Mars in the Solar Wind

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The basic interaction between Mars and the solar wind is reexamined by using recent spacecraft observations and model calculations. It is found that the particle pressure is not large enough to stand off the solar wind unless the electron temperature is 4 times the ion temperature in the ionosphere. However, the additional pressure is presumably magnetic provided by a planetary magnetic field, although an induced field cannot be excluded. A planetary field corresponding to a surface field of ~20 gammas and a dipole moment of $\sim 8 \times 10^{21}$ gauss cm^3 (0.01% of the earth's dipole moment) are implied. On the basis of our calculation, 60–70% of the pressure is supplied by the magnetic field, and the remaining 30–40% by the ionosphere. This suggests that the interaction of Mars in the solar wind is unique in that it is both atmospheric (i.e., Venuslike) and magnetospheric (i.e., similar to that at earth and Jupiter). Which mode of interaction is dominant is likely to depend on the external solar wind, the magnetic field interaction and the atmospheric interaction being characteristic of quiet and disturbed conditions, respectively. The implications of an earthlike interaction are reexamined by using magnetospheric scaling laws, and it is found that plasma convection may play a major role in the Martian magnetosphere and ionosphere and that the auroral oval may extend to low latitudes. The implications of a Venuslike interaction are also examined, in particular the heating and removal of atmospheric ions as a result of the direct interaction between the solar wind plasma and the ionosphere. The existence of a planetary field also implies that Mars has a liquid rather than a frozen core.

1. INTRODUCTION

The solar wind interaction at Mars not only is of scientific importance in its own right but may have significance for the evolution of the Mars atmosphere [*McElroy et al.*, 1977]. It is apparent that the interaction is presently affecting the properties of the Mars atmosphere as measured by Viking [*Chen et al.*, 1978]. In addition, a knowledge of this interaction can also provide insight into other aspects of the planetology such as the likelihood of the existence of a liquid core.

The purpose of this paper is to discuss the nature of the solar wind interaction at Mars and to present new evidence based on Viking data, recent theoretical calculations, Pioneer Venue orbiter and Mars 2, 3, and 5 observations. We find that the solar wind interaction at Mars is unique, being an interaction both with the atmosphere and with the planetary magnetic field. This type of interaction was suggested by *Vaisberg* [1976] on the basis of Mars 2, 3, and 5 measurements. Our analyses imply that solar wind conditions can even drive the interaction, thereby making one of them dominant.

To date, two different types of interactions between the solar wind and a planet have been observed: (1) the solar wind interaction with a planetary magnetic field and (2) the solar wind interaction with the planetary atmosphere/ionosphere.

Figure 1 is a schematic illustrating the solar wind interaction with a planetary field such as, in this figure, the earth's dipole field. Figure 1 shows the solar wind, the supersonic rarefied gas interacting at the magnetopause with the earth's dipole field, so that there is no direct interaction with the atmosphere of the earth, which is located very close to the surface of the planet and hence deep inside the magnetosphere. Since the solar wind is supersonic, a bow shock is formed upstream of the magnetopause. In the magnetosheath the postshock solar wind plasma is heated and compressed and flows downstream around the large magnetic obstacle (the magnetosphere) and its associated tail.

In contrast, Figure 2 depicts the solar wind interaction with the ionosphere/atmosphere at Venus, where a relatively small obstacle is formed, the solar wind interacts directly at the ionopause with the ionosphere/atmosphere of the planet, a bow shock is formed upstream, and the postshock heated and compressed solar wind flows past the planet in the ionosheath. There are perhaps other structures or regions formed in association with this interaction, but the definition and nature of these are not known at this time. There is also the possibility [*Bauer et al.*, 1977] that the solar wind interaction at Venus leads to the heating of the atmosphere and other phenomena such as the mass loading of field lines. It is anticipated that these and many other issues will be resolved by the complement of experiments on the Pioneer Venus orbiters.

At Mars either a Venuslike interaction or an earthlike interaction might apply. It is unknown at this time which type of interaction at Mars is correct. In this paper therefore we will investigate the implications of an earthlike interaction or a Venuslike interaction at Mars. In the next section of this paper we perform some pressure balance calculations to emphasize the similarity and differences in the basic solar wind interaction at earth, Venus, and Mars.

2. PRESSURE CALCULATION

In the interaction of the earth's magnetosphere with the solar wind the earth's dipole field supplies sufficient magnetic pressure at the magnetopause to balance (or stand off) the external pressure of the shocked solar wind. The convective pressure of the preshocked solar wind at the earth's orbit is $P_{SW} = 130 \times 10^{-10}$ dyn/cm^2. Since the solar wind is both slowed and deflected across the bow shock, the typical stagnation pressure (P_{ST}) at a solar zenith angle of $\psi = 45°$ is a factor of 2.5 smaller. At earth therefore while a magnetic field strength of 55 γ is needed near the nose of the magnetopause

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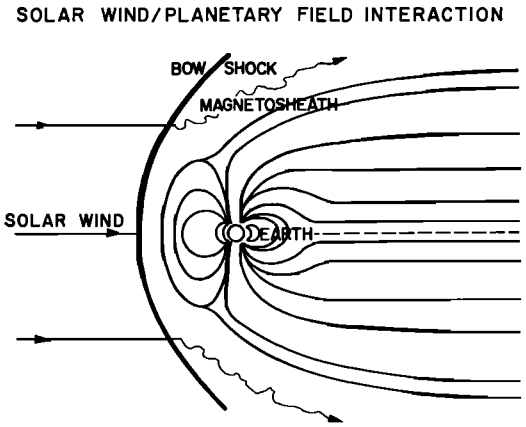

Fig. 1. Solar wind/planetary magnetic field interaction at earth.

to stand off the shocked solar wind, a magnetic field strength of only 35 γ is needed at a solar zenith angle (SZA) of 45° [*Mead and Fairfield,* 1975; *Smith et al.,* 1978]. The first column in Table 1 summarizes the pressure balance calculation at earth.

We can extrapolate this calculation to the orbits of Venus and Mars to determine the stagnation pressures needed at these planets to stand off the shocked solar wind. These calculations are also summarized in Table 1, where columns 2 and 3, respectively, refer to these quantities for Venus and Mars.

A calculation of fundamental importance to ascertain the validity of the solar wind atmospheric/ionospheric interaction model at Venus is to test whether or not the atmospheric/ionospheric ion and electron thermal pressure is sufficient to stand off the solar wind and interplanetary magnetic field pressure. The typical stagnation pressure at Venus for a SZA of 45°, as scaled from the typical values at the earth's orbit, is 100×10^{-10} dyn/cm^2 (the first entry in column 2). By using the values of the ionospheric ion density and the ion temperature reported by *Knudsen et al.* [1979] as summarized the second entry in column 2, it is found that the pressure available from atmospheric ions is $\sim 30 \times 10^{-10}$ dyn/cm^2. Similarly, by assuming that $N_E \simeq N_I$ and using the in situ electron temperatures measured on the Pioneer Venus orbiter [*Knudsen et al.,* 1979], the pressure available from atmospheric electrons is 80×10^{-10} dyn/cm^2 (the third entry in column 2). Therefore the total atmospheric pressure available at Venus ($P_{ATM} = P_E + P_I$) is $\sim 110 \times 10^{-10}$ dyn/cm^2 and is sufficient to stand off the solar wind. This implied primarily nonmagnetic planetary solar wind interaction is consistent with the recent Pioneer Venus magnetic field measurements [*Russell et al.,* 1979*a, b*] and unlike the interaction at earth.

