9. THE VENUS IONOSPHERE AND SOLAR WIND INTERACTION

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Abstract. The current state of knowledge of the chemistry, dynamics and energetics of the upper atmosphere and ionosphere of Venus is reviewed together with the nature of the solar wind–Venus interaction. Because of the weak, though perhaps not negligible, intrinsic magnetic field of Venus, the mutual effects between these regions are probably strong and unique in the solar system. The ability of the Pioneer Venus Bus and Orbiter experiments to provide the required data to answer the questions outstanding is discussed in detail.

1. Introduction

The interaction of the solar wind with each of the presently explored planets appears, in many respects unique, but at the same time forms part of a continuum of possible interactions. In the terrestrial interaction, the solar wind is deflected by the magnetic field far above the ionosphere, and the flow associated with the drag

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of the solar wind on the magnetosphere, i.e., convection, dominates the flow associated with co-rotation over most of the outer magnetosphere. Despite the dominance of the magnetic field in deflecting the flow, the well-developed ionosphere at the base of the field lines plays an integral role in many magnetospheric processes, being strongly coupled to the outer magnetosphere by field-aligned currents. Jupiter also has a strong magnetic field, but it appears that centrifugal forces are dominant in many aspects of the Jovian magnetosphere–solar wind interaction. Mercury has a magnetic field of sufficient strength to deflect the solar wind well above the planet, but in contrast to the Earth, it has no ionosphere. Venus has at most a weak magnetic field and hence the solar wind must directly interact with the ionosphere. Yet at the same time, there is evidence that the planetary magnetic field still plays an important role in the interaction. Finally, Mars appears to have an interaction intermediate between that of the Earth and Venus (cf. Ness, 1976).

The contrast between the terrestrial and Venus ionospheres and magnetospheres is essential to understanding the basic physical processes occurring within each of them. In the terrestrial ionosphere, motions of the ionosphere across field lines drive currents. On Venus, currents in the ionosphere may be a significant contributor to the magnetic field. In another area, shocked solar wind flows directly into the Earth's ionosphere only in a narrowly defined polar cleft, but the entire sunlit hemisphere of Venus may be directly bombarded by shocked solar wind plasma. In many ways, the situations at Earth and Venus represent limiting cases in which the basic concepts, and even the equations modelling ionospheric behavior, can be put to the test.

Understanding the present solar wind interaction with Venus will also enable us to predict the possible conditions in the terrestrial paleomagnetosphere when the field strength was weak and perhaps the solar wind was more intense. Could the terrestrial atmosphere be significantly affected by such a process? We note in this regard that ozone can be significantly depleted by energetic particle bombardment and thus modulate the intensity of ultraviolet radiation reaching the surface of the planet. The upper atmosphere may be very sensitive to what appear to be small changes.

The study of the solar wind interaction with Venus is also directly applicable to the interaction with comets. Comets appear to have little intrinsic magnetic field but they have plasma tails which often exhibit apparent magnetic features. The mystery which surrounds these often spectacular denizens of nearby space will soon entice mission planners to send probes to sample them directly. The knowledge gained at Venus will aid in the design of such missions.

In the sections that follow, we first briefly describe the instrumentation. We then describe the outstanding problems in the study of the solar wind interaction with Venus and the nature of the upper atmosphere and ionosphere. Where applicable we will also briefly sketch the present state of knowledge and how the Pioneer Venus mission will resolve these questions and add to our present understanding.

2. Instrumentation

The complement of Pioneer Venus instruments devoted to the study of the solar-wind interaction and the ionosphere of Venus is the most comprehensive set of such instruments ever sent to another planet, other than the Earth. There are neutral mass spectrometers and ion mass spectrometers on both the bus and orbiter. The Pioneer Venus orbiter is a spinning spacecraft allowing the instruments to scan. It carries a magnetometer, a plasma analyzer, an electron temperature probe, a retarding potential analyzer and an AC electric field detector. The neutral mass spectrometers (ONMS) will measure the number density and composition of the upper atmosphere over the mass range of 1–46 amu down to an altitude of about 150 km. The ion mass spectrometer (OIMS) will do the same for the ions in the upper atmosphere over a mass range of 1–60 amu. The magnetometer (OMAG) will measure the planetary and interplanetary magnetic field with a resolution of $\pm 0.06\gamma$. The plasma analyzer (OPA) will provide three-dimensional information on the distribution function of the hot plasma over the energy per charge range of 50–8000 eV for ions and 1–500 eV for electrons. The electron temperature probe (OETP) will measure the electron temperature, concentration, and mean ion mass of the 'cold' component of the plasma. The retarding potential analyzer (ORPA) will probe the temperature and concentrations of most abundant ions, and their drift velocity, and measure the photoelectron energy distribution, the electron concentration and temperature. The electric field detector (OEFD) measures the oscillating electric field in four narrow band channels centered at 100 Hz, 730 Hz, 5.4 kHz and 30 kHz using a balanced vee-type short electric antenna.

These direct *in situ* measurements are supplemented both by the radio occultation (ORO, DGPE) data and by the remote sensing instruments. The repeated occultations of the orbiter telemetry signal will provide ionospheric density profiles below the altitude which can be probed directly and at latitudes not accessible to the spacecraft. These profiles will help elucidate the problem of the variability of the ionosphere. The infrared radiometer (OIR) will provide data on the temperature at the base of the upper ionosphere and the ultraviolet spectrometer (OUVS) will provide data on the airglow of Venus between 1100–3400 Å which may in part be stimulated by the 'hot' plasma in the upper ionosphere. In short, the instrumentation devoted to these measurements is both comprehensive and complementary and seems quite adequate to unfold the complex interrelationships we expect to occur in the ionosphere and interaction region around Venus.

