SOLAR-WIND CONTROL OF THE EXTENT OF PLANETARY IONOSPHERES

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ABSTRACT

In our solar system there are at least four magnetic planets: Earth, Jupiter, Mercury, and Mars; while at least one planet, Venus, appears to be essentially nonmagnetic. The ionospheres of the magnetic planets are imbedded in their magnetosphere and thus shielded from the solar wind, whereas the ionosphere of Venus, at least, interacts directly with the solar wind. However, the solar-wind interaction with the planetary environment, in both cases, affects the behavior of their ionospheres. In this paper, the role the solar-wind interaction plays in limiting the extent of the ionospheres of both magnetic and nonmagnetic planets will be discussed.

IONOSPHERES OF MAGNETIC PLANETS

In the first decades of ionospheric research when ground-based observations were limited to altitudes up to the ionization maximum (F_2 peak), the question regarding the extent of the terrestrial ionosphere was either ignored or completely arbitrary assumptions were made about the upper boundary of the ionosphere.

The question became relevant, however, when in the early 1950s the ground-based whistler technique (Storey, 1953) indicated measurable concentrations of cold plasma to distances of several Earth radii (R_E). In the mid and late 1950s, ground-based observations of radio waves reflected from the Moon, utilizing the Faraday rotation experienced by these waves as they traversed the entire ionosphere (Evans, 1956; Bauer and Daniels, 1958), showed that about three times more ionization lies above the F_2 peak than below. Whistler observations during the IGY (Carpenter, 1963) and early *in situ* measurements of cold plasma on spacecraft (Gringauz, 1963) led to the discovery that the cold plasma concentrations decrease rather abruptly at distances of ~4 R_E (or on L shells corresponding to this equatorial distance). Furthermore, it was recognized that the position of this knee in the plasma density distribution moved inward with increasing geomagnetic activity (Carpenter and Park, 1973). Nishida (1966) and Brice (1967) suggested that this rapid decrease in the thermal plasma density (the knee, or as it was later called, the plasmapause), which occurs well within the closed magnetosphere, is the result of the solar-wind interaction with the planetary magnetic field. According to this explanation the convection electric field generated by the solar-wind interaction (Axford and Hines, 1961; Dungey, 1961) plays an important role in the formation of the plasmapause. The plasmapause can thus be defined as the boundary between the corotating ionospheric plasma and the tenuous plasma controlled by the convection electric field induced by the solar-wind interaction.

To first order, the plasmapause occurs where the corotation electric field equals the convection electric field. The corotation electric field is given by

$$\vec{E}_{rot} = -(\vec{\Omega} \times \vec{R}) \times \vec{B} \tag{1}$$

where Ω is the angular rotation velocity of the planet and B is its magnetic field. The magnitude of the solar-wind-induced convection electric field can be estimated according to Dungey (1961) and Petschek (1966) as

$$E_{conv} \cong K\, V_A\, B_{ip} \propto \left(\frac{B_{ip}^{\ 3}}{\rho_{sw}}\right)^{1/2} \tag{2}$$

where

V_A = the Alfvén velocity,

B_{ip} = the interplanetary magnetic field in the vicinity of the planet,

ρ_{sw} = the solar-wind mass density,

K = a factor describing the efficiency of the solar-wind-magnetosphere connection and is of the order of 1/3 to 1.

A comparable convection electric field can be obtained from a potential resulting from the viscous solar-wind interaction model of Axford (1964). The convection electric field is directed from dawn to dusk (for Earth) causing convective motions toward the Sun. (For Jupiter, because of its reverse magnetic polarity, these motions will be in the opposite direction.) The plasmapause can also be viewed as a surface, whose equatorial distance is given by the Roche Limit, that is, the locus of points where the total gravitational and centrifugal potential has a maximum along a magnetic field line according to Lemaire (1974),

$$L_c = \left(\frac{2}{3}\ \frac{GM_E}{\Omega^2 R_E^{\ 3}}\right)^{1/3} \tag{3}$$

where

M_E = the mass of the Earth,

R_E = the radius of the Earth,

G = the universal gravitational constant, and

Ω = the angular speed of plasma around the dipole axis.

(For the neutral gas, the Roche limit is given by $r_{RL} = (GM_E/\Omega^2)^{1/3}$, that is, at a distance $r_{RL} = 6.6\ R_E$, whereas for a plasma this distance is L = 5.78 according to equation 3.)

The actual topology and time behavior of the plasmapause is vastly more complex, however. Figure 1 shows the local time variation of the plasmapause for low magnetic activity $K_p = 1$. The position of the plasmapause in the midnight-dawn sector is found from statistical studies of whistler observations to be (Carpenter and Park, 1973)

$$L_{pp} = 5.7 - 0.47\ K_p\ . \tag{4}$$

Noting that K_p is a measure of the solar-wind interaction with the magnetosphere, the solar-wind control of the position of the plasmapause can be seen. It should also be noted that outside the plasmasphere the equipotential surfaces are open, and over the polar cap, extensive outflow of light ions H^+, He^+ (polar wind) becomes possible (Banks and Holzer, 1968).