Similarly, a calculation of correspondingly fundamental importance at Mars is whether the atmospheric/ionospheric particle pressure available at Mars is sufficient to stand off the solar wind. Scaling again from our stagnation pressure calculation at earth, we find that the typical stagnation pressure needed to stand off the solar wind at a SZA of 45° at Mars is $\sim 25 \times 10^{-10}$ dyn/cm^2, as shown in the first entry in column 3.

Using the recent Viking 1 and 2 lander data and recent theoretical models, we can calculate the pressure available from the particles in the outer atmosphere/ionosphere at Mars. *Chen et al.* [1978] constructed a theoretical model of the Martian ionosphere based on the Viking 1 and 2 lander data of *Hanson et al.* [1977]. (The Viking 1 and 2 lander data were both obtained at an SZA of 44°.)

The *Chen et al.* [1978] model, which is discussed in more detail in section 6, can be used to provide us with estimates for the ion and electron number densities and temperatures in the upper ionosphere of Mars. The theoretical curves in this model extend up to an altitude of 360 km (see Figure 8). At this height the curves are essentially vertical, so that we can assume that the ion temperatures and number densities above this height have the same values as those at 360 km. Therefore using the best fit theoretical model of *Chen et al.* [1978] with $N_I = 10^3$/cm^3 and $T_I = 3 \times 10^3$ °K, we obtain a pressure associated with atmospheric ions of $P_I = 5 \times 10^{-10}$ dyn/cm^2 (the second entry in column 3). Assuming that $N_E = N_I$ and $T_E = T_I$ [*Chen et al.,* 1978], we obtain a similar pressure associated with atmospheric electrons: $P_E = 5 \times 10^{-10}$ dyn/cm^2, as indicated in the third entry in column 3.

The total atmospheric pressure available to stand off the solar wind at Mars is shown in the fourth entry in column 3. While there is some uncertainty in the validity of this assumption concerning the electron temperature, for our purposes it is adequate, since even if the electron temperature were much higher (e.g., $T_E \simeq 2.5T_I$), the total atmospheric pressure available at 400 km would not be enough to stand off the solar wind.

It is evident that an additional pressure contribution is needed to balance the external solar wind pressure. The additional pressure required to stand off the solar wind is shown in the fifth entry in column 3, where we indicate the magnetic field pressure contribution that could be implied. If this additional pressure contribution were, in fact, due to a magnetic field, there are several possible origins of the field. There could be an instrinsic planetary magnetic field or an induced field or a pileup of the interplanetary magnetic field lines associated with the solar wind. Irrespective of the origin of the inferred magnetic field, the calculations in Table 1 indicate that the probable pressure contribution from the field is larger than the total pressure contribution of the atmospheric ions and electrons. Therefore the pressure calculation discussed above implies that the solar wind interaction at Mars is both atmospheric/ionospheric and magnetic. This result indicates that the solar wind interaction at Mars is unique in this respect, being intermediate between Venus and earth.

We must conclude therefore that while the atmospheric/ionospheric thermal pressure is significant at Mars, unlike the case of Venus, where the thermal pressure is large enough to balance the external pressure, at Mars it appears that a magnetic field pressure is also needed to stand off the solar wind. If this magnetic field pressure is due to an intrinsic planetary field, then we can estimate the magnetic moment of Mars (M_M), the surface field (B_S), and the field at the stagnation

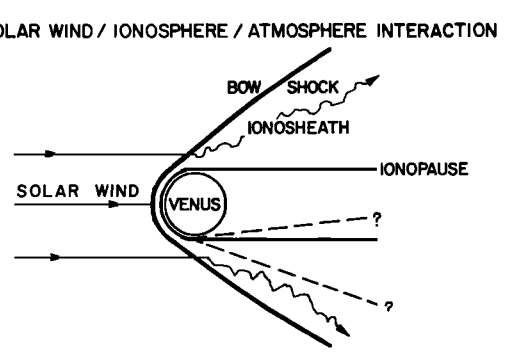

Fig. 2. Solar wind/ionosphere/atmosphere interaction at Venus.

TABLE 1. Pressure Calculation

Parameter	1 Earth Pressure, $\times 10^{-10}$ dyn/cm^2	2 Venus Pressure, $\times 10^{-10}$ dyn/cm^2	3 Mars Pressure, $\times 10^{-10}$ dyn/cm^2
$P_{\text{Stagnation}}$ at SZA 45°	50	100	25
Pressure available from atmospheric ions $P_I = N_I K T_I$	...	30	5
Pressure available from atmospheric electrons $P_E = N_E K T_E$, $N_E = N_I$	...	80	5
Total atmospheric Pressure available $P_{\text{ATM}} = P_E + P_I$	...	110	10
Magnetic pressure required	50	...	15

point (B_{MP}). In the next section of this paper we will discuss the magnetic moment of Mars.

3. THE MAGNETIC DIPOLE MOMENT OF MARS

The pressure balance calculation leads to an estimate for the magnetic field strength at the stagnation point. A more appropriate parameter that characterizes the planetary field and governs the interaction of Mars with the solar wind is the magnetic dipole moment, which is a measure of source strength. The dipole moment can be obtained from the field strength at the magnetopause provided the distance of the magnetopause from the surface or center of Mars if known. This location cannot be derived from the pressure balance calculation; inspection of the Viking ionospheric measurements and the theoretical models merely suggests that the magnetopause is at altitudes in excess of 360 km.

To find the location of the magnetopause at the subsolar point requires an additional piece of information. Since there have been few, if any, legitimate magnetopause crossings, even at local times well away from noon, we infer the location of the magnetopause from observations of the Martian bow shock. Such a procedure involves some uncertainty in establishing the average shock location and in inferring the corresponding magnetopause location.

The available information derived from space observations and attempts at scaling them is summarized in Table 2. The table is organized in terms of descending magnitudes of M_M. The following discussion is a brief summary of the chronological order in which the estimates were derived. The earliest estimates of $M_M/M_E = 3 \times 10^{-4}$ and then 10^{-4} (see Figure 3) were based on penetration of the bow shock by Mariner 4 [*Smith et al.*, 1965; *Smith*, 1967, 1969]. An independent theoretical modeling of the shock location led to a slightly reduced value of M_M [*Dryer and Heckman*, 1967].