3. Chemistry, Dynamics and Energetics of the Venus Ionosphere

In spite of several missions to Venus such as the Russian Venera entry probes and orbiters and the two U.S. planetary flyby missions, Mariner 5 and 10, we still know very little about the ionosphere of Venus and its interaction with the solar wind. In many respects our understanding of the Venus ionosphere is similar to that of the terrestrial ionosphere some twenty years ago. At that time we had measurements of bottom and topside electron density profiles, but no simultaneous information was available as to the composition and thermal structure of the ionosphere. We now know that detailed understanding of the physical and chemical processes in the ionosphere requires data on the heat sources, motions and composition of both the neutral and ionized constituents in addition to the electron densities. At present even our knowledge of the Venus plasma densities is limited to a few snapshots obtained by the Mariner 5 and 10 flyby missions and the Venera 9 and 10 orbiter radio occultation observations. There is as yet no experimental information regarding the ion composition nor is there any experimental clue regarding the temperatures of the electrons and ions, all parameters crucial for the understanding of the physical processes occurring in the Venus ionosphere. These processes may also be directly influenced by the solar wind interaction with the Venus ionosphere, and, at the same time, are likely to influence the nature of the interaction itself.

3.1. What is the ion composition and what controls the plasma distribution of the Venus ionosphere?

The observed main ionospheric layer has been interpreted successfully in terms of CO_2^+ and O_2^+ ions, the latter resulting from the reaction $CO_2^+ + O \rightarrow O_2^+ + CO$ (e.g., Kumar and Hunten, 1974; Nagy *et al.*, 1975). The neutral species involved in this reaction have been identified from airglow observations, although accurate values of their concentration are still lacking. The topside ionosphere of Venus has been considered to consist of He^+ and O^+ ions. At the present time there is no unique interpretation of the Mariner 5 and Mariner 10 electron density profiles because of the essentially unknown ion composition and possible effects of transport processes and plasma temperatures on these profiles. One possible interpretation is shown in Figure 1. The role of H^+ appears to be small because of the low photoionization rate coefficients. However, if substantial amounts of O^+ should be present in the ionosphere, the accidentally resonant charge transfer reaction with hydrogen might be an important source of protons, similar to terrestrial conditions.

Modifications of the ion density distribution through solar wind transport processes are highly suggestive from the Mariner 10 radio occultation profiles (Bauer and Hartle, 1974). A modification to a photochemical distribution could also occur as the result of the electron temperature dependence of the dissociative recombination coefficient for the two molecular ions CO_2^+ and O_2^+ (Nagy *et al.*, 1975). Neither of these alternatives can be resolved without *in situ* measurements of ion composition and plasma temperatures. The OIMS, ORPA, and OETP experiments on the orbiter are uniquely suited to answer these questions. No information on the source or composition of the observed night time ionization is

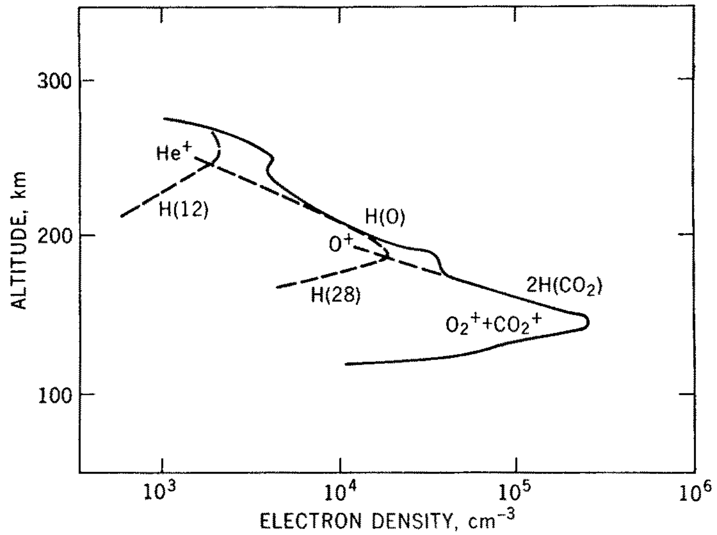

Fig. 1. Dayside electron density profile (solid curve) of Venus ionosphere observed by the Mariner 10 radio occultation experiment. Low-density features above 260 km have been omitted since they are of the order of the experiment noise level ($\sim 10^3$ cm^{-3}); they probably are indicative of time variations caused by the solar-wind scavenging process. Dashed curves represent the ion density distributions proposed to fit the observed electron density profile (Bauer and Hartle, 1974).

available at present; suggestions have been made in terms of ion transport from the day side and/or direct ionization or charge exchange with solar wind particles (cf. Bauer, 1973; Butler and Chamberlain, 1976) but the large variabilities in the nightside layer shown by the Venera results (Keldysh, 1976) make steady transport processes an unlikely source of this ionization.

3.2. What is the plasma temperature of the Venus ionosphere and what controls its thermal structure?

Following the Mariner 5 radio occultation observations a number of models of the thermal structure of the Venus ionosphere were generated (Whitten, 1970; Bauer *et al.*, 1970; Herman *et al.*, 1971). The latter study also considered the possible role of solar wind interaction as well as that of a small planetary magnetic field controlling transverse heat conduction and making high electron and ion temperatures in the Venus ionosphere possible. The presence of a small intrinsic magnetic field (Russell, 1976a) may also be of importance for non-local heating via photoelectron fluxes. There is at present no experimental evidence regarding the actual values of electron and ion temperatures, since scale heights of the main ionospheric layer provide only information on neutral temperatures, while the scale heights of the topside ionosphere cannot be uniquely interpreted in terms of plasma temperatures because of the lack of knowledge of ion composition and possible transport effects. The OETP and ORPA experiments on the orbiter should provide direct information on plasma temperatures, while OMAG observations and solar wind parameters measured by the OPA should give some clues regarding the possible effects of the solar wind on the thermal structure of the Venus ionosphere.

