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The abrupt termination of the daytime ionosphere of Venus at about 500 km as observed with the Mariner V two-frequency occultation experiment provides an extremely interesting picture of the direct solar wind interaction with a planetary ionosphere.[1,2] It has been suggested that a pseudo-magnetopause is formed due to the presence of magnetic fields carried along by the solar wind and forced to pile up on the topside of the highly conducting planetary ionosphere.[3,4] This magnetic obstacle then interacts with the super-alfvenic and supersonic solar wind to form a bow shock; evidence for such a bow shock has been obtained by Mariner V and Venera IV experiments.[2,5]

We have used the observed solar wind properties to determine order of magnitude estimates of the characteristic parameters in this interaction. The solar wind density observed by Mariner V was $n = 3\ cm^{-3}$ and the corresponding solar wind speed was $v = 590$ km/sec while the proton temperature was $T_p = 3 \times 10^5\ {}^0K$.[2]

With these data and a $\gamma = \frac{5}{3}$, the Rankine-Hugoniot relations applied across the shock boundary lead to a shocked gas ion density of about $12\ cm^{-3}$ and a corresponding proton temperature of about $4.0 \times 10^6\ {}^0K$. Using these values, a pressure balance at the stagnation point formed with the streaming pressure of the solar wind leads to a magnetic field buildup of approximately 50 γ. A balance between the streaming pressure of the solar wind $P_W = K\, n\, mv^2 \cos^2 \Psi$ and the plasma pressure $P_C = Nk\,(T_e + T_i)$ in the topside Venus ionosphere is consistent with the sharp cutoff in the electron density profile. We have calculated this balance at 45^0 from the sub-solar point where the topside ionosphere electron density was observed to be $N \simeq 10^4\ cm^{-3}$ at the 500 km cutoff ("ionopause").[1] Correcting for this aspect angle $\Psi = 45^\circ$, we calculate the streaming pressure of the solar wind to be about 8.8×10^{-9} dynes cm^{-2}. Based on gas-dynamical considerations, the possible range of the accomodation coefficient K, used to determine the streaming pressure, lies between 0.88 and 2; for the earth's magnetosphere a value of 1 is frequently used.[6] Since the appropriate value of K is a matter of conjecture, we have used K = 1 in our calculations. With the solar wind pressure and the observed topside ionosphere electron density, we obtain about 6000 °K for the plasma temperature $(T_e + T_i)$ of the topside ionosphere. In the following we shall discuss the interaction of the solar wind with the Venus ionosphere and the important constraint it places on a self-consistent model of ionospheric temperatures and densities.

The presence or absence of a magnetic field within the ionosphere has important consequences for the structure of the Venus ionosphere. There are two extreme cases: (1) where the presence of an essentially horizontal magnetic field inhibits thermal conduction across field lines, and (2) where either due to the complete absence of a magnetic field or the presence of a tilted magnetic field the thermal structure is controlled by parallel heat conduction. The first case could arise from the fact that the ionospheric plasma is not infinitely conducting and the boundary magnetic fields penetrate into the ionosphere. These fields, in the absence of any appreciable intrinsic magnetic field, would be essentially horizontal, especially in the vicinity of the sub-solar point. However, there is also a possibility of an induced magnetic field due to the interaction of the solar wind with the conducting ionosphere, as well as the presence of a small intrinsic planetary magnetic field which can lead to a non-horizontal field within the Venus ionosphere. The upper limit for such a magnetic field inside the ionosphere is estimated to be about 40γ.[7] To account for the possible effects of a tilted magnetic field, or field irregularities, we have used a value for the thermal conduction coefficient of $0.25\ K_\parallel$. We also considered as a special case the idealized condition of a horizontal magnetic field which would inhibit thermal conduction. However, the following discussion will emphasize the more likely case of a non-horizontal magnetic field within the Venus ionosphere. Since it is not our intention to discuss the detailed ionic composition, we selected a relatively simple photo-chemical model for the lower regions of the ionosphere based on McElroy's work.[8] We have taken CO_2 to be the dominant heavy neutral species at 100 km and have included about 0.5% N_2 to test the expected small effect of a minor heavy constituent. H and He are taken to be the important light neutral constituents. These together with N_2 make up no more than 1% of the neutral atmosphere at 100 km. We also have investigated the effect of the presence of H_2 or deuterium (D), but their presence does not affect our results significantly. As a result of using hydrostatic equilibrium for the neutral gas density distribution, H and He become the dominant species at higher altitudes. It follows, therefore, that the ionization peak between 120 and 130 km will be controlled by the neutral CO_2, while the charged particle pressure in the topside is strongly influenced by H and He. For the light ions H^+ and He^+ we have solved the usual hydrostatic pressure balance equations including gravitational and electrical forces. Combining these with the equations arising from the thermal balance in a multi-component plasma (including the neutral gases) a self-consistent solution for the temperatures and densities has been obtained.[9]