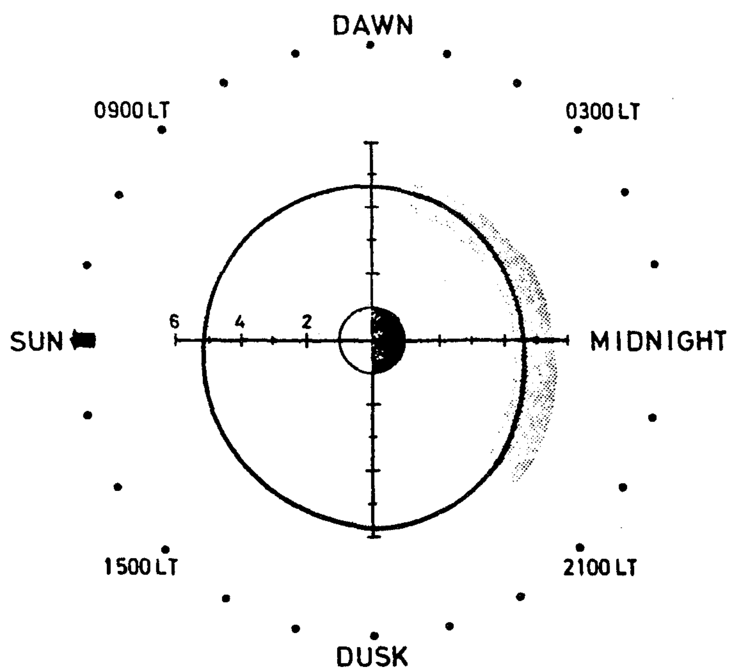

Figure 1. Plasmapause location for $K_p = 1$.

With the criteria for the limit of a planetary ionosphere in terms of the corotation and convection electric field in mind, we can try to estimate the extent of the ionospheres of the other magnetic planets. A comparison of Earth and Jupiter was first made by Brice and

Ioannides (1970). A useful parameter is the ratio of E_{rot}/E_{conv}. It can be shown that the approximation

$$E_{conv} \approx \frac{kV}{R_0} \tag{5}$$

holds approximately for the magnetic planets Earth, Jupiter, and Mars. In figure 2, log (E_{rot}/E_{conv}) is plotted for Earth, Jupiter, and Mars, whose corresponding magnetic moments are $M_E = 8.07 \times 10^{25}$ G cm³, $M_J = 1.31 \times 10^{30}$ G cm³, and $M_M = 2.47 \times 10^{22}$ G cm³ (Dolginov, 1975).

It is apparent that the three magnetic planets represent completely different regimes of behavior of E_{conv} and E_{rot}. For Jupiter, $E_{rot} \gg E_{conv}$ throughout the magnetosphere ($<50\ R_J$). Thus, the thermal plasma should be controlled by corotation, that is, the ionosphere could extend to the magnetopause unless other processes limit its extent at closer distances. For Earth, $E_{rot} = E_{conv}$ at $\sim 5.8\ R_E$, that is, we have a distinct plasmapause within the magnetosphere ($\leqslant 10\ R_E$) with a corotating ionosphere. For Mars, on the other hand, the entire magnetosphere/ionosphere region is dominated by E_{conv}.

Mercury is not included because, according to observations on Mariner-10, it does not possess an observable ionosphere ($N < 10^3$ cm^{-3}). This is consistent with the air-glow observations of upper limits for the total content of possible constituents (He, Ar) $N_T \lesssim 10^{+14}$ cm^{-2} (Broadfoot et al., 1974), that is, corresponding to an exosphere. In such a case an ionosphere cannot form since this requires an optical depth $\tau = 1$ which corresponds to the condition that $N_T = (\sigma_a)^{-1}$. Since typical absorption cross sections are of the order $\sigma_a \approx 10^{-18}$ cm^{+2} so that ionizing radiation will penetrate unattenuated to the planetary surface and thus, similar to the Moon, an ion-exosphere associated with a surface photoelectron layer may form.

Figure 3 shows a comparison of the field line pattern delineating the corotating and convective regions for cold plasma for Earth and Jupiter according to Brice and Ioannides (1970) and figure 4 shows a sketch for the convective regime on Mars according to Bauer and Hartle (1973). Accordingly, convective motions can penetrate deeply into the Martian ionosphere until they are inhibited by other processes. The Martian ionosphere is now generally agreed to be a photochemical equilibrium F_1 layer with an ionization maximum at $h_m \approx 140$ km. Radio occultation observations show within their limit of sensitivity that the ionosphere extends to at least ~300 km. We can estimate the depth to which convective motions can penetrate into this ionosphere, which is coupled to the corotating neutral atmosphere by virtue of photochemical processes, by considering the equation of continuity

$$\nabla \cdot (N\vec{v}) = \frac{\partial(Nv)}{\partial s} = q - L \tag{6}$$

where $\vec{v}$ is the drift velocity induced by the solar-wind interaction, that is, $|\vec{v}| = |(\vec{E}_{conv} \times \vec{B})/B^2| \approx E_{conv}/B$, s is the path length, and q and L are the ion production and loss rates,