When Russian magnetometer data became available, they led to the identification of more bow shock crossings as well as to the claim of a direct observation of the planetary field which implied $M_M = 2.4 \times 10^{22}$ gauss cm^3 [*Dolginov et al.*, 1973]. However, a controversy then developed among the Russians as to the proper location of the bow shock as based on plasma measurements [*Gringauz et al.*, 1976; *Vaisberg*, 1976]. In particular, Vaisberg claimed that the average bow shock location was somewhat nearer Mars, which, if correct, would result in a smaller M_M. The nature of the differences can be viewed in terms of the respective estimates of the distances to the bow shock and magnetopause at the subsolar point.

Dolginov et al. infer a bow shock altitude of 3400 km, whereas Vaisberg favors an altitude of 1600 km. The latter estimate has received support from *Russell* [1977] on the basis of fitting ellipses to the bow shocks of Mercury, Venus, earth, and Mars. Russell's best fit bow shock to Gringauz's data is consistent with the Vaisberg altitude.

It is customary to scale the radial distances of the subsolar bow shock and magnetopause of a planet in the ratio 4/3, a scaling that is supported by hydromagnetic models of the solar wind interaction with Mars [*Spreiter and Rizzi*, 1972]. Such a scaling when applied to the two above bow shock locations yields an altitude for the magnetopause that lies between 1700 (Gringauz) and 400 km (Vaisberg and Russell).

Table 2 also contains a significantly lower estimate for M_M made by *Russell* [1978*a*, *b*], who has demonstrated a nonuniqueness in the claim by Dolginov that the planetary magnetic field has been observed inside Mars' magnetosphere. Russell, furthermore, questioned whether a planetary field exists at all.

Our present view of this recent history is that *Dolginov et al.* [1973] have derived an M_M that is too large. They carried out a spherical harmonic analysis of magnetic field measurements near the magnetopause while ignoring the compression of the field by the solar wind. In the initial modeling of the bow shock, Gringauz favored models which led to a large distance of the shock from the planet and were thus consistent with the large value of M_M inferred by Dolginov. However, Russell has shown that the bow shock data are more consistent with a close shock model, which in turn is consistent with the original Mariner 4 models. We adopt this second interpretation. Although, as will now be shown, we infer a smaller value of

TABLE 2. Martian Planetary Field Estimates

M_M, gauss cm^3	M_M/M_E	B_S, gamma	Reference
$\leq 2.4 \times 10^{22}$	$\leq 3 \times 10^{-4}$	64	*Smith et al.* [1965]
2.4×10^{22}	3×10^{-4}	64	*Dolginov et al.* [1973]
$\leq 1.7 \times 10^{22}$	$\leq 2 \times 10^{-4}$	45	*Dryer and Heckman* [1967]
9×10^{21}	1.1×10^{-4}	23	*Russell* [1977]
$\leq 8 \times 10^{21}$	$\leq 10^{-4}$	21	*Smith* [1967; 1969]; this paper
$\leq 2 \times 10^{21}$	$\leq 2.5 \times 10^{-5}$	5	*Russell* [1978*a*, *b*]

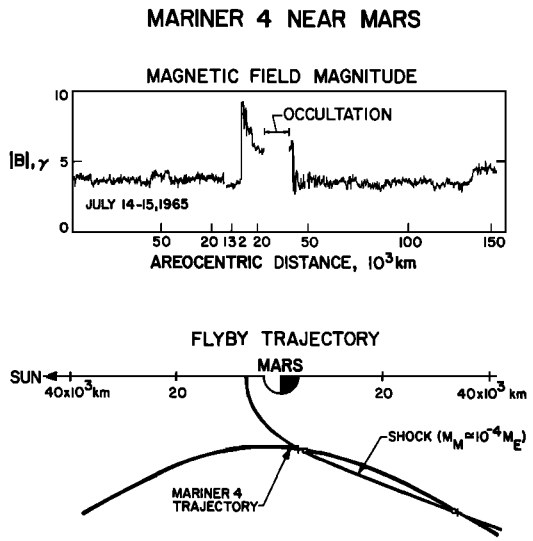

Fig. 3. (Top) Mariner 4 magnetic measurement near Mars. Approximately 16 hours data, centered about encounter, is shown with a gap occurring where Mars occulted the spacecraft as seen from earth. Areocentric distance is given in the upper legend with closest approach designated CA. The magnitude $|B|$ is shown; the two angles α and β give the direction of the field in solar-interplanetary coordinates. The two abrupt changes in |B| may be ingress and egress through a shock around Mars caused by the solar wind. (Bottom) Mariner 4 trajectory near Mars. The path followed by the spacecraft is shown in terms of the instantaneous sun-Mars-spacecraft angle and areocentric distance. In these cylindrical coordinates the shock, which is assumed to be a simple surface of revolution about the solar wind direction, reduces to the contour shown. The open circles of the trajectory designate the locations of the abrupt changes in |B| that appear in Figure 3 (top). A straight line through these two circles is essentially asymptotic to the shock around earth for a sun-earth-spacecraft angle between 0° and 90° scaled to correspond to $M_M = 10^{-4}M_E$. Owing to the motion of Mars around around the sun, there is a 4.5° aberration of the solar wind as shown.

M_M, corresponding to a ratio of 10^{-4}, our results are not consistent with an M_M as small as that suggested by *Russell* [1978*a*, *b*].

We can estimate the dipole moment by inferring the location of the magnetopause at a sun zenith angle of 45°. The bow shock distance at 45°, consistent with the Russell scaling of $R_{BS} = 3.0/(1 + \cos\psi)$, is 1.76 R_M (where R_M is Mars radii) at earth, the corresponding shock and magnetopause ellipses derived by *Holzer et al.* [1972] imply a ratio of $R_{BS}/R_{MP} = 1.47$ at $\psi = 45°$. Thus we infer $R_{MP}(45°) = 1.76/1.47 = 1.20$, corresponding to an altitude of 680 km.

The pressure balance calculation above implies that at that zenith angle, $B^2/8\pi = 15 \times 10^{-10}$ dyn/cm² or B = 20 γ. It is customary to attribute one half of the magnetopause field strength to the dipole field, implying that the Martian field is 10γ at 1.2 R_M and implying a SZA of 45°. This factor of 2, which assumes a plane magnetopause boundary, is slightly in error because of the more of less hemispherical confinement of the planetary field, *Spreiter* [1976] quotes a value of 2.2 to 2.4 as more correct; however, as we would not claim to estimate M_M to within 10 or 20%, we simply adopt the factor of 2 and the dipole field value of 10 γ.

The magnetic moment can now be calculated as $M_M = 10 \times 10^{-5}\ (1.20 \times 3380 \times 10^5)^3 = 8.1 \times 10^{21}$ gauss cm³. This moment is 10^{-4} times the dipole moment of the earth. This moment implies an equatorial surface field of 21 γ, which is comparable to the field strength at the magnetopause.