We have selected several boundary conditions based, wherever possible, on published values: At the lower boundary of 100 km we used a neutral temperature of $T_n = 250^0$ and a CO_2 density of 1×10^{12} cm^{-3} comprising at least 99% of the total density. The remaining 1% or less was adjusted so that the corresponding topside plasma pressure balances that of the solar wind and simultaneously approximated the observed electron density scale height. Since the light ion composition is experimentally unknown, we have assumed H^+ (or D^+) and He^+ to be the main constituents of the topside ionosphere. The electron density $N = [He^+] + [H^+] + [CO_2{}^+]$ was selected to match the observed electron density at 500 km.

Figure 1 shows the computed ionospheric model with He^+ as the dominant ion. In this model the electron temperature has the value of $T_e = 4090$ ^0K, as compared to the ion temperatures which have a value of $T_i \approx 1900$ ^0K, considerably higher than the neutral gas temperature $T_n = 550$ ^0K. The electron density peak differs somewhat from the observed value seen from Mariner V; however, a small decrease in the electron ion recombination coefficient from the used value of 3.8×10^{-7} cm^{-3} sec^{-1} would easily bring the peak into agreement with the observations. The topside electron density scale height for this model is seen to be quite large in conformity with the Mariner occultation data. It should be noted that when He^+ is the dominant ion, the H^+ ion density increases with altitude due to the polarization electric field.

The most important constituent of the lower Venus ionosphere is neutral CO_2 which plays the role of atomic oxygen on the earth as the principal heat loss channel for the neutral gas.(10) CO_2 is also the major absorber of solar radiation and in its ionized form is the major means for electron-molecular ion recombination. However, unlike the earth's atomic oxygen, the high mass (i.e. small scale height) of CO_2 limits its effects to the lowest altitudes. Because of its dual role as recombination sink and ionization source and its limited height range, changes in the CO_2 density at 100 km produce surprisingly small effects on both temperature and density as compared with atomic oxygen in the earth's atmosphere. This is not the case for neutral He. Helium with its large scale height and good thermal contact with the He^+ ions is able to affect the upper portion of the ionosphere substantially. Specifically, (when He^+ is dominant) a decrease in the He concentration increases the ion temperature while the plasma pressure increases or decreases depending on the relative change of the ion and electron temperatures along with the electron density.

A similar ionospheric model satisfying the observed conditions has been considered where H^+ (or D^+) is the dominant ion in the topside ionosphere. The peak electron density is hardly changed since it is controlled by the photoionization of neutral CO_2 and the recombination with CO_2^+ ions. Although such a model also gives reasonable agreement with the observed values, we would like to argue that the high value required for the H^+ density (and/or D^+ density) in the topside ionosphere seems unlikely, since the observed density of neutral hydrogen is thought to be relatively low (11) and, in contrast to earth, H^+ is produced by photoionization rather than by charge exchange. The solar wind protons are an unlikely source of supply since most of those which can penetrate the "ionopause" will reach the CO_2^+ ion-dominated region where they would be lost by chemical processes. Therefore, unless there is some storage mechanism for protons, we are led to favor the model in which He^+ is the dominant topside ion with relatively hot electrons compared to the ion and neutral gases.