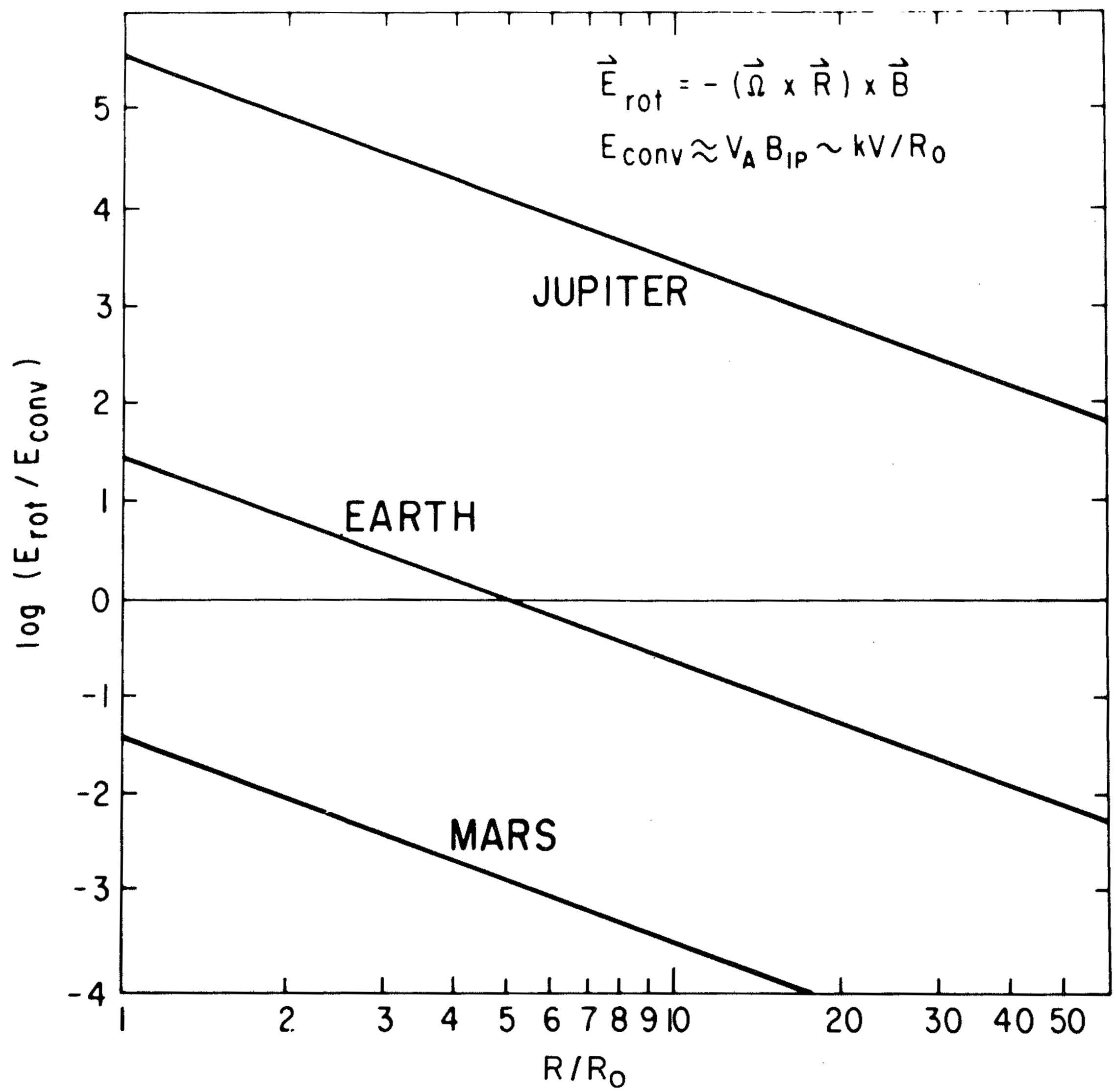

Figure 2. Corotation and convection regimes for magnetic planets.

respectively. The importance of the different processes in equation 6 can be estimated from the appropriate time constants. The chemical time constant is given by

$$\tau_c = \frac{1}{\alpha N} \tag{7}$$

where α is the dissociative recombination coefficient for the major ions O_2^+ and CO_2^+ while the time constant for mass transport is given by

$$\tau_v = \frac{L}{v} \tag{8}$$

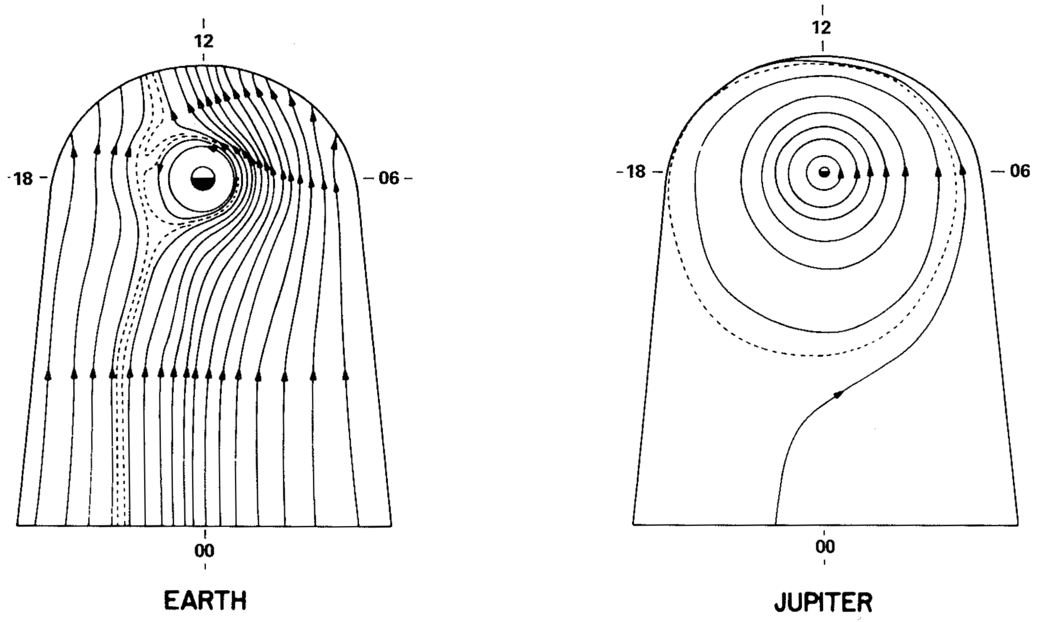

Figure 3. Corotating and convective regions in the magnetospheres of Earth and Jupiter (from Brice and Ioannides, 1970).