3.3. What are the mechanisms and the significance of mass, momentum and energy transfer from the solar wind to the upper atmosphere/ionosphere?

The observation of an 'ionopause' in the Mariner 5 radio occultation profile suggested a direct interaction between the solar wind and the Venus ionosphere. A simple static picture of these interactions can be visualized in terms of pressure balance between the solar wind and the ionospheric plasma (Spreiter *et al.*, 1970). The interaction between the solar wind and the ionosphere, however, may not be static nor may the ionosphere alone be fully responsible for the pressure balance, if a small intrinsic planetary field should exist (Russell, 1976a). There is evidence from Mariner 10 radio occultation observations of the ionosphere that a dynamic interaction, i.e., momentum transfer between solar wind and the ionosphere may actually take place (Bauer and Hartle, 1974). In addition, there is evidence of mass transfer, i.e., thermal ion pick up by solar wind from Mariner 5 (Bridge *et al.*, 1974) as well as from Venera 9 and 10 plasma observation (Vaisberg *et al.*, 1976). The role of ion pick up by solar wind (Michel, 1971; Hartle and Wu, 1973; Cloutier *et al.*, 1974) may play an important role in the solar wind interaction in the Venus atmosphere. Many of the Pioneer/Venus orbiter experiments (OETP, ORPA, OIMS, OMAG, AND OPA) are uniquely suited to study the mass and momentum transfer between solar wind and ionosphere. They can also provide measurements in the lower altitude regime, which were not feasible with the Venera 9 and 10 orbiters. Similarly, the energy transfer from the solar wind to the ionosphere requires, in addition to these observations, a knowledge of dissipation processes in the solar wind which can be obtained from the experiments just listed together with OEFD observations. Thus, the complete set of parameters measured simultaneously, with excellent temporal and spatial resolution, on the Venus orbiter provides a unique opportunity to answer these important questions regarding the interaction of the solar wind with the Venus ionosphere.

4. Nature of the Solar Wind–Venus Interaction

Even though the interaction of the solar wind with Venus has been probed on Mariners 5 and 10 and Venera's 4, 6, 9, and 10, many fundamental questions about the nature of the interaction remain unresolved. We do not know how to specify the physical processes by which the Venus ionosphere deflects the solar-wind and we do not know the ranges of variability of these mechanisms. We do not know whether to consider the cavity behind Venus to be like the lunar wake or the terrestrial magnetotail. We do not know what maintains the night time ionosphere and airglow. We do not know whether the magnetosheath (or ionosheath) and shock resemble those of the Earth, or have some peculiarities all their own because of differences in the interaction. In the following section we enumerate some of these outstanding questions, indicate the present status of the investigation and note how the data from Pioneer Venus may be used to resolve these questions.

4.1. The obstacle

4.1.1. *Is there an Intrinsic Magnetic Field?*

The first attempt to study the interaction of the solar wind with Venus was the Mariner 2 flyby in 1962 (Smith *et al.*, 1963; 1965) which detected no evidence of a planetary disturbance of the solar wind at the 6.6 planetary radii distance of closest of approach. In 1967 both the USA and USSR sent probes to Venus: Mariner 5 on a flyby trajectory approaching within 1.7 R_V of the center of the planet; and Venera 4 on an impact trajectory (Bridge *et al.*, 1967; Dolginov *et al.*, 1968). The location of the bow shock led Bridge *et al.* to estimate an upper limit for the venus magnetic moment of 8×10^{22} G cm^3. Venera 4 provided data down to 200 km altitude, and, based on the fact that the total field did not increase on approach to the planet, Dolginov *et al.* (1969) quoted an upper limit on the surface field of 2 to 4γ.

Based on these results, Venus is generally believed to be a non-magnetic planet. However, Russell (1976a) has recently questioned this limit on the grounds that Dolginov *et al.* did not remove the effects of spacecraft fields, that they made no attempt to separate external sources of the field from the internal or planetary sources, and that the Venera 4 vector components of the field show a gradual and coherent variation during the entry period. According to Russell, the upper limit is 6.5×10^{22} G cm^3, corresponding to a surface field of roughly 30γ, insufficient to stand off the solar wind but large enough to play a significant role in the interaction.

The moment obtained in the analysis of Russell was northward. Thus, the magnetic field in the wake behind Venus should be away from Venus in the northern hemisphere and towards in the southern hemisphere independent of the interplanetary field direction if the observed moment is indeed intrinsic to the planet. Mariner 5 crossed behind the planet in the northern hemisphere and saw a field directed away from the planet (Russell, 1976b) and Venera 9 crossed behind Venus in the southern hemisphere and saw a field towards the planet (Dolginov *et al.*, 1976; Russell, 1976c). These results strengthen the case for a planetary field.

The repeated sampling of the wake region by Pioneer Venus, the high inclination of its orbit which will enable the spacecraft to sample both the northern and southern wake regions on a single pass and the very low altitude of periapsis should permit an unambiguous answer to this question. Furthermore, Pioneer Venus, by virtue of its low periapsis altitude, will provide a measure of the tilt angle of the dipole, and the relative importance of multipole components of the intrinsic field of the planet.