It is interesting to consider some of the implications of this moment for the subsolar magnetopause. The bow shock height of 5000 km, and a standoff ratio of $R_{BS}/R_{MP} = 4/3$ (the accepted value at the stagnation point corresponding to a gas constant of $\gamma = C_P/C_V = 5/3$), imply a magnetopause altitude of 420 km, i.e., essentially the value of 400 km inferred by Vaisberg. The dipole field strength associated with our magnetic moment is $8.1 \times 10^{21}/[(3380 + 420) \times 10^5]^3 = 14.8$. The magnetic pressure exerted by the field is then $\simeq (30)^2/8\pi = 35 \times 10^{-10}$ dyn/cm². Our scaling from the terrestrial magnetosphere implies that the average stagnation pressure at Mars is 60×10^{-10} dyn/cm². The difference between these two pressures is presumably supplied by the ionospheric plasma, i.e., 25×10^{-10} dyn/cm². Thus approximately two thirds of the pressure is provided by the field at both 0° and 45° SZA.

We recognize that our pressure balance calculations do not necessarily imply that the magnetic field is planetary. Instead, some type of induced field associated with the solar wind interaction could be responsible. For example, it was pointed out many years ago, in connection with the interaction of Venus with the solar wind, that the draping of field lines around a spherical plasma shell is susceptible to the interchange instability (R. Lüst, private communication, 1965). If such an instability is operative, the piled-up interplanetary field lines might work their way toward the surface by changing places with the ionospheric plasma. This process may be responsible for the recent observations by Pioneer Venus orbiter of flux ropes within the Venusian ionosphere [*Russell et al.*, 1979*a*]. It is conceivable that sufficient field is accumulated in this way to counteract the solar wind pressure. If an induced field model proves able to explain the needed magnetic field, the effect would be unlike any interaction about which we have knowledge at present and would be very interesting to study further.

Once the existence or absence of a planetary field is established beyond reasonable doubt, it will have important consequences for the interior of Mars. Recent estimates of the size of Mars' core have tended to be somewhat larger than was originally computed (for example, see *Jacobs* [1975] for a summary of various models). The spread in core sizes is 1400 ± 600 km, i.e., 0.4 ± 0.18 R_M. Of course, even a reasonably large core does not guarantee that Mars will have a planetary dynamo. For example, *Young and Schubert* [1974] have hypothesized that the Martian core has frozen owing to enhanced convection of the mantle. Thus the existence of an intrinsic field would contradict the Young and Schubert hypothesis and imply that the core is fluid.

4. Implications of an Earthlike Solar Wind Interaction

Figure 4 contains a summary of the stagnation field, the surface field, various parameters used to derive the magnetic moment, and the locations of the bow shock and magnetopause. The approximate scales of the bow shock and magnetopause are shown in relation to Mars, but their shapes are scaled from the average positions of these boundaries at earth.

The main qualitative feature to be noted is that Mars occupies a large fraction of its magnetosphere. By contrast, the average distance to the terrestrial magnetopause is 10 planetary radii, so that the earth lies well inside the magnetosphere. It is only on rare occasions, corresponding to extreme values of P_{SW}, that the magnetopause is pushed to within 5 R_E (earth radii). This point is demonstrated graphically in Figure

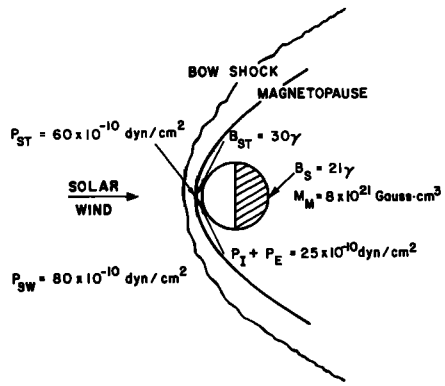

Fig. 4. Scaling of the bow shock and magnetopause at Mars. The upper half of the figure shows the relations used to determine (1) the magnetic field strength at the stagnation point, B_{ST}, (2) the distance to the magnetopause at an angle, ψ, between the solar wind direction and the radial to the point of observations of zero, $D_M(0)$, (3) the altitude of the magnetopause above Mars' surface, and (4) the distance to the bow shock at $\psi = 0$. The lower half of the figure shows the shock and magnetopause drawn to scale and various pressures, field strengths, and other parameters, derived from the scaling.

5, which is adapted from the work of *Siscoe* [1978]. Mars is shown transposed to the terrestrial magnetosphere and can be seen to occupy a very large volume of the magnetosphere.

This figure is shown principally to introduce several other features, in addition to the bow shock and magnetopause, of the earth's interaction with the solar wind. These features are associated with the process of convection, which basically controls the distribution of plasma within the magnetosphere.

Three distinct regions are shown. The dayside cusp contains shocked solar wind plasma, which is able to penetrate into the magnetosphere to relatively low altitudes at high latitude. The plasma sheet extends downstream to the earth and separates the magnetotail into two lobes containing stretched out magnetic fields. The plasmasphere corresponds to dipole field lines which are corotating with the earth and contain plasma which has diffused upward from the ionosphere. The inward extensions to the earth of the cusp and magnetotail plasma sheet coincide approximately with the location of the north and south auroral ovals. The auroral regions are the location of a strong interaction between the magnetosphere and ionosphere, which leads to the production of intense field-aligned currents, a horizontal electrojet, precipitation of energetic particles, etc.

Plasma convection is thought to arise as the result of a merging of oppositely directed planetary and interplanetary magnetic fields. As a consequence, planetary field lines at high latitude have one end connected to earth while the other is connected to the interplanetary field which continues to be swept downstream by the solar wind. The electric potential derived from the rate of change of magnetic flux in the merging region is imposed on the magnetosphere and drives various convective motions. Although direct observational evidence for magnetic merging is scant, this process, or a suitable equivalent, is needed to account for many of the most important features of the earth's magnetosphere.

If plasma convection is as important at Mars as it is at earth, it would be dangerous to ignore its possible effect on the Martian magnetosphere. However, the parameters involved in these phenomena depend on both the magnetic moment and the size of the magnetosphere relative to the planet. Fortunately, various scaling relations appropriate to an earthlike interaction have been developed in the last few years and applied principally to the outer planets. The most important of these relations are summarized in Figure 6, which also contains a schematic that illustrates the results of our calculations.

The convection electric field, E_{CV}, which scales with the magnitude of the interplanetary field (since $\mathbf{E} = \mathbf{V} \times \mathbf{B}$), as expressed in terms of planetary radii, is 300 V/R_M. In spite of being weaker the electric field can have a significantly greater effect on Mars than at earth. This conclusion can be substantiated by a comparison with the electric field E_{CR}, produced by the corotating planetary magnetic field. Thus $E_{CR} \leq 2\pi R_{MP} B_{MP}/T$, where T is the rotation period of Mars. Substituting the values derived above, $E_{CR} \leq (2\pi \times 3{,}800 \times 10^3 \times 30 \times 10^{-9})/(24.5 \times 3{,}600)$, or $E_{CR} \leq 8.1 \times 10^{-6}$ $V/M \cong 28$ V/R_M.