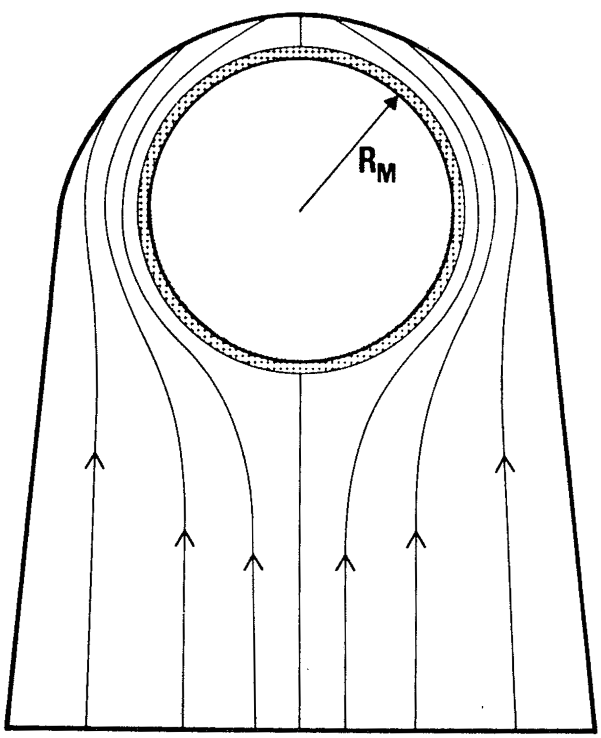

Figure 4. Convective regime of the Martian magnetosphere (from Bauer and Hartle, 1973).

where L is the scale length of interaction of convective motion with the ionosphere. Corotation of the ionosphere should cease where

$$\tau_v \cong \tau_c \tag{9}$$

leading to the condition

$$N \lesssim \frac{v}{\alpha} R_M \tag{10}$$

if we consider that the scale length of interaction, L, at the terminator is of the order of a planetary radius, R_M. For appropriate numerical values we can infer from equation 10 that the upper boundary of the Martian ionosphere (chemopause) may lie in the 300- to 350-km altitude range. The detailed magnetospheric convection system on Mars will undoubtedly be more complex (primarily due to the large Pedersen conductivity) because of the small surface magnetic field (Rassbach et al., 1974), but the above simple considerations should provide a useful guide in estimating the extent of the Martian ionosphere, if the convection-dominated regime should apply in this weak Martian magnetosphere.

NONMAGNETIC PLANETS (VENUS)

The Mariner-5 flyby mission in 1967 provided the first experimental evidence for a direct interaction of the solar wind with the ionosphere of Venus. The dayside electron-density profile obtained with the two-frequency radio occultation experiment indicated a rather abrupt decrease of plasma density at ~500 km, which was taken as an indication of the boundary between the solar wind and the ionosphere and was called the ionopause or anemopause because of the absence of a significant planetary magnetic field. The nightside ionosphere, although of lower concentration, seemed to fall off very slowly with altitude (figure 5).

Considering the dayside and nightside occultation points, the following schematic picture of the Mariner-5 Venus ionosphere emerges if the ionopause is interpreted as the surface where the solar-wind streaming pressure and the ionosphere plasma pressure balance each other according to Spreiter et al. (1970).

$$p_{st} \cos^2 \psi = p_0 \exp\left[\frac{r_0}{H}\left(\frac{1}{r} - \frac{1}{r_0}\right)\right] \tag{11}$$

where

p_{st} = the solar-wind pressure at the stagnation point, $(Nmv^2)_{sw}$ in terms of the solar-wind number density (N), the proton mass (m), and the solar-wind speed (v),

ψ = the solar-wind aspect angle,

p_0 = $N k(T_e + T_i)$, the ionospheric plasma pressure with N the plasma density and T_e and T_i the electron and ion temperatures, respectively,