4.1.2. *How do Ionospheric Currents Contribute to the Deflection of the Solar Wind?*

It is generally believed that the Venus ionosphere contributes significantly to the deflections of the solar wind flow, so that a shock would form even without an intrinsic planetary field. One of the most promising mechanisms for accomplishing this deflection is the magnetic barrier model in which the motional electric field of the solar wind drives a current through the ionosphere of Venus forming an induced magnetosphere (Johnson and Midgley, 1969; Cloutier and Daniell, 1973). However, the effects could have been masked by temporal fluctuations and more ionospheric traversals are required at a variety of local times before the importance of the contribution of ionospheric currents can be judged. It is of importance to locate these current systems and to determine if they are strong enough to be limited by plasma instabilities that lead to turbulent (or anomalous) electrical resistivity. The Pioneer Venus mission, with its low periapsis and core memory to ensure full coverage, is ideal for probing these ionospheric currents. Local wave-particle interactions can be studied with data from the OPA and the OEFD (cf. Hartle and Wu, 1973).

4.1.3. *How important are Processes such as Charge-exchange and Mass-addition?*

The weakness of the planetary magnetic field, and the consequent close approach of the solar wind to the planet permits direct interaction of the flowing plasma, be it shocked or unshocked solar wind, with the neutral atmosphere. This interaction could occur by charge-exchange, in which a fast neutral is created, removing momentum from the flow (Wallis, 1973); the mass-addition of neutrals photoionized in the flow (Cloutier *et al.*, 1969) can also be significant. The removal of momentum and the addition of mass will perturb the flow in predictable ways and these perturbations can be measured on Pioneer Venus. The orbiter instrumentation will also be able to provide information on the microscopic interaction mechanisms, which can involve ordinary collisions, or wave-particle interactions associated with plasma instability.

Mass addition has a clear signature, the presence of a second component in the flow. A second component has already been reported by Vaisberg *et al.* (1976). Pioneer Venus will be able to probe this component more effectively, both because of its lower periapsis, and because of its spin which enables the instruments to measure flows with arbitrary azimuth.

4.1.4. *What is the Source of the Variability of the Dayside Ionosphere?*

The dayside ionosphere was probed by means of radio occulation on Mariner 5 at a solar zenith angle of 33° and on Mariner 10 at an angle of 67°. The Mariner 5 data showed an abrupt decrease in electron density with altitude at 500 km, while the Mariner 10 data showed a similar decrease at 350 km. Furthermore, the density just inside this ionopause was about $10^4\,\mathrm{cm}^{-3}$ on Mariner 5 and $2\times 10^3\,\mathrm{cm}^{-3}$ on Mariner 10. One possibility is that the solar wind conditions were different. A complete set of solar wind measurements was not available from either Mariner 5 or Mariner 10. Thus, the reason for these differences must remain speculation until such a time as full solar wind measurements are available during occultations as on the Pioneer mission. One possible model (Bauer and Hartle, 1974) illustrated in Figure 1, attributes the difference in the profiles to a deeper penetration of the solar wind into the ionosphere leading to downward transport of ionospheric ions. A possible controlling agent of the transmission coefficient of the ionosphere is the direction of the interplanetary magnetic field.

4.1.5. *How Much of the Solar Wind is Absorbed by the Ionosphere?*

The model of Bauer and Hartle (1974) leads to the hypothesis of significant downward mass flux during the Mariner 10 flyby. In fact, it was comparable to the solar wind flux. Furthermore, fits of the bow shock location using Mariner 5 and 10 and Venera 4, 6, and 9 data, suggest the possibility that the nose of the bow shock is too close to the planet to allow all the solar wind to be deflected around the planet (Russell, 1977). We note that gas dynamic models may not provide a good estimate of the shock location because of their implicit assumption of no absorption (cf. Spreiter *et al.*, 1970). A rough estimate of the average absorbed fraction of the solar wind flux incident on the planetary cross-section is 30% (Russell, 1977). Pioneer Venus will be able to explore this problem not just by providing more bow shock crossings and more occultation data, but by probing the interaction region itself.

4.2. The cavity

4.2.1. *Is there a Magnetotail?*

Three possible field configurations might be expected in the cavity behind Venus: a lunar-type wake; a terrestrial-like magnetotail; or an induced comet-like magnetotail. In all three cases, the field should be greater than the interplanetary field in the region of the cavity from which hot plasma is excluded. In the lunar case, the field is not 'hung up' by the moon and consequently the field in the wake is generally not parallel to the wake axis. In contrast, as illustrated in Figure 2, the Mariner 5 field measurements in the wake region clearly show a field predominantly along the Venus–Sun line (Russell, 1976b). If the tail field were induced, i.e., generated by ionospheric currents, the direction of the field would be expected to change in response to external changes. The Mariner 5 passage and the Venera 9 passage through the wake region suggest, rather, that field direction depends only on whether the spacecraft is in the northern or southern lobe. Thus, the evidence presently favors the existence of an Earth-like tail. As mentioned above, the Pioneer orbiter has an ideal orbit for investigating this question.