It must be concluded that convection electric fields are potentially much stronger than corotation electric fields throughout the magnetosphere of Mars, as previously argued by *Bauer and Hartle* [1973]. It is customary to take the boundary of the plasmasphere, the plasmapause, as roughly the distance at which the corotation and convection electric fields are equal. Although a more careful calculation is required to obtain a precise limit, it is clear that any plasmasphere at Mars is likely to be very small and perhaps nonexistent.

The voltage across the Martian magnetosphere from dawn to dusk is approximately 1.0 kV, which is about a factor of 30 times smaller than that at earth. This parameter is a measure of the rate of merging of planetary and interplanetary fields and hence of the rate at which magnetic flux is being transferred into the magnetotail. That rate, the assumption of equilibrium conditions, and an estimate of the convection time or length of the tail, when combined with the dimensions of the magnetosphere, allow the field in the magnetic tail of Mars, B_T, to be estimated [*Kennel*, 1973]. The result as shown in Figure 5, corresponding to an average field in the earth's magnetotail of $B_T^* = 40$ γ, is the value of B_T in excess of 20 γ. This field is comparable to the field strength at the magnetopause, as is the case at earth.

This value of B_T is also comparable to the field strength at the surface of the planet, which implies that the Martian polar caps may cover most of the planet. An alternative way to state this consequence is to point out that the auroral zone on Mars

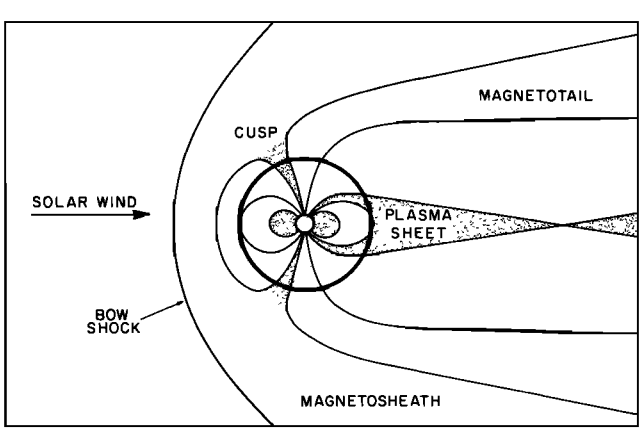

Fig. 5. The magnetosphere of earth compared to the equivalent size to Mars in its magnetosphere. The major plasma regions associated with the earth's magnetosphere are shaded. The bow shock, magnetosheath, and magnetopause are shown. The dark circle shows how much of the volume of the magnetosphere is occupied by Mars. This figure is adapted from a figure in the work of *Siscoe* [1978].

would be located at very low latitudes in comparison with the auroral zone on the earth. An estimate of the latitude of the auroral zone can be derived by simply identifying the auroral zone with the last closed field line which corresponds to the location of the magnetopause. As is shown in Figure 6, the approximate latitude is then given by $\cos \Lambda = 1/(D_M)^{1/2} = 1/(1.12)^{1/2}$ and is only 19°.

Two main points emerge from the foregoing analysis. First, even for an earthlike interaction, a strong interaction of the solar wind with Mars atmosphere can be expected. A large fraction of the Mars ionosphere may be involved in circulating convective motions. The 'polar' caps which could extend to mid-latitudes or lower may be accessible to a substantial flux of solar wind particles which have been energized in the magnetotail. Furthermore, strong winds are possible at high altitudes in the ionosphere. The open field lines are essentially equipotentials, and the convection electric field could be transferred to the ionosphere. Since the magnetic field is at most 10 times larger than the interplanetary field, say 40 γ as compared to 3.5 γ, convection speeds of up to one tenth of the solar wind speed are possible, i.e., speeds of $\simeq$40 km/s. This possible consequence has also been noted earlier by *Bauer and Hartle* [1973].

Second, the magnetosphere of Mars may be convection dominated and, in many respects, may be very unlike the magnetosphere of earth. The extent to which this is true and the extent to which plasma convection affects the atmosphere will depend on complex questions involving the electrical conductivity of the ionosphere and its influence on the magnetic merging rate. These implied differences between the Martian and terrestrial magnetospheres are sufficiently great to warrant careful reexamination of the extent to which the convection scaling laws actually apply to Mars. An initial step in this direction has been taken by *Rassbach et al.* [1974], who point out that frictional drag associated with ion-neutral collisions essentially 'ties' the ionospheric magnetic field to the field at lower altitudes and inhibits convection. They suggest that at Mars the rate of field line merging is dominated by ionospheric rather than interplanetary conditions and that this may lead to substantially reduced convection in the Martian ionosphere and magnetosphere.

Finally, it should also be noted that our calculations have been based on average solar wind conditions. When fast solar wind streams arrive at Mars, it is likely that the solar wind pressure will increase momentarily by as much as an order of magnitude. Under these circumstances, the available field pressure is totally inadequate to withstand the solar wind. It therefore seems likely that the solar wind will reach much nearer the surface until restrained by the pressure of the compressed ionosphere. The interaction should then be dominated by the atmosphere rather than by the planetary field, and the nature of the magnetoionosphere may be altered qualitatively from what it is during average or quiet solar conditions.

It would be possible in this article to discuss evidence in the available plasma and field data that supports an earthlike solar wind interaction at Mars. However, much of this material has been published recently in a series of articles in which *Russell* [1978*a*, *b*], *Dolginov* [1976], *Gringauz et al.* [1976], and *Vaisberg* [1976] have exchanged their views. The interested reader is referred to these more detailed treatments.

In summary, the major implications that result from a scaling of an earthlike interaction to Mars are as follows. The sunward magnetosphere would be very small, i.e., only slightly larger than the planet itself. The effects of plasma convection could be much more important than at earth with a much larger fraction of Mars magnetosphere participating in convective motions. The polar cap could cover most of the planet, which could imply, in turn, a strong interaction of the solar wind with the Martian atmosphere even if the planetary field is strong enough to hold off the average solar wind. The susceptibility of the magnetosphere to changing solar wind conditions can be expected to lead to a very dynamic interaction featuring major changes in the topology of the magnetosphere and in the mode of interaction during intervals of storms and substorms.

SCALING RELATIONS

$$E_{CV} = E^*_{CV}(B_{SW}/B^*_{SW}) = 300\ v/r_M$$

$$V = 3R_{MP}E_{CV} = 1.0\ kv$$

$$B_T = B^*_T(B_{SW}/B^*_{SW}) = 23\gamma$$

$$\Lambda = \cos^{-1}(1/\sqrt{R_{MP}}) = 19\ deg$$

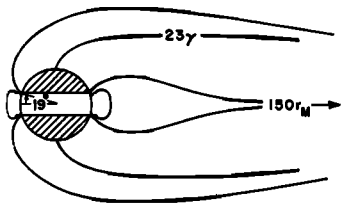

Fig. 6. Scaling of plasma convection relations at Mars. The upper half of the figure gives the scaling laws used to determine (1) the convection electric field E_C, (2) the voltage across the dawn-dusk magnetosphere, V, (3) the field strength in the magnetotail, B_T, and (4) the latitude of the polar cap/auroral zone, Λ. The parameter B_{SW} is the strength of the solar wind magnetic field. The magnetosphere, cusp, and tail are drawn to scale and labeled with representative values of a few selected parameters in the bottom half of the figure.

