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A modified flow/field model of the solar wind interaction with Mars

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A MODIFIED FLOW/FIELD MODEL OF THE SOLAR WIND
INTERACTION WITH MARS

by

BRIAN K. STEWART

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ABSTRACT

A modified steady state flow/field model is applied to the direct interaction of the solar wind with the Martian ionosphere. The original flow/field model (Cloutier et al., 1987) is a one-dimensional, self-consistent derivation of differentials in vertical velocity, magnetic field, and ion densities from the coupled MHD equations. While successful in reproducing features of the ionosphere of Venus (Cloutier et al., 1987; McGary, 1987) and of Mars (Stewart, 1989), the flow/field model required an independently specified heating term (Q). The requirement of this term implies the presence of an energy source not accounted for in conventional calculations. This source was previously simulated with the inclusion of Q, but an unrecognized momentum or pressure term may also provide the coupling with the solar wind without the need of the free parameter Q. An in-depth analysis of Pioneer Venus data in relation to the total conservation of momentum of the system led to the discovery that the total momentum was in most cases not entirely accounted for, and that this "missing" term was correlated with solar wind dynamic pressure. By including this missing pressure, a new set of differential equations, which were also extended to include horizontal velocity terms, was derived. Extrapolation of the missing pressure to Mars gave results that faithfully reproduced the ionospheric features associated with previous flow/field models while maintaining agreement with Viking 1 and 2 observations. Finally, we suggest that the source of $P_{\text{missing}}$ could be a population of suprathermal particles within the ionosphere. The missing pressures in the Viking simulations are consistent with measured suprathermal pressures at Mars (Hanson and Mantas, 1988).
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Introduction

The motivation for this thesis stems from attempts to theoretically model the plasma and associated fields of an ionosphere in a direct solar wind/ionospheric interaction. The ground work was laid with the flow/field model of Venus by Cloutier et al. (1987). This model reproduces features of the ionosphere of Venus, including magnetic field structures, and is currently the only model that explains the prevalent $[O_2^+]$ ledge found near 170 km. Other research based upon this work (McGary, 1987; Stewart, 1989) has also been successful in reproducing observations at Venus and Mars. The original model is a 1-dimensional, self-consistent derivation of differentials in vertical velocity, magnetic field, and ion densities from the coupled MHD equations. This work does not make corrections to, but rather, defines and extends features already implicit in the flow/field models.

First attempts to solve the continuity equation coupled with momentum and energy demonstrated the need for a heating term specified independent of the plasma temperatures. This term (Q) in the energy transfer equation was required to simultaneously solve the equations with a finite, stable solution. Specification of the plasma temperatures along with an independent energy equation self-consistently accounts for the energetics of the flow without the need for a separate detailed calculation of energy sources (e.g. photoelectrons, chemistry) and sinks (e.g. radiative cooling, conduction). The requirement of an independent heating term implies the presence of an additional energy source not accounted for in conventional calculations. This source most likely originates from the solar wind ionospheric interaction; however, details of
this coupling have remained ambiguous. While this source can be simulated with the inclusion of Q, it has become clear that an additional momentum or pressure term could also provide this coupling while possibly eliminating the need for the free parameter Q.

This realization prompted an in-depth analysis of Pioneer Venus data in their relation to the total conservation of momentum of the system. The study led to the discovery that the total momentum was, in most cases, not entirely accounted for, and that this "missing" term was correlated with solar-wind dynamic pressure. Not only did a discrepancy exist at high altitudes (above the ionopause), but also throughout the ionosphere (altitudes to 150 km). By including this missing pressure, a new set of differential equations, which were also extended to include horizontal velocity terms, was derived.

The first chapter of this thesis provides background on the solar wind interaction with non-intrinsically magnetized planets, specifically Venus and Mars. The next chapter describes the recent Phobos mission to Mars; these observations provide the best evidence to date that the solar wind interaction with Mars is an ionospheric (Venus-like), rather than an intrinsic magnetic field (Earth-like) interaction. We then present the results of the statistical analysis of Pioneer Venus (PV) data that was prompted by the re-evaluation of the heating term and eventually led to the rederivation of the flow/field equations. The incorporation of the missing pressure term from this analysis and the inclusion of horizontal velocities that provide 2-dimensional effects is demonstrated in the derivation of the ionospheric flow/field equations in Chapter 4. The model is then applied to Mars for differing incident solar wind pressures at solar zenith angles (SZA)
of 0° and 45° and compared to observations. The results are presented in Chapter 5.