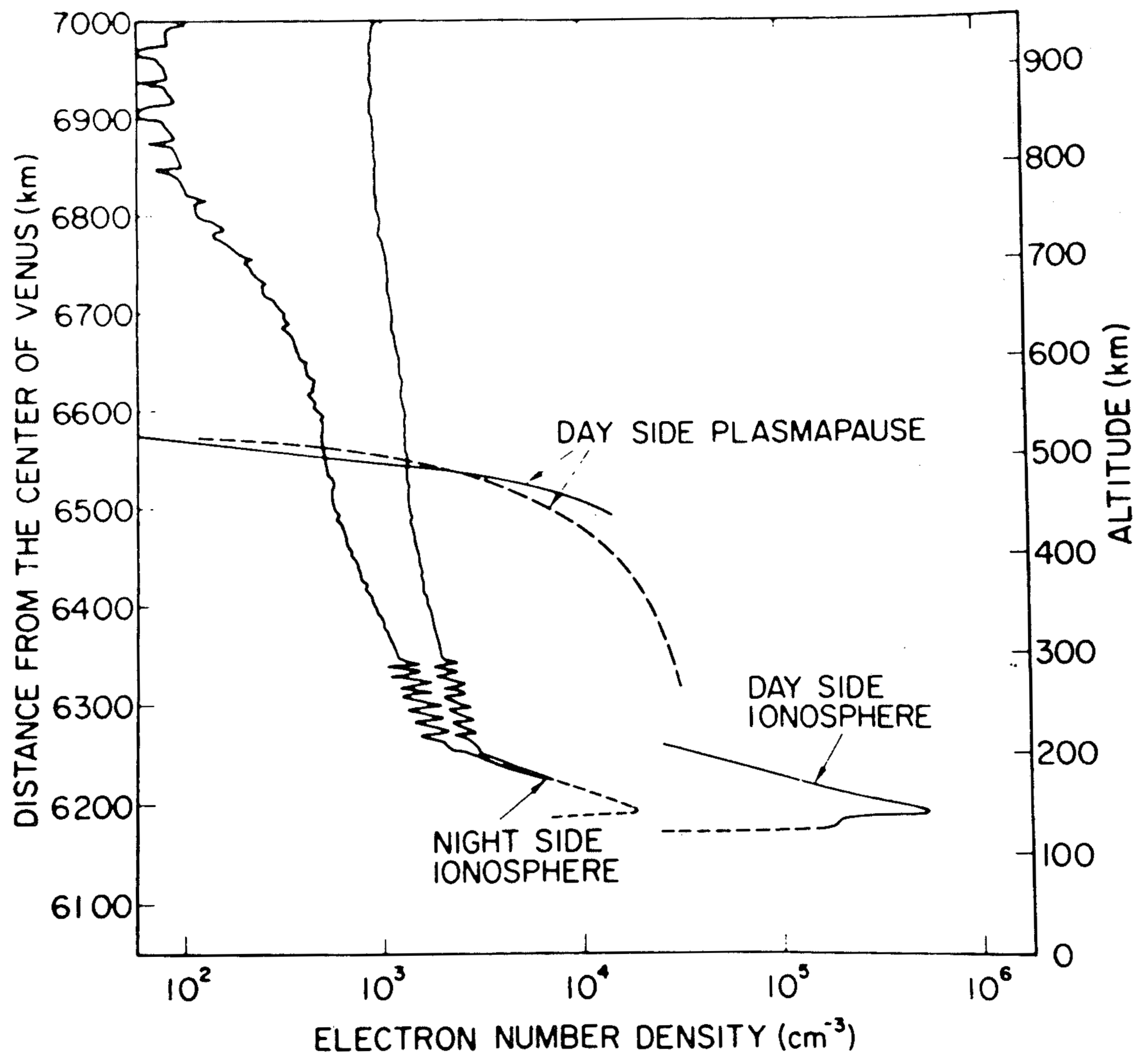

Figure 5. Mariner-5 profiles of the Venus ionosphere.

r_0 = the planetocentric distance of the obstacle (ionopause), and

$H = k\,(T_e + T_i)/mg$, the ionospheric plasma scale height.

This configuration is appropriate for conditions during the Mariner-5 flyby showing the pertinent ionospheric and solar-wind parameters (figure 6).

With the Mariner-10 flyby, another snapshot of the Venus ionosphere became possible. The dayside and nightside ionosphere was again observed with the radio occultation experiment (figure 7). This dayside ionosphere exhibits features which can best be explained in terms of a dynamic interaction with the solar wind, that is, a compression of the topside ionosphere by the solar wind (Bauer and Hartle, 1974), similar to the one first proposed for Mars

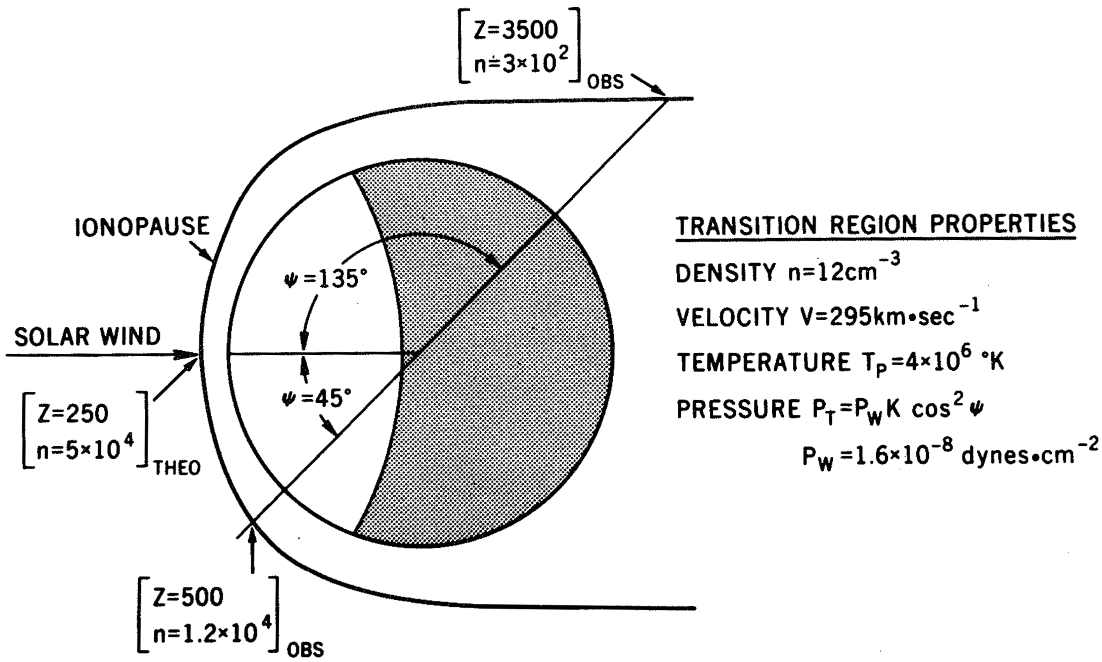

Figure 6. Venus ionopause configuration.