These consequences taken individually, or collectively, indicate that the interaction of Mars with the solar wind is likely to be unique in comparison with that of the other terrestrial planets. The interaction is likely to represent an extreme case when viewed in the context of the infant science of comparative magnetospheres.

5. Implications of a Venuslike Interaction

In this section we discuss the implications for Mars of a Venuslike interaction. Since we are not aware of any necessity for scaling the interaction at Venus, we will discuss the implications of this type of interaction in light of the recent Pioneer Venus and Venera observations. We will also make a direct comparison between these observations and observations at Mars.

In addition to the information on this interaction shown in Figure 2, the Pioneer Venus orbiter observations [*Wolfe et al.*, 1979] indicate the existence of a strong bow shock, of an ionosheath in which the postshock solar wind is deflected around the obstacle, and of a well-defined ionopause where the ionosheath ion flow field is first excluded.

The Pioneer Venus orbiter magnetic field observations [*Russell et al.*, 1979*b*] in the tail region are consistent with the

lack of a planetary magnetic field. As was discussed in section 2, the absence of a planetary magnetic field is consistent with our pressure balance calculation for Venus (see Table 1, column 2), where we found that the contribution of the ionospheric pressure was sufficient to stand off the external solar wind.

On the dayside the Pioneer Venus orbiter (PVO) magnetic field observations [*Russell et al.*, 1979*a*] show evidence of an increased magnetic field strength just outside the ionopause. This observation is consistent with the pileup of the interplanetary magnetic field, since inside the ionopause the field strength drops abruptly to zero, as one might anticipate if there were no large planetary magnetic field.

The features of the ionosheath plasma energy spectra are indicative of the thermalization of solar wind ions across the bow shock and the conversion of the solar wind streaming energy into particle heating. In the ionosphere there is an absence of measureable plasma in these energy ranges. The low-energy ion spectra (0 to 40 volts) of the PVO plasma analyzer, however, indicate the presence of nonflowing ions which appear to be impinging on the instrument from a direction along the ram velocity of the spacecraft. For example, when the ram speed was ~9.7 km/s, the peak in the spectrum at ~8 volts was consistent with an ion of mass 16, such as O^+. Additional peaks in the low-energy ion spectra are consistent with the presence of other prominent ions expected at this altitude (e.g., 310 km) in the Venus ionosphere.

The Pioneer Venus orbiter observations indicate [*Intriligator et al.*, 1979] that plasma ion flow velocities in the ionosheath near the downstream wake may, at times, be consistent with the deflection of plasma into the tail, the cavity downstream from Venus closing on some occasions as close to the planet as 5 Venus radii. This result is consistent with the Venera 9 and 10 measurements by *Vaisberg et al.* [1976] and with the work of *Perez de Tejada and Dryer* [1976].

As was discussed in section 3, Mariner 4 established the existence of a strong bow shock at Mars [*Smith et al.*, 1965], and the Mars 2, 3, and 5 further explored the solar wind interaction [*Dolginov*, 1976; *Gringauz et al.*, 1976; *Vaisberg*, 1976]. Figure 7 is adapted from *Vaisberg* [1976] and depicts the solar wind interaction at Mars on the basis of measurements of the near-Martian plasma performed on the Mars 2 and 3 spacecraft in 1971–1972 and on the Mars 5 spacecraft in 1974. One can easily ascertain the general similarity between the solar wind interaction at Mars shown in Figure 7 and the solar wind interaction at Venus shown in Figure 2. The mean position (I) and the individual crossings of the bow shock are shown. Also shown are different parts of the observed boundary layer that were identified: an external boundary layer (between II and IV) and an internal boundary layer with variable flux (between III and IV). *Vaisberg* [1976] has also reported the presence of light ions and heavier ions during the Mars 5 crossing of the nightside boundary layer at a distance of 6000 km from the sun-Mars axis. The presence of these ions downstream from the planet is consistent with some very recent observations of the PVO plasma analyzer which may indicate the presence of heavier ions in the ionosheath close to the inner boundary at a distance of 11–12 R_V downstream. These Mars 5 observations of heavier ions may also be consistent with the PVO observations (discussed above) of the presence of nonflowing heavier ions in the outer ionosphere. It is also tempting to speculate that the low-energy plasma fluxes [*Bogdanov and Vaisberg*, 1975] observed on Mars 2, 3, and 5 near periapsis may actually be measurements of nonflowing ions in the outer ionosphere of Mars.

The PVO observations have emphasized the dynamic and variable nature of the solar wind interaction at Venus, and the Mars 2, 3, and 5 observations of *Vaisberg* [1976] indicate the variability of the interaction at Mars.

At present more is being learned about the solar wind inter-

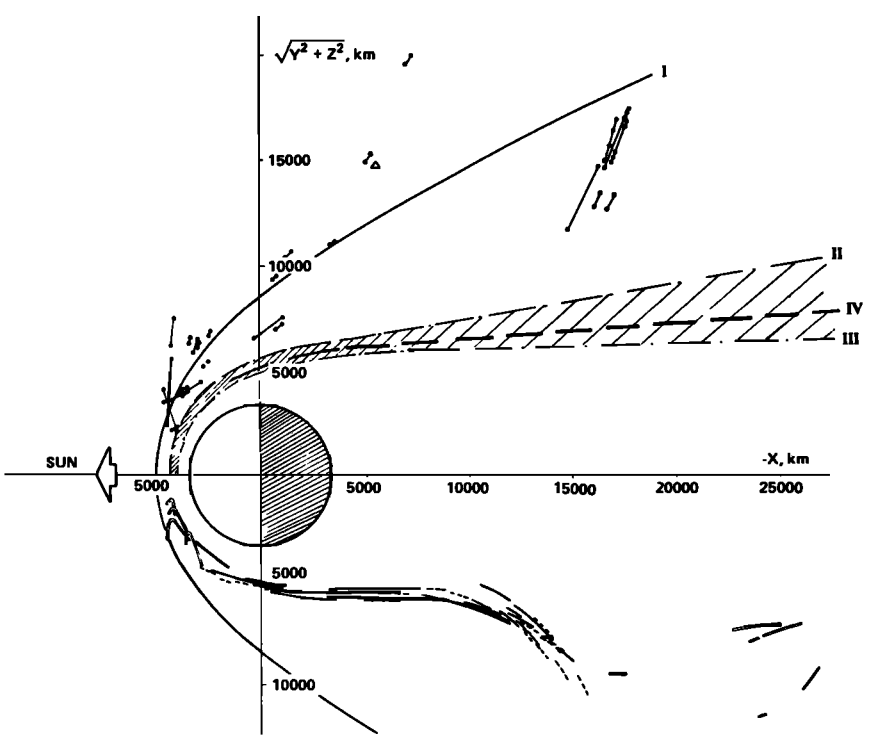

Fig. 7. Mars 2, 3, and 5 bow shock crossings in a common plane. This figure shows the similarity between the Mars 2, 3, and 5 solar wind observations at Mars and the solar wind interaction at Venus depicted in Figure 2.

action at Venus than is now known about the solar wind interaction at Mars. Therefore while there are several general features of the observed solar wind interaction at Mars that may be consistent with a Venuslike interaction at Mars, one must await observations of the magnetic field in the downstream region near the planet and inside the ionopause/magnetopause on the dayside to ascertain the nature of the planetary magnetic field at Mars.