Finally, discussion and concluding remarks follow in Chapter 6.
1.0 Solar Wind Interactions with Non-Intrinsically Magnetized Bodies

1.1 Solar Wind Interaction with Mars

Before the recent Soviet Phobos mission, the nature of the solar wind interaction with Mars was even less well understood than the interaction with the more distant planets Jupiter, Saturn and Uranus. The only previous missions to study aspects of this interaction were Mariner 4 in 1965, which at closest approach barely crossed the bow shock, and Mars 2, 3 and 5 in the early 1970's. The Soviet spacecraft never came closer than 1,000 km to Mars. So, whether the solar wind was deflected totally by an ionosphere (Venus) or an intrinsic magnetic field (Earth) was unclear. Most authors now agree that the intrinsic field, at most, contributes to a hybrid obstacle to the solar wind (Lundin et al., 1991). Furthermore, based upon the most conclusive evidence provided by Phobos, the solar wind at Mars interacts dominantly with an ionosphere (Riedler et al., 1989; Lundin et al., 1989).

Dessler (1968) first suggested an interaction between the solar wind and the conducting planetary atmosphere at Mars. A dynamo electric field, \( E = -v \times B \) where \( v \) is the plasma flow velocity and \( B \) is the magnetic field, is induced by the flowing magnetized plasma and produces an electric current that interacts with the flow and alters it. The deviation of the supersonic, super-Alfvenic solar wind flow must be accomplished by a magnetohydrodynamic bow shock. Dessler (1968) recognized that the exact nature of the interaction of the solar wind with a conducting body is critically dependent on the conductivity of the body. As long as the conductivity forces the magnetic diffusion time through the body to be longer than the time for the solar wind to sweep past, the magnetic
field will "pile-up" in front of the obstacle. If the conductivity is smaller than this critical value, there would be no apparent build up of magnetic field on the sunward side. In the case of the moon, which is not highly conductive nor possessing a highly conductive ionospheric layer, Michel (1964) predicted that the incident solar wind simply impacts and is neutralized on the lunar surface. In considering whether a bow shock is formed in front of the obstacle, the limiting case for a planet excludes the effects of an atmosphere. Dessler (1968) predicted that Mars could produce a standing bow-shock to deviate the solar wind flow around the planet based solely on the conductivity of the planet. Cloutier et al. (1969) further investigated the effects of this type of interaction by including the planetary atmosphere. They demonstrated that a standing bow-shock is required by the interaction of the solar wind with the ionosphere.

Since the intrinsic magnetic field on Venus is insufficient to deflect the solar wind, the solar wind impinges upon the top of the atmosphere. The flowing magnetized plasma induces a dynamo electric field in the rest frame of the object.

\[ E = -v \times B \]

where \( v \) is the plasma velocity and \( B \) is the magnetic field as measured in the flowing plasma frame. When an electric field is created by this type of process, it is often called a "dynamo" in analogy to a motor-driven electric generator in which a conductor is moved across a magnetic field. Any ions formed in the neutral atmosphere would be accelerated to the bulk flow velocity by \( E \times B \) drift motion. If the atmosphere could rapidly absorb and neutralize the incident solar wind plasma, as in the case of the surface of the moon (Michel, 1964), the solar wind particles could eventually transfer their momentum and energy to the neutrals through collisions. The incident supersonic flow could be deflected
without a shock wave. However, photoionization produces ions at high altitudes (above 200 km) where collisions with the neutral gas is negligible. These photoions are picked up by the flow at a higher rate than the solar wind can accommodate them. In order to accommodate this mass addition of photoions, the flow conditions must be modified; a collisionless shock wave moves upstream to deflect most of the incident flow around the planet. Cloutier et al. (1969) showed that a steady solution where the supersonic solar wind simply enters the planetary atmosphere, picking up newly created photoions and carrying them along can not exist. They concluded that the solar wind must enter the atmosphere with subsonic velocity: a shock is unavoidable.

Therefore, the Venusian and Martian ionospheres act as hard obstacles to the solar wind flow and deflect most of the flowing plasma around their planets. Only a few percent of the solar wind flux is absorbed as a result of the formation of an upstream shock in response to mass loading of photoions to the flow.

1.2 Previous Models

represent the realization that the solar wind interaction at Mars does not require an intrinsic field. Formerly Slavin and Holzer (1982) along with Intriligator and Smith (1979) had concluded prematurely that an intrinsic field was necessary to stand-off the solar wind.