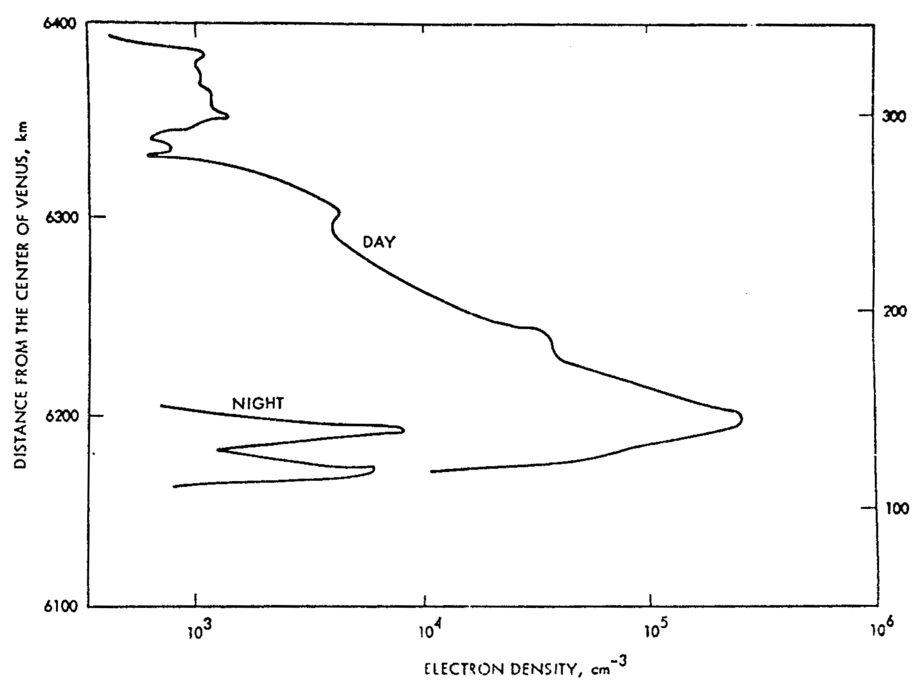

Figure 7. Dayside and nightside electron number density from Mariner-10 open loop differential S- and X-band measurements.

(Cloutier et al., 1969) (figure 8). Accordingly, momentum transfer from the solar wind to the ionosphere is inferred, causing a downward transport (and compression) of the ionospheric plasma with a solar-wind-initiated transport velocity of about 100 m/s. In addition to the ionospheric measurements, the Mariner-10 magnetic field and solar-wind plasma experiments have unequivocally determined the presence of a bow shock around Venus (Bridge et al., 1974; Ness et al., 1974). Earlier observations on Mariner-5 and also the USSR Venera-4 and -6 probes already showed evidence of such a bow shock, although none of these observations provides any details of the actual solar-wind interaction, that is, the nature of the obstacle. The bow-shock observations of these earlier spacecraft experiments are summarized, together with magnetic field measurements on Mariner-10, in figure 9. The obstacle parameter H/r_0 for Mariner-5 seems to have been larger (0.25) than the one for Mariner-10 (H/r_0 = 0.01) which is, however, consistent with the different ionospheric distributions (Bauer and Hartle, 1974).

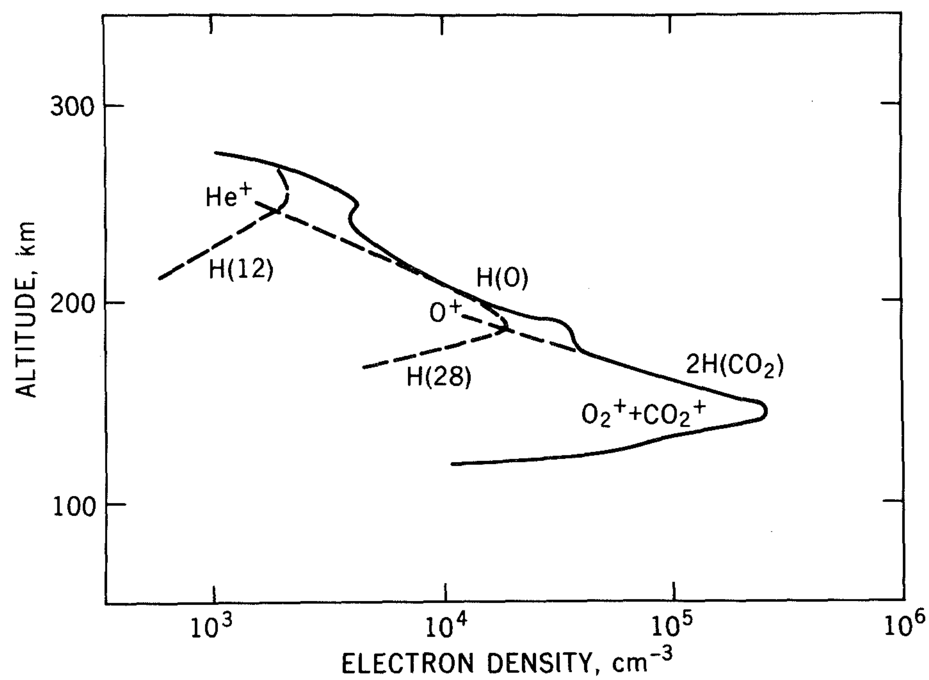

Figure 8. Model ionosphere to explain Mariner-10 data.