One must also await more detailed observations to ascertain the extent of the heating and removal of atmospheric ions as a result of the direct interaction between the solar wind plasma and the ionosphere. Other observations such as those of the bow shock location and shape, the ionosheath flow field, the shape and configuration of the boundary layer, and the nature of the downstream wake (or cavity) region at both Venus and Mars will enable us to ascertain the similarities and differences of other aspects of these interactions.

6. Discussion

We have investigated two alternative modes of interaction of the solar wind with Mars. One is based on the interaction of the solar wind with Venus, which is an atmospheric interaction in which the pressure of the ionosphere holds off the solar wind. The other is based on the interaction of the solar wind with the earth, which is magnetospheric, the pressure to hold off and deflect the solar wind being provided by the planetary magnetic field.

In order to test whether one type of interaction is dominant a comparison was made of the ionospheric pressures at Venus and Mars to see if the pressures are adequate to withstand the solar wind. We find that recent PVO ionospheric measurements and recent modeling are consistent with a balancing of the solar wind stagnation pressure by a dense, cool ionosphere at Venus. At Mars, however, the calculated ionospheric pressure turns out to be too small by a factor of 4. The deficit in pressure is presumably provided by a planetary magnetic field, although an induced field cannot be excluded. Therefore on the basis of our calculations for average solar wind conditions at Mars, neither the influence of the atmospheric interaction nor the influence of the magnetic interaction is dominant. There are probably times, however, when the external solar wind pressure increases, and then more pressure is provided by the Martian ionosphere than by the magnetic field.

The deficiency in pressure enabled us to calculate the magnetic field strength at the stagnation point and, by implication, to derive a new estimate of the Martian planetary magnetic moment. This estimate is 8×10^{21} gauss cm^3 or 10^{-4} times the earth's dipole moment. The surface magnetic field at the equator is $\simeq 20$ γ. Both values are a factor of 3 less than the largest estimate based on an analysis of Russian magnetometer data by *Dolginov* [1976] but a factor of 4 larger than the lowest estimate derived by *Russell* [1978*a*, *b*].

However, the influence of the planetary field indicates the usefulness of considering the consequences of an earthlike interaction. We have investigated a purely magnetospheric interaction at Mars using scaling relations developed recently and applied to the outer planets which are thought to be strongly magnetized, so that their interaction with the distant solar wind is magnetospheric in nature.

Using our inferred value of the magnetic dipole moment in these scaling relations, we find that the structure of the magnetosphere and the relative importance of various physical processes could be significantly different at Mars than at earth. In particular, plasma convection may be more significant at Mars and could lead to extensive polar caps with the auroral zones at low latitudes.

The existence of a planetary magnetic field at Mars is supported by other Viking observations. For example, *McElroy et al.* [1977] calculated that under the present solar wind conditions a magnetic field of ~ 20 γ would be required to shield the upper atmosphere of Mars and account for the noble gas abundances. The existence of a planetary magnetic field also leads to magnetic field strengths in the atmosphere that are consistent with those used in the model of *Johnson* [1978] to inhibit heat conduction.

Since part of the pressure to stand off the solar wind is supplied by the ionosphere, the influence of an atmospheric type interaction at Mars cannot be disregarded. Some of the implications of this type of interaction were examined by comparisons between the recent Pioneer Venus orbiter results and the Mars 2, 3, and 5 observations. The PVO results indicate the presence of atmospheric ions in the outer ionosphere near the ionopause at Venus and perhaps their removal as a result of the direct interaction between the solar wind plasma and the ionosphere. In retrospect, the presence of such ions in the outer ionosphere may be indicated in the Mars spacecraft observations near periapsis in addition to the previously reported Mars spacecraft observations of heavier ions downstream from the planet.

We note some additional implications of the influence of the atmosphere on the interaction. The theoretical models of *Chen et al.* [1978] are shown in Figure 8 and indicate that the best agreement is found between the models and the data when there is a direct energy source of 10^8 eV/cm^2 s at the top of the ionosphere; they suggest that the solar wind is perhaps the source of this energy. If this were the case, then our calcu-

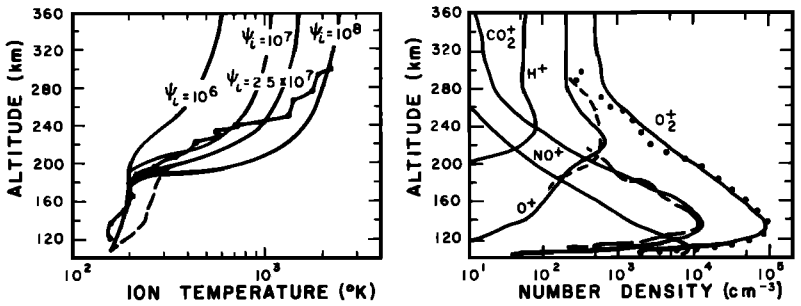

Fig. 8. Observed values (dotted, dashed, and jagged lines) from Viking lander ionospheric data [*Hanson et al.*, 1977] and model calculation (smooth lines) assuming energy balance and various rates of heat input [*Chen et al.*, 1978]. The best agreement between theoretical models and the observed temperature and number density data was obtained with a direct energy input at the top of the ionosphere of 10^8 eV/cm^2 s (see text).

lations could imply that this energy is deposited at ~400 km. The total solar wind energy available is 10×10^{10} eV/cm^2 s, so that if only less than 1% of this available energy were used to directly heat the ionosphere, it could supply the energy required for agreement between the Viking data and the model of *Chen et al.* [1978]. This very small percentage of the energy of the solar wind could be supplied through a viscous interaction [*Perez de Tejada and Dryer*, 1976] or some other mechanism.

Thus we conclude that the interaction of Mars with the solar wind is neither Venuslike nor earthlike but represents an intermediate case. In order to make further progress, theoretical models are needed which take into account both the interaction with the ionosphere on the dayside and the strong coupling between the Martian atmosphere and magnetosphere caused by enhanced plasma convection and by correspondingly large electric fields in the ionosphere.

Ultimately, there is an even more critical need for direct observations of the solar wind interaction and of the magnetic field of Mars. What is required to make substantial progress is a suitably instrumented spacecraft carrying an appropriate complement of field and particle experiments and orbiting Mars on a trajectory similar to that recently achieved with PVO.