Development of the Venus flow/field model (Cloutier et al, 1987) was prompted by several unexplained observations and inconsistencies within the theory supported by Johnson and Hanson (1979), Russell and co-workers (Russell et al., 1983; Luhmann et al., 1984). Cloutier and co-workers contend that through convection, electric and magnetic fields resulting from solar wind interaction permeate the ionosphere as a steady state condition. The ionosphere is simply an extension of solar wind flow where the ionopause represents a steady state transition from one type of flow to another. A pressure balance ionopause defined as the altitude where magnetic pressure equals thermal particle pressure is therefore nonexistent. Finally, the total momentum of the system is approximately constant until it is transferred through the ion-neutral collisional drag force to the neutral atmosphere at the base of the ionosphere. The counterview, held by Russell et al., (1983), states that solar wind magnetic fields and convection are excluded from the ionosphere except at times of extreme solar wind pressures; they only permeate the ionosphere as a transient event. The solar wind momentum is converted into magnetic pressure and then balanced at the ionopause by static plasma pressure where $\rho v_{sw}^2 = B^2/2u_o = n e k ( T_e + T_i )$ defines the ionopause height. As a result, the ionopause represents a real physical barrier to solar wind momentum with no steady state flow through this boundary.

The principal PV observations that highlight the contrasts between the competing
theories are large magnetic fields consistently observed by PV within the ionosphere (greatest surprise is the large magnitudes at low altitudes), the lack of agreement between a pressure balance ionopause and the true ionopause, and the relative maximum in O+ ion densities which has been unexplained by chemical or diffusion attempts. While the opposing view has difficulties explaining these observations, they are a natural consequence of the physics involved in Cloutier's Venus flow/field model (Cloutier et al., 1987). Most importantly, the Venus flow/field model demonstrates how these features are a result of the transfer of solar wind momentum to the neutral atmosphere, and ultimately to the planetary surface.

Let us investigate how the total momentum takes on various forms within several regions of the interaction. First, above the bow shock, roughly all of the momentum is in the form of \( \rho v_{sw}^2 \). Crossing the shock, the flow is thermalized. Dynamic pressure is converted to \( \rho v^2 + P + B^2/2\mu_0 \) because of the decrease in \( v \), and increase in \( T \) and \( \rho \). Note that \( P \) represents contributions from particle pressure: both thermal and non-thermal components. Nearer the ionopause, \( B \) is enhanced and \( \rho v^2 \) becomes small as flow goes around the obstacle. The enhanced magnetic field pressure and suprathermal pressure make up for the decrease in \( \rho v^2 \); whatever is necessary to conserve momentum. Within the ionosphere, chemistry, along with gravity and heating due to wave interactions drive exchanges between the two dominant terms \( P \) and \( B^2/2\mu_0 \). Next, in the lower ionosphere neutral collisions become increasingly important. In a critical region, the flow is accelerated; once again, \( \rho v^2 \) becomes significant. The ion-neutral drag force begins to dominate. Consequently magnetic and particle pressure terms are dissipated until the total momentum approaches the weight of the atmosphere. The momentum of the solar wind is successfully transferred by means of the ion-neutral drag force to the neutral atmosphere and finally, to the ultimate obstacle, the planet itself.
If the solar wind momentum is transferred through the ionosphere to the neutrals and the planet, does a pressure balance ionopause have any significance? In a magnetospheric interaction, the compression of the intrinsic field in effect directly transfers momentum to the core of the planet. While widely accepted in a purely ionospheric interaction, no mechanism has been put forward to explain how the momentum is transferred to the planet from a pressure balance ionopause \( \frac{B^2}{2\mu_0} = nk(T_i + T_e) \). Moreover, this equality often misses the true ionopause by hundreds of kilometers. Cloutier et al. (1987) show that the interaction does require a pressure balance - a total and continuous pressure balance. The ionopause is simply a transition layer from one flow to another resulting in a tangential discontinuity in density. The bow shock is also a transitional region where momentum is exchanged from one form to another. In terms of providing the ultimate barrier to the flow, no significance should be placed in either of these transitional layers. These regions are not barriers to the momentum at all; it is transferred through them in one form or the other. One would also naturally expect occasional equalities of individual terms of momentum as it is exchanged throughout the interaction region. This is inconsequential; no significance exists in \( \rho v^2 = P \) or \( \frac{B^2}{2\mu_0} = P \) or any other equality of terms.
2.0 The Phobos Mission