If we consider the other limiting case of a horizontal rather than a slightly inclined magnetic field, the thermal structure of the topside ionosphere is significantly different because heat conduction does not play a significant role due to the inhibiting effects of this horizontal magnetic field. In this case, the electron temperature is higher and the ion temperature is lower than in the model presented in Figure 1.

Figure 2 shows the total pressure distribution based on the density and temperature distributions of Figure 1. The pressure curve extended to 600 km was obtained by solving the density and temperature equations simultaneously with pressure balance between solar wind and ionospheric plasma pressure at 500 km. The very slow pressure decrease with altitude suggests that the altitude at which the ionosphere terminates (ionopause or anemopause[2]) is a strong function of solar wind pressure. If the solar wind pressure changes by a small amount our model predicts a substantially unchanged ionosphere with an ionopause at a different altitude. It also suggests that the ionospheric boundary is flat-nosed at the sub-solar wind point and somewhat bulged out near the terminator due to the effect of the aspect angle in the pressure balance equation. Since the streaming pressure of the solar wind on the night side of Venus is negligible, the ionosphere would there extend to considerable altitudes as reported by Mariner V. [(1)]

Our present study shows that the solar wind places important constraints on the topside ionosphere of Venus and that these constraints in turn allow one to infer properties of the topside ionosphere. Presently, a range of possible models satisfying the experimental boundary conditions are being investigated in some detail and will be reported elsewhere.

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Figure Captions

Figure 1

Charged particle densities and temperatures for the Venus ionosphere when the electron thermal conductivity is 0.25 K_{11}. The dashed line $P_c = P_w$ represents the cutoff in electron density ("ionopause") arising from the pressure balance between the solar wind and the charged particle of the Venus ionosphere.

Figure 2

Charged particle pressure $P_c = Nk(T_e + T_i)$ in the topside Venus ionosphere. At the altitude of the ionopause (500 km), $P_c = 8.8 \times 10^{-9}$ dyne cm^{-2}.