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REFERENCES

Bauer, S. J., and R. E. Hartle, On the extent of the Martian ionosphere, *J. Geophys. Res.*, *78*, 3169, 1973.

Bauer, S. J., L. H. Brace, D. M. Hunten, D. S. Intriligator, W. C. Knudsen, A. F. Nagy, C. T. Russell, F. L. Scarf, and J. H. Wolfe, The Venus ionosphere and solar wind interaction, *Space Sci. Rev.*, *20*, 413, 1977.

Bogdanov, A. V., and O. L. Vaisberg, Structure and variations of the solar wind–Mars interaction region, *J. Geophys. Res.*, *80*, 487, 1975.

Chen, R. C., T. E. Cravens, and A. F. Nagy, The Martian ionosphere in light of the Viking observations, *J. Geophys. Res.*, *83*, 3817, 1978.

Dolginov, Sh. Sh., The magnetosphere of Mars, in *Physics of Solar Planetary Environments*, vol. 1, edited by D. J. Williams, p. 872, AGU, Washington, D. C., 1976.

Dolginov, Sh. Sh., Ye. G. Yeroshenko, and L. N. Zhuzgov, Magnetic field in the very close neighborhood of Mars according to data from the Mars 2 and Mars 3 spacecraft, *J. Geophys. Res.*, *78*, 4779, 1973.

Dryer, M. R., and G. R. Heckman, Application of the hypersonic analog to the standing shock of Mars, *Solar Phys.*, *2*, 112, 1967.

Gringauz, K. I., V. V. Bezrukikh, M. I. Verigin, and A. P. Remizov, On electron and ion components of plasma in the antisolar part of near-Martian space, *J. Geophys. Res.*, *81*, 3349, 1976.

Hanson, W. B., S. Sanatani, and D. R. Zuccaro, The Martian ionosphere as observed by the Viking retarding potential analyzer, *J. Geophys. Res.*, *82*, 4351, 1977.

Holzer, R. E., T. G. Northrop, J. V. Olson, and C. T. Russell, Study of waves in the earth's bow shock, *J. Geophys. Res.*, *77*, 2264, 1972.

Intriligator, D. S., H. R. Collard, J. D. Mihalov, R. C. Whitten, J. H. Wolfe, Electron observations and ion flows from the Pioneer Venus orbiter plasma analyzer experiment, *Science*, *205*, 116, 1979.

Jacobs, J. A., *The Earth's Core*, pp. 220–226, Academic, New York, 1975.

Johnson, R. E., Comment on ion and electron temperatures in the Martian upper atmosphere, *Geophys. Res. Lett.*, *5*, 989, 1978.

Kennel, C. F., Magnetospheres of the planets, *Space Sci. Rev.*, *14*, 511, 1973.

Knudsen, W. C., K. Spenner, R. C. Whitten, J. R. Spreiter, K. L. Miller, and V. Novak, Ionosphere of Venus: First observations of the effects of dynamics on the dayside ion composition, *Science*, *203*, 757, 1979.

McElroy, M. B., T. Y. Kong, and Y. L. Yung, Photochemistry and evolution of Mars' Atmosphere: A Viking perspective, *J. Geophys. Res.*, *82*, 4379, 1977.

Mead, G. D., and D. H. Fairfield, A quantitive magnetospheric model derived from spacecraft magnetometer data, *J. Geophys. Res.*, *80*, 523, 1975.

Perez de Tejada, H., and M. Dryer, Viscous boundary layer for the Venusian ionopause, *J. Geophys. Res.*, *81*, 2023, 1976.

Rassbach, M. E., R. A. Wolf, and R. E. Daniell, Jr., Convection in a Martian magnetosphere, *J. Geophys. Res.*, *79*, 1125, 1974.

Russell, C. T., On the relative locations of the bow shocks of the terrestrial planets, *Geophys. Res. Lett.*, *4*, 387, 1977.

Russell, C. T., The magnetic field of Mars: Mars 3 evidence reexamined, *Geophys. Res. Lett.*, *5*, 81, 1978*a*.

Russell, C. T., The magnetic field of Mars: Mars 5 evidence reexamined, *Geophys. Res. Lett.*, *5*, 85, 1978*b*.

Russell, C. T., R. C. Elphic, and J. A. Slavin, Initial Pioneer Venus magnetic field results: Nightside observations, *Science*, *203*, 745, 1979*a*.

Russell, C. T., R. C. Elphic, and J. A. Slavin, Initial Pioneer Venus magnetic field results: Nightside observations, *Science*, *205*, 114, 1979*b*.

Siscoe, G. L., Towards a comparative theory of magnetosphere, in *Solar System Plasma Physics*, edited by C. F. Kennel, L. J. Lanzerotti, and E. N. Parker, North-Holland, Amsterdam, 1978.

Smith, E. J., L. Davis, Jr., P. J. Coleman, Jr., and D. E. Jones, magnetic field measurements near Mars, *Science*, *149*, 1241, 1965.

Smith, E. J., A review of lunar and planetary magnetic field measurements using space probes, in *Magnetism and the Cosmos*, edited by S. K. Runcorn, p. 271, Oliver and Boyd, Edinburgh, 1967.

Smith, E. J., Planetary magnetic field measurements, in *Advanced Space Experiments*, vol. 25, p. 103, American Astronautical Society, Tarzana, Calif., 1969.

Smith, E. J., R. W. Fillius, and J. H. Wolfe, Compression of Jupiter's magnetosphere by the solar wind, *J. Geophys. Res.*, *83*, 4733, 1978.

Spreiter, J. R., Magnetohydrodynamic and gasdynamic aspects of solar-wind flow around terrestrial planets: A critical review, Solar-Wind Interaction With the Planets Mercury, Venus, and Mars, *NASA SP-397*, 135, 1976.

Spreiter, J. R., and A. W. Rizzi, Martian bow wave—Theory and observations, *Planet Space Sci.*, *20*, 205, 1972.

Vaisberg, O. L., Mars-plasma environment, in *Physics of Solar Planetary Environments*, vol. 2, edited by D. J. Williams, p. 845, AGU, Washington, D. C., 1976.

Vaisberg, O. L., S. A. Romanov, V. N. Smirnov, I. P. Karpinsky, B. I. Khazanov, B. V. Polenov, A. V. Bogdanov, and N. M. Antonov, Ion flux parameters in the solar wind–Venus interaction region according to Venera 9 and Venera 10 data, in *Physics of Solar Planetary Environments*, vol. 1, edited by D. J. Williams, p. 104, AGU, Washington, D. C., 1976.

Wolfe, J., D. S. Intriligator, J. Mihalov, H. Collard, D. McKibbin, R. Whitten, and A. Barnes, Initial observations of the Pioneer Venus orbiter solar wind plasma experiment, *Science*, *203*, 750, 1979.

Young, R. E., and G. Schubert, Temperatures inside Mars: Is the core liquid or solid?, *Geophys. Res. Lett.*, *1*, 157, 1974.

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