4.2.2. *Is there a Plasma Sheet?*

If there is an intrinsic magnetic field and an Earth-like magnetotail, one would expect that a plasma sheet would also exist. The signature of a plasma sheet entry

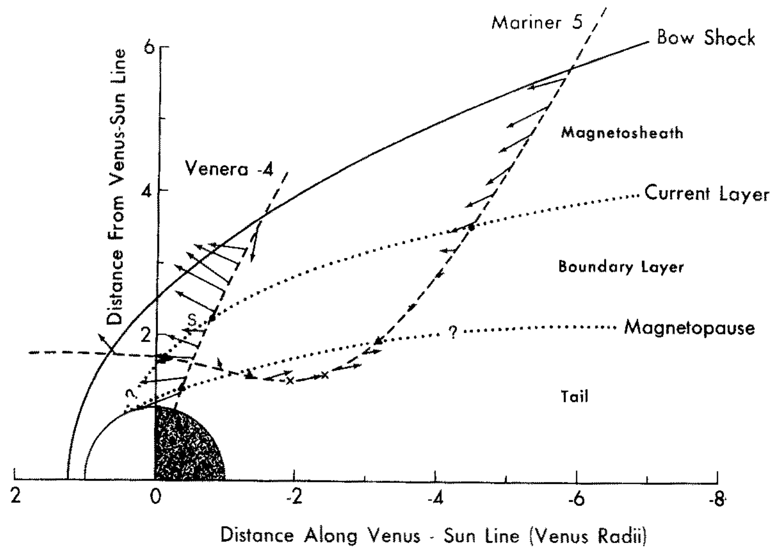

Fig. 2. The trajectories of Mariner 5 and Venera 4 in solar cylindrical coordinates. One minute averages of the Mariner 5 field projected into the spacecraft–Venus–Sun plane, are shown every 10 min. Representative field values from Venera 4 in the solar equatorial $X-Y$ plane are shown along the Venera trajectory. The magnetopause crossings identified by appropriate field changes in the original records, are indicated by triangles. The field values interior to the magnetopause parallel the boundary drawn through these magnetopause crossings as expected for a tail field source rooted in the planet (Russell, 1976c).

has been inferred from the Venera 9 magnetic field data (Russell, 1976c). Further, Gringauz *et al.* (1976) have reported sporadic and unusual ion fluxes up to > 4 keV. However, neither of these observations provide an unambiguous identification. Part of the identification problem is that these features, which are about an order of magnitude smaller on Venus, are traversed rapidly and that the data rate of these vehicles is low compared to that of Earth-orbiting spacecraft. The Pioneer Venus orbiter will likewise traverse these regions quickly but can transmit at higher data rates than the Venera spacecraft. The orbiter plasma and wave instruments can also study the stability of the non-Maxwellian plasma distributions apparently detected by the Venera experimenters.

4.2.3. *Are there Substorms on Venus?*

The terrestrial substorm is a phenomenon in which energy stored in the magnetotail is impulsively deposited in the auroral ionosphere (Siscoe, 1975). During this process particles are accelerated to high energies. No such particles have been reported at Venus. However, it is not clear that any spacecraft before Venera 9 and 10 passed near the expected acceleration region in the center of the tail, and Venera 9 and 10 are not instrumented with very energetic particle detectors. Nor is the Pioneer Venus spacecraft so instrumented. On the other hand, as shown in Figure 3 the Venera 9 spacecraft may have detected the magnetic field signature

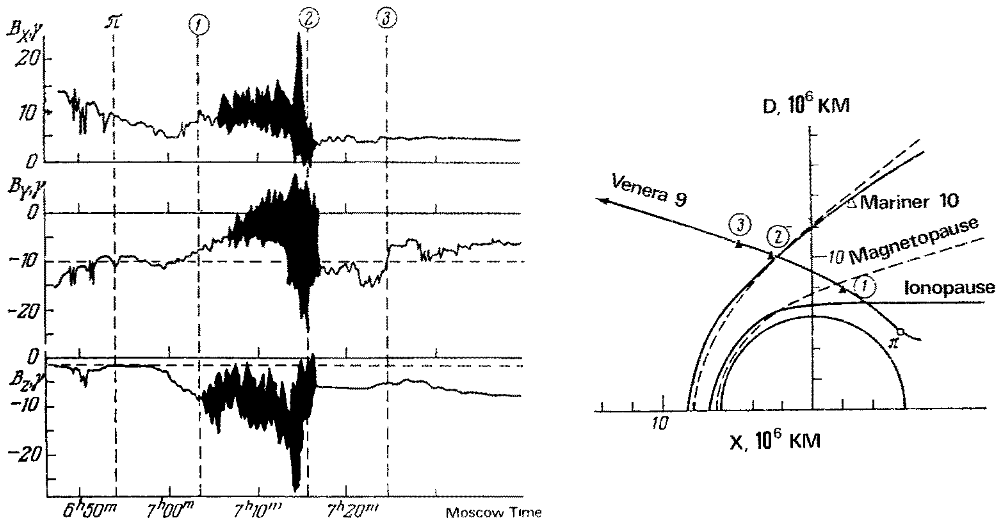

Fig. 3. Left panel: The solar ecliptic components of the magnetic field measured on a pass of the Venera 9 spacecraft through the Venus Wake, magnetosheath and shock front on October 28, 1975 (Dolginov *et al.*, 1976). The horizontal dashed lines give estimates of the corrected zero levels derived by Russell (1976b). Right panel: The trajectory of Venera 9 during this pass in solar cylindrical coordinates.

of a plasma sheet expansion and field dipolarization reminiscent of terrestrial substorm signatures in the magnetotail (Russell, 1976c). At 0650, the sunward B_X component drops and the B_Z component becomes more negative than expected for a tail field relaxing to a more dipolar condition. Furthermore, as in the terrestrial plasma sheet expansion, B_Y fluctuations, the signature of field aligned currents, are seen bounding the apparent plasma sheet entry. Indeed, the highly-variable nightside ionospheric profiles reported by the Venera experimenters are consistent with a substorm-type model in which precipitating particles produce the ionization. Thus, we might expect to see substorm-like phenomena on the Pioneer Venus orbiter in the field and plasma data.

