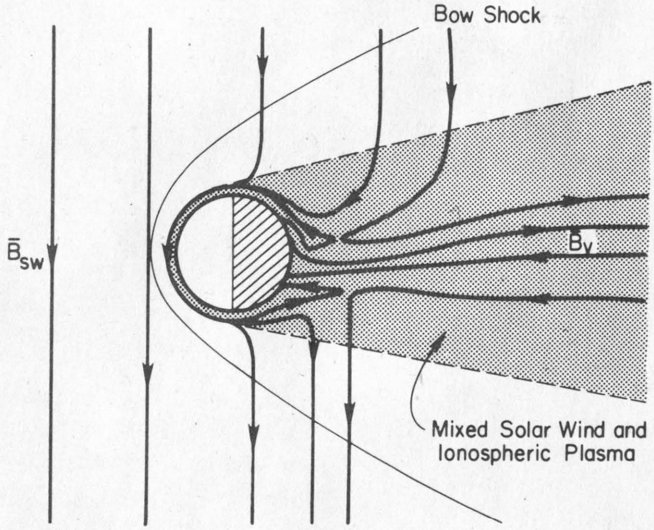

Fig. 2. Schematic representation of a possible magnetic geometry in the Venusian wake. The diagram shows the projection of the magnetic field lines on the plane formed by the magnetic dipole axis and the sun-Venus line.

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