2.1 Evidence for an Ionospheric-Solar Wind Interaction

Despite the premature failure of both Phobos spacecraft (Phobos I was lost enroute, and Phobos II after 57 days in orbit around Mars), new and important information was returned. Actually, regarding Mars, a significant amount of data had already been returned. Phobos II was lost while maneuvering to study Phobos more closely. The question, as it relates to this work, is whether or not an intrinsic field shields the atmosphere from the solar wind. Before Phobos, it was unclear whether the solar wind at Mars was deflected totally by an ionosphere or an intrinsic magnetosphere. The Phobos mission has answered this question, at least in part. Most authors now agree that the intrinsic field, at most, contributes to a hybrid obstacle to the solar wind. Furthermore, based upon the most conclusive indirect evidence provided by Phobos, the solar wind at Mars interacts dominantly with an ionosphere (Riedler et al., 1989).

Previous missions to Mars had established the existence of a bow shock, a dayside and nightside ionosphere, a magnetotail, and set upper limits on any intrinsic magnetic moment. These missions included the Mariner 4 flyby in 1965, three Soviet orbiters in the early 1970's, and the Viking orbiters and landers of the mid 1970's. Mariner barely crossed the bow shock and the Mars missions never came closer than 1,000 km. The Viking missions could have unambiguously determined the type of interaction, but a magnetometer was not included in the scientific payload. The available observations suggest that Mars either presents a hybrid weak intrinsic field/ionosphere obstacle to the solar wind (Dolginov, 1976; Gringauz, 19---; Bauer and Hartle, 1973; Slavin and Holzer, 1982; Lundin et al., 1990; Slavin, 1990) or exhibits a purely ionospheric interaction

Upon arrival at Mars, Phobos II was placed into a highly elliptical orbit with a periapsis of 850 km. After four of these elliptical orbits, the spacecraft was moved into a nearly circular orbit at an altitude of 6,000 km. (see Figure 1) Data was taken from 80 of these orbits before contact was lost on March 27, 1989. From these 84 orbits, the magnetotail data is the most compelling. The following section will demonstrate why these data suggest that the character of the near Martian space is controlled by the solar wind and the interplanetary magnetic field (IMF).

2.2 The Solar Wind Dominated Martian Magnetotail

The existence of a magnetotail is not by itself evidence for or against an intrinsic planetary magnetic field. All of the planets, whether or not they possess an intrinsic field, have a magnetotail. For a magnetized planet, the stresses of the interaction of the solar wind on the planetary magnetic field pull the planetary field lines in the antisolar direction forming two lobes of oppositely directed fields. (Figure 2). These lobes are separated by a plasma sheet; it carries the current that maintains the oppositely directed magnetic fields. The basic tail lobe configuration is at most weakly sensitive to the direction of the interplanetary magnetic field. The tail of an unmagnetized planet with an atmosphere forms in a much different way. The IMF is carried through the bow shock where it is slowed down as compared to
Figure 1 Depiction of the orbits of Earth, Mars, Phobos and the orbits of Phobos 2. (not to scale) (from Sagdeev and Zakharev, 1989)
Figure 2 Configuration of Earth's dipole field with flow directions. The major magnetospheric regions are also labelled. (from Hill and Dessler, 1991).
the field lines outside the shock. Closer to the planet they pick up mass from photoionization of the neutral atmosphere and charge exchange processes; their velocity is further decreased. As the IMF is held up by the obstacle, the less encumbered ends are swept along with the flow. The result is a tail-like field configuration. (Figure 3). The tail geometry must reflect the rotation of the IMF as it varies about the solar wind direction.

In summary, the wake of an intrinsically magnetized planet is a region of magnetic fields with a large sunward or antisunward component. A current sheet separates the regions of opposite magnetic polarity or tail lobes. The polarity is controlled only by the intrinsic magnetic moment of the planet. In contrast, an induced magnetotail has lobes with polarities solely controlled by the interplanetary magnetic field. Thus, the existence of a magnetotail may be assumed. Determining whether the tail is induced or intrinsic requires evidence for one type of interaction over the other. The Phobos mission is ideally suited to address this question at Mars. During the early elliptical phase four passes were made down the tail. While in the nearly circular orbit, Phobos made repeated passes through the center of the tail. One can examine the magnetometer data MAGMA (Riedler et al., 1989) to determine whether the properties of the tail are consistent with an induced or an intrinsic magnetic field. Indeed, Phobos discovered that the martian magnetotail lobes are very sensitive to the IMF (Riedler et al., 1989; Yeroshenko et al., 1990).