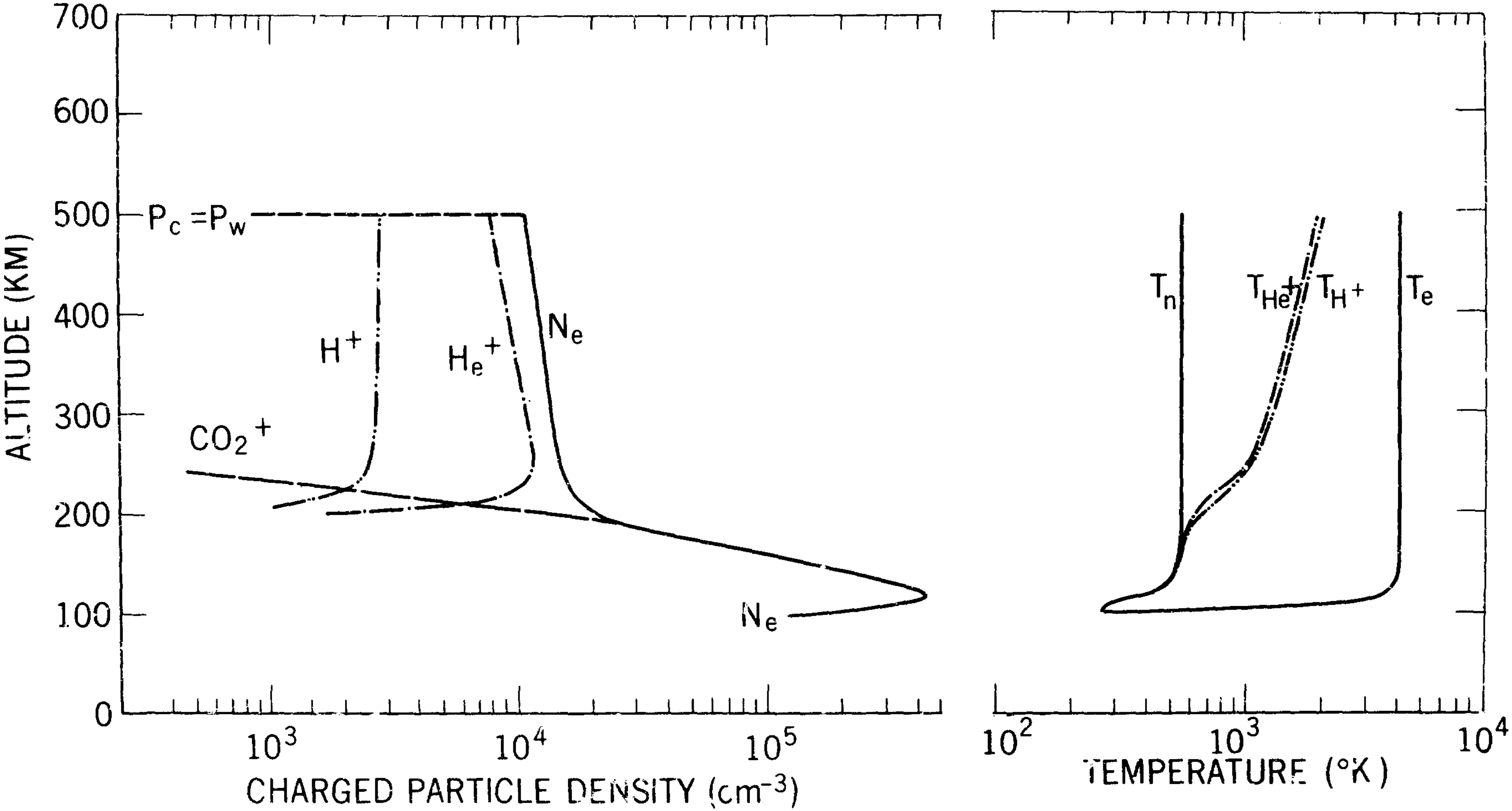
ALTITUDE (KM)
700
600
500
400
300
200
100
0
$P_c = P_w$
H^+
H_e^+
N_e
CO_2^+
N_e
10^3
10^4
10^5
CHARGED PARTICLE DENSITY (cm^{-3})
T_n
T_{He^+}
T_{H^+}
T_e
10^2
10^3
10^4
TEMPERATURE (°K)

Figure 1

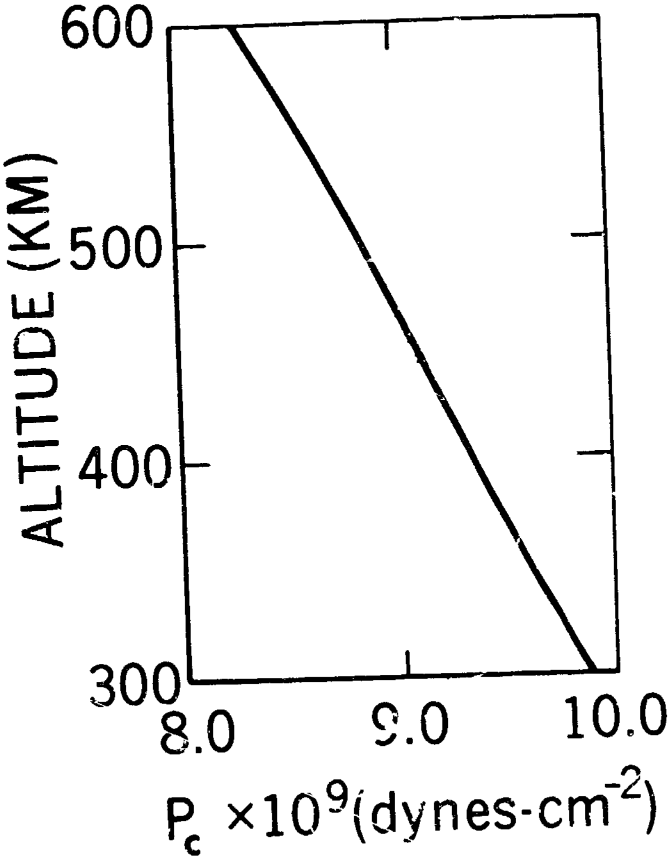

Figure 2