4.2.4. *How does the Plasma Close Behind the Planet?*

In the lunar wake there is a region devoid of flowing plasma immediately behind the moon, into which the solar wind expands slowly with increasing distance. In the terrestrial magnetotail, there is also a region devoid of flowing plasma, and a region of apparent penetration of solar wind on to tail field lines. The velocity and density, in this region, called the plasma mantle, is less than that in the adjacent magnetosheath, and phenomena involving diffusion and viscosity are generally considered to be important here. As shown in Figure 4 the Venera 9 and 10 plasma analyzers detect a slow, less dense plasma as the spacecraft pass from the magnetosheath into the optical shadow of Venus and then a void (Gringauz *et al.*, 1976; Vaisberg *et al.*, 1976). In analogy with the moon, Gringauz *et al.* have termed these regions the umbra and penumbra, respectively. However, they may

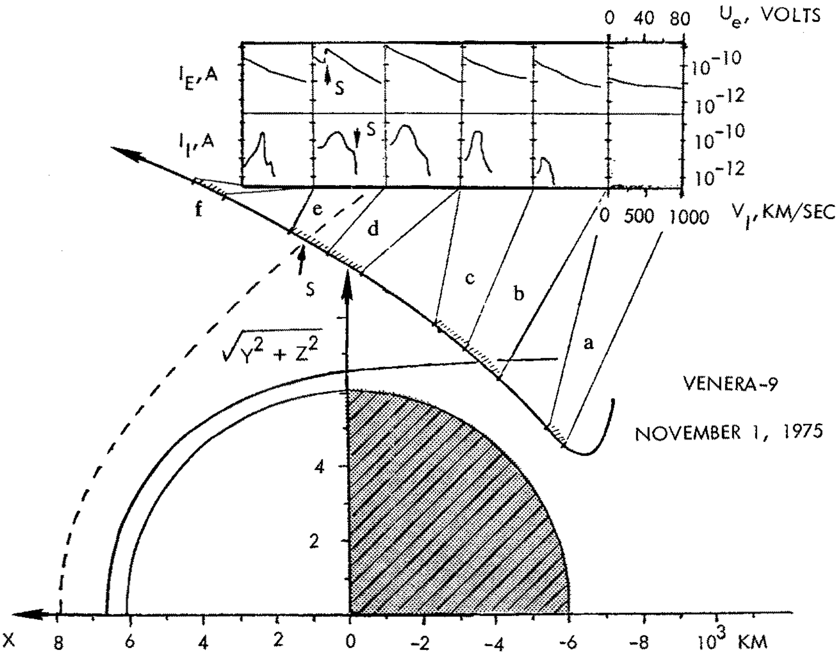

Fig. 4. Venera 9 plasma measurements on 11/1/75 from 0427 to 0457 Moscow time on a pass from the Venus wake region (a), through the boundary layer (b) and (c), the magnetosheath (d), and the shock front, (at time 'S' in spectrum (e)), and into the undisturbed solar wind (f). The boundary layer is characterized by less dense and slower moving plasma than in the magnetosheath; the wake region by strongly non-Maxwellian and erratic fluxes (Gringauz *et al.*, 1976).

be more like the terrestrial plasma mantle (Hones *et al.*, 1972; Rosenbauer *et al.*, 1975), or more like a viscous boundary layer (Perez-de-Tejada and Dryer, 1976). Since the Pioneer Venus orbiter plasma measurements have both latitudinal and azimuthal resolution, it is quite probable that a different picture will emerge than presently available from the Venera data.

4.3. Night time ionosphere and airglow

4.3.1. *What Maintains the Nightside Ionosphere?*

The night time ionosphere has a peak electron density of $\sim 10^4$ cm^{-3} compared with the dayside peak density of $\sim 3 \times 10^5$ cm^{-3} (Fjeldbo *et al.*, 1975). McElroy and Strobel (1969) proposed that lateral transport of He^+ from the dayside topside ionosphere would provide a source for the nightside ionosphere by means of charge exchange with CO_2 and CO_2^+ ions. However, this mechanism would produce a layer at too high an altitude (Bauer, 1973). Another possibility is the leakage of solar wind protons into the nightside atmosphere, charge-exchanging with CO_2 to produce hot H atoms which can penetrate deep into the atmosphere. Only 1 to 2% of the solar wind energy flux is required (cf. Bauer, 1973). The Pioneer Venus OPA will be able to test this hypothesis directly by measuring the hot ion flows in the wake region, while the ODMS simultaneously measures the species of thermal ions present and their spatial distribution.

4.3.2. *What Produces the Two Peaks in the Electron Density Profile in the Nightside Ionosphere? What Causes their Variability?*

The nightside electron density profiles deduced from the radio occultation on Mariner 10 (Fjeldbo *et al.*, 1975) and on Venera 9 and 10 (Keldysh, 1976) often exhibit a double peaked structure at around 120 and 140 km altitude, as shown in Figure 5. The peaks at times have equal densities of $\sim 7 \times 10^3\ \text{cm}^{-3}$, but at other times the upper peak becomes enhanced to densities greater than $1.5 \times 10^4\ \text{cm}^{-3}$. The reason for the double peaked structure is unknown. It does not appear to be present in the Martian night time ionosphere (Savich *et al.*, 1976). Additional radio occulations of the nightside on Pioneer Venus, together with simultaneous and near simultaneous direct observations of the solar wind, the wake and local ionospheric conditions, will help resolve this mystery.