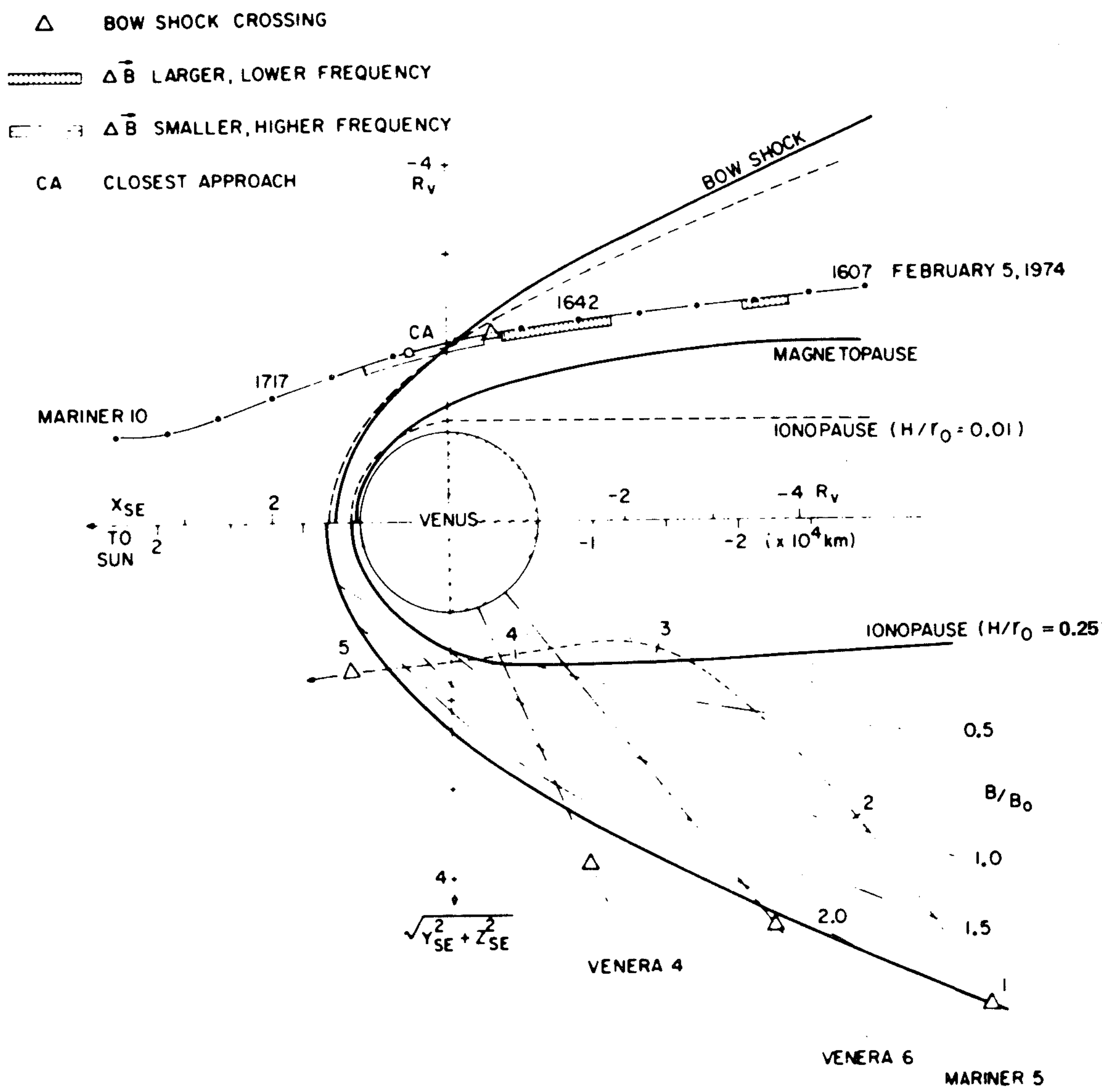

Figure 9. Comparison of bow-shock observations around Venus (from Ness et al., 1974).

Except for the fact that the ionosphere represents the obstacle to the solar wind, the details of the interaction with the Venus ionosphere is still a matter of debate. There are basically three types of possible interactions with a planetary ionosphere (Michel, 1971a) shown in figure 10:

1. Direct Interaction. In this case, inflowing postshock solar-wind plasma depresses the ionosphere until a transition occurs from plasma flow to chemical control (Cloutier et al., 1969; Bauer and Hartle, 1974). Because of mass-loading of the solar wind by the ionospheric plasma (Michel, 1971b) a bow shock is formed.

2. Tangential Discontinuity. Since magnetized plasmas are immiscible, the solar-wind plasma with its frozen-in interplanetary field can be considered as running into the ionospheric plasma which represents the obstacle that causes the formation of a standing bow shock (Dessler, 1968; Spreiter et al., 1970; Bauer et al., 1970). In this case there is a pressure balance between the solar-wind streaming pressure and the ionospheric plasma pressure. The ionospheric plasma (containing possibly a small intrinsic magnetic field) provides a virtually impenetrable surface at the ionopause. Below it, the ionosphere is essentially unperturbed; above it, the solar wind flows tangentially to the surface. At the ionopause the horizontal flow velocity and the horizontal magnetic field change abruptly, causing a tangential discontinuity.

3. Magnetic Barrier. Because of its difficulty in penetrating a conducting ionosphere, the solar wind, in trying to convect field lines into the ionopause, will cause them to accumulate, forming an induced magnetopause. Viewed differently, the $-\vec{v} \times \vec{B}$ electric field of the solar plasma in the planetary rest-frame drives ionospheric currents that generate a magnetic field barrier between the ionosphere and the solar wind. This model was first suggested by Johnson and Midgley (1968). More recently it has been treated in some detail by Cloutier and Daniell (1973). In this model, the solar-wind pressure is balanced by the magnetic pressure of the induced magnetic field.

The integrated ionospheric current density required to cancel the shock-compressed interplanetary field has been calculated by Cloutier and Daniell (1973), with appropriate assumptions regarding ionospheric conductivities to be of the order of 10^{-2} to 10^{-1} amps/m. This model requires a magnetic field reversal as one moves through the ionopause.

Although the detailed understanding of the solar-wind interaction with Venus is still lacking, the fact that the Venus ionosphere represents the obstacle to the solar wind is firmly established. It may well be that most of the processes envisioned in the different models are in fact operating in the actual interaction between the solar wind and the Venus ionosphere.

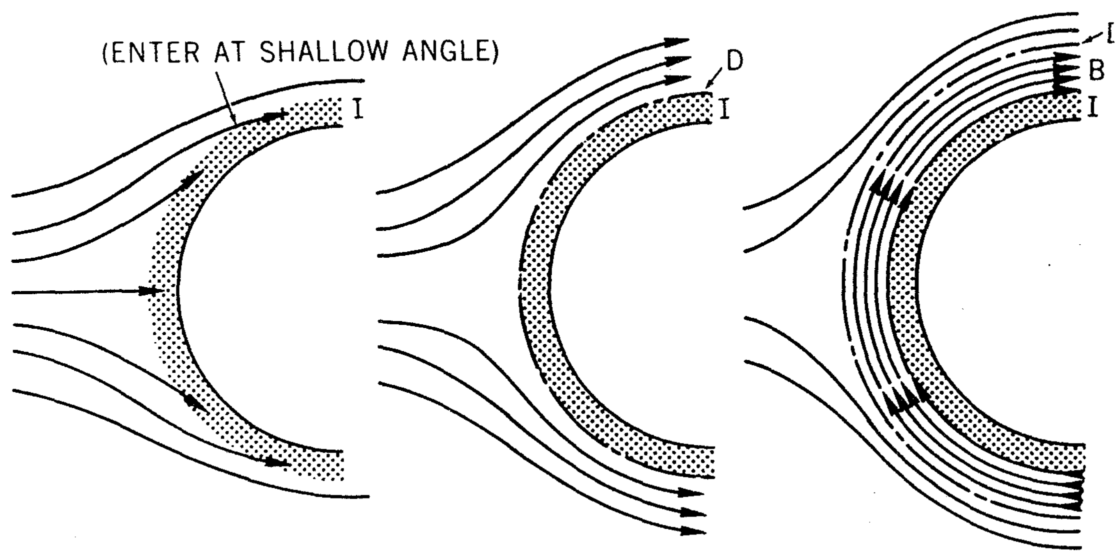

Figure 10. Three types of solar-wind interactions with Venus (from Michel, 1971a).

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QUESTIONS

Bauer/Vaisberg: As far as I understand, you can modify the ionospheric profiles either by a downward drift or by the removal of ions from the topside ionosphere. Do you think it is possible to explain the profile by lateral plasma drift caused by solar-wind drag?

Bauer: Yes I do. But it would be very difficult to argue this point from the one profile available. When a more complete latitude variation of electron density on Venus is known, it will definitely be possible to distinguish and evaluate this possibility.

Bauer/Cloutier: The convection rates may be much different on the day and nightsides of Mars due to the differences of ionospheric conductivities if Mars possesses a magnetic dipole of the strength reported by Dolginov. On the dayside, the ionospheric conductivity limits the convection rates to very small value but on the nightside, the rates may be much higher. The secondary ion peak on Venus above the F peak may be due to charge exchange if solar wind H^+ interacts with O_2 or CO_2 and thus this does not require a large O^+ concentration.

Bauer: From some earlier calculations of the nightside ionosphere of Venus, I believe the charge exchange of H^+ with CO_2 falls short in explaining the secondary ion peak in the Venus ionosphere.

Bauer/Dessler: It is commonly agreed that for the case of the Earth, the convection speed is controlled by dayside magnetic merging between interplanetary and terrestrial magnetic fields. The dayside conductivity of the ionosphere of Mars is approximately 10^3 times better than that of the Earth. Therefore, convection of the Martian magnetosphere is 10^3 times slower than convection in the terrestrial magnetosphere (see Rassbach et al., 1974).

Bauer: I believe that an enhancement factor of 10^3 for the ionospheric conductivity of Mars relative to that of the Earth is perhaps one order of magnitude too high. However, the larger ionospheric conductivity will obviously affect the magnetospheric convection. But the actual consequences depend on just how large the conductivity of the Martian ionosphere is.

Bauer/Bridge: In view of the low frequencies used for the Mariner-5 radio propagation measurements on the nightside ionosphere of Venus and the known problems in interpreting the data, that is, multipath and caustics, do you think there is any evidence for an extended ionospheric tail? Or should one believe the Mariner-10 results which are less sensitive but show no evidence for an extended nighttime ionosphere?

Bauer: It is true that the Mariner-5 data interpretations suffer from uniqueness problems because of their lower frequency. But at the same time their sensitivity is higher. Mariner-10 data and microwave frequencies are easier to interpret but the lower limit for the electron density is not as sensitive and thus the Mariner-10 nighttime profile does not rule out a nighttime tail.