4.3.3. *What is the Source of the Night Time Airglow and the Ashen Light?*

Observations of an Ashen Light on the nightside of Venus have been reported for well over three centuries (Baum, 1957). The phenomenon is episodic and correlated with geomagnetic activity and thus has been attributed to solar particle bombardment (Levine, 1969), but it also has been dismissed as simply earthshine

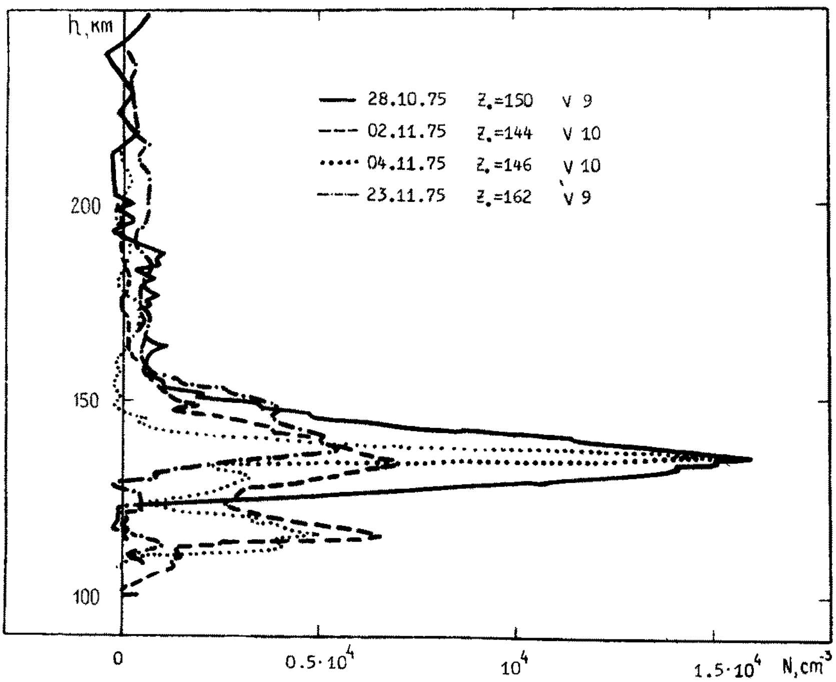

Fig. 5. Night time ionospheric electron concentration variations from the Venera 9 and 10 radio occultation measurements (Keldysh, 1976).

(Napier, 1971) or as psychological artifact. The observations of the Venera 9 and 10 spectrometers confirm the presence of night airglow on Venus (Krasnopolsky *et al.*, 1976), but have not yet identified the source of these emissions, what excites these molecules, how variable this phenomenon is, nor even whether this airglow can be responsible for the Ashen Light observations. The Pioneer Venus OUVS covers a different portion of the spectrum, and thus will complement the Venera measurements in this identification problem. Further, since Pioneer Venus will be launched near solar maximum, rather than solar minimum, there will be more opportunities for the Ashen Light to be stimulated, if indeed it is stimulated by an increased number of high speed streams in the solar wind.

4.4. The Magnetosheath and Shock Front

4.4.1. *Is there a Boundary Layer or Rarefaction Region in the Flow?*

If the magnetosheath flow closed behind Venus, one would expect an expansion fan in the flow beginning at the terminator and led by a rarefaction wave. There are suggestions that this is indeed the case. Rizzi (1971) has pointed out that the characteristic that passes through the drop in field strength observed on the in-bound Mariner 5 trajectory, intersects the terminator. Russell (1976b) has noted that a similar boundary can be seen in the outbound Mariner 5 data close to the planet and in the Venera 4 data. Lepping and Behannon (1976) have seen a similar phenomenon in the Mariner 10 data. Vaisberg *et al.* (1976) have suggested that a rarefaction wave can be identified in the Venera 9 and 10 data also. A summary of their observations is shown in Figure 6.

If Venus had no magnetic tail, closure of the flow and the attendant rarefaction wave would be expected. However, if a well developed magnetotail exists which allows only minor interpenetration of the magnetosheath flow, this interpretation must be incorrect. An alternative explanation is that this region is a boundary layer consisting of flow that has been altered by its interaction with the ionosphere in some way. The direct probing of this region by Pioneer Venus should resolve this question.

4.4.2. *How Does the Venus Bow Shock and Upstream Region Differ from that of Earth?*

The Earth's bow shock has a well understood general structural variation that depends primarily on the solar wind Mach number, the angle between the shock normal and the interplanetary magnetic field, and β, the ratio of the thermal to magnetic energy in the solar wind (Greenstadt, 1976). For quasi-perpendicular conditions, the shock is thin ($c/\omega_p^- < \delta < c/\omega_p^+$), where c is the speed of light and $\omega_p^\pm = (4\pi Ne^2/M_\pm)^{1/2}$ are the electron or proton plasma frequencies. For quasi-parallel conditions, whistler mode waves play a very important role, and electromagnetic turbulence propagates upstream, producing very broad and irregular shock structures. In both cases, the collisionless bow shock at earth leads to

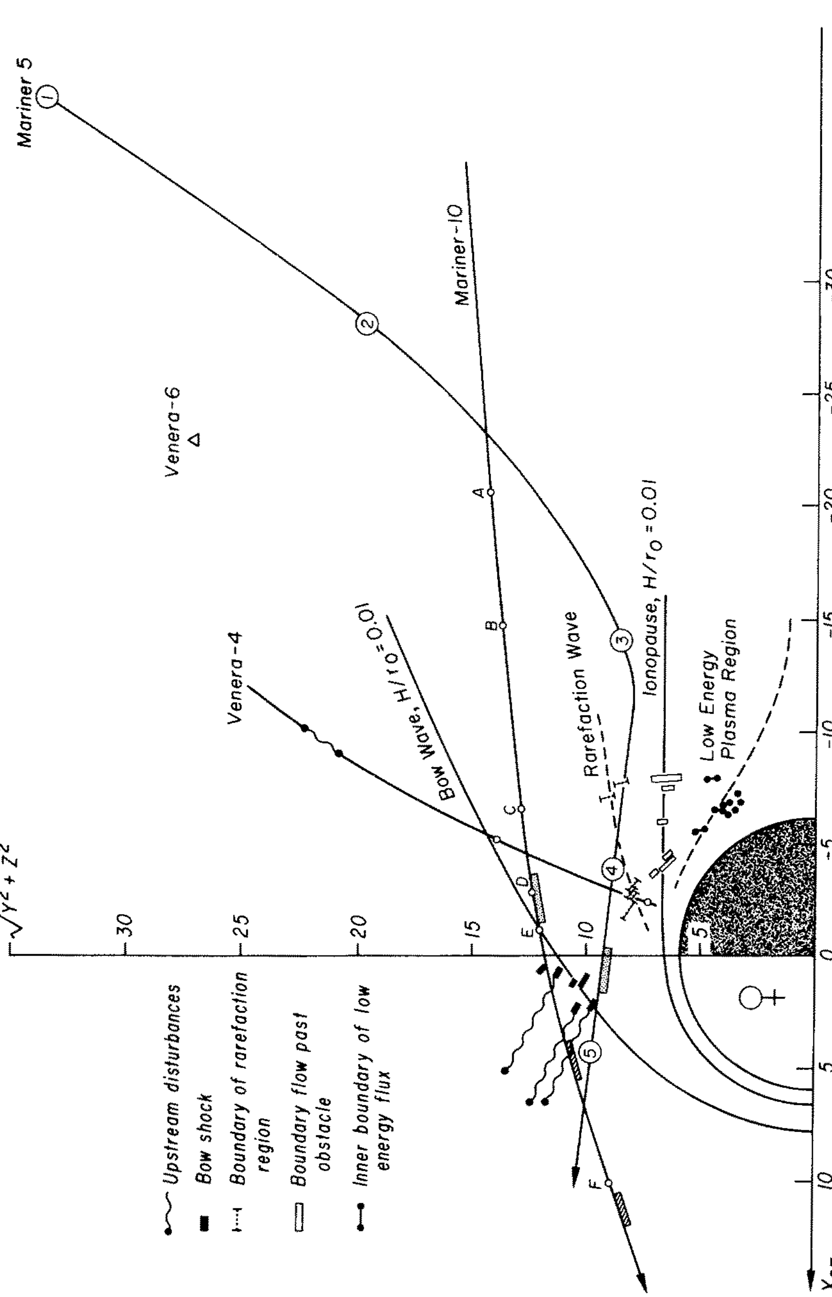

Fig. 6. Summary of Venera and Mariner plasma data (Vaisberg *et al.*, 1976).

significant local acceleration of protons and electrons that can propagate upstream to at least 60 R_e, and these suprathermal particles radiate energy by generating plasma oscillation.

The Venus interaction region must have at least as much variability as the bow shock–upstream interaction region around Earth, and the interplanetary field direction should be of importance with respect to shock thickness, plasma wave generation, local acceleration, etc. In addition, the Venus shock–upstream region may have novel phenomena associated with escape of neutral exospheric atoms into the upstream region.

Wallis (1972) proposed a novel 'soft interaction' theory based on the assumption that the neutral planetary exosphere is imbedded in the upstream solar wind. In this case, planetary ions 'born' in the solar wind can result in a large region of subsonic flow ahead of the planet, so that a bow shock can be avoided. Hartle and Wu (1973) and Hartle *et al.* (1973) noted that the newly-born ions in the wind will generate electromagnetic and electrostatic plasma instabilities, resulting in rapid thermalization of the exospheric ions with the solar wind. The Pioneer Venus OEFD instrument will detect the presence of the resulting instabilities.

5. Concluding Remarks

The Pioneer Venus orbiter seems to be ideally suited for attacking the remaining first order questions about the Venus ionosphere and the solar wind interaction. The instrumentation appears to be adequate to characterize the important ionospheric and solar wind parameters. The spinning spacecraft permits resolution of flow directions to an extent not possible on the Venera and Mariner spacecraft. The *in situ* measurements are complemented with a set of remote sensing instruments to characterize the atmosphere and ionosphere in regions inaccessible to the spacecraft. Most importantly, this region of inaccessible ionosphere will be kept to a minimum. The nominal periapsis altitude is 200 km, almost an order of magnitude smaller than that of Venera 9 and 10, and this altitude can be actively maintained against solar-gravitational perturbations. Furthermore, the instruments on the bus spacecraft will be able to penetrate into the atmosphere even deeper than the orbiter.

The major questions which Pioneer Venus was designed to address still remain, despite the success of Venera 9 and 10. The main impact of the Soviet results is to sharpen the focus of some of our objectives but they have not changed their direction. In several instances, for example, the Venera observations have shown what occurs without giving clues as to why it occurred. The nightside ionosphere is seen to be variable; there is significant night airglow; there is a boundary layer in the magnetosheath flow; there is ion-pickup, etc. The answers to why, to what extent and under what conditions these processes occur requires a coordinated multidisciplinary approach using a variety of simultaneous and complementary diagnostics in the region of interaction itself. Pioneer Venus provides such an approach.

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