The two lobe structure of the magnetotail allows one to make a simple test of whether the tail is induced or intrinsic. A schematic view of the solar magnetic field
Figure 3 Diagram of the solar wind interaction with Mars, which is consistent with Phobos 2 findings, that demonstrates the structure of an accreted magnetotail. (from Saunders, 1989)
is given in Figure 4. As the solar wind expands, the magnetic field is stretched into a disklike geometry that has a fluted structure. The crosshatched surface represents the current sheet that separates the adjacent antiparallel magnetic fields. This pattern rotates with the 27-day rotation period of the sun. As the pattern rotates past the planet, the position of the current sheet is alternately above and below the ecliptic plane. The magnetic field is directed sunward or anti-sunward depending on whether the current sheet is above or below the plane; these magnetic field structures are called sectors. The traversal from one directed sector to another is called a sector boundary crossing. The inclination of the sheet with respect to the ecliptic plane produces a northward or southward component to the IMF. Figure 5 shows the typical magnetospheric structure of the intrinsic field interaction at Earth for a southward IMF. The numbered circles represent the evolution of the IMF field lines as they are swept past the planet. With a southward IMF, the magnetosphere is highly disturbed by magnetic merging of intrinsic field lines with the IMF. However the tail lobe polarity remains unchanged. A northward IMF produces a more closed magnetosphere. (Figure 6). In this orientation, merging is minimal and the tail lobe polarity once again remains unaffected. Referring to Figure 3 (Mars induced field), an induced field would clearly show a switch of tail lobe polarity with reversal of IMF.

During the period when Phobos was taking data, Mars was passed by a transition between two IMF sectors. The direction of the IMF before the sector boundary crossing was such that an induced dusk tail lobe must be directed towards the sun and the dawn lobe directed antisunward. Any given intrinsic tail could have either orientation. After the sector crossing, however, only the induced tail would
Figure 4. Three-dimensional sketch of the solar equatorial current sheet and associated magnetic field lines. The current sheet is shown as lying near the solar equator with spiraled, outward pointing magnetic fields lying above it and inward-pointing fields lying below it. An observer near the ecliptic will alternately lie above and below this sheet and will see a changing sector pattern. (from Kelley, 1989)
Figure 5  Earth's Magnetic field topology for a southward IMF. The figure demonstrates the time evolution of the IMF "connecting" and "reconnecting" as it flows past the planet. (from Kelley, 1989)
Figure 6  Earth's Magnetic field topology for a northward IMF. Although some merging still exists, the topology of the field is much more "closed" than the field for a southward IMF.
show an accompanying switch in polarity. Indeed, the two lobes did have the necessary polarity of an induced tail, and a reversal was seen when the sector boundary crossed Mars. When the IMF was perpendicular to the flow, the lobe structure was also well defined. When the IMF was nearly aligned with the solar wind flow, the two-lobe pattern was almost completely replaced by an unidirectional tail. Furthermore, within uncertainties, the Mars tail is very similar to the only other well-studied induced tail - Venus. (Yeroshenko et al., 1990) As Yeroshenko et al. (1990) concluded, "If there is an influence of a Martian intrinsic magnetic field on the magnetotail of Mars that influence is weak."

Other authors have argued both sides of the issue based primarily on circumstantial evidence from one Phobos instrument or the other. Slavin et al. (1990) argue that the interaction is a hybrid based upon their study of bow shock positions. While Schwingenschuh et al. (1990) state, "Hence the variable shock position does not seem to be caused by any intrinsic planetary magnetic field ". Lundin et al. (1990) conclude, based primarily on plasma measurements, that Mars constitutes a hybrid obstacle to the solar wind. Nagy et al. (1990), however, state that the available plasma environment data related to the mantle/planetosphere regions of Mars and Venus show significant similarities. Clearly, Phobos can not put to rest the question of whether Mars has a small or zero intrinsic field. A surface lander with a magnetometer may be required for a definitive answer. Therefore the basic assumption intrinsic to our model, that the solar wind directly interacts with the ionosphere of Mars, is not only possible, but in light of the Phobos mission results, likely.
3.0 Momentum Transfer: Conservation and the Missing Pressure.

3.1 Momentum Conservation

The solar wind in steady-state imparts a momentum flux of $\rho v^2$ to any object in the flow. This momentum can take on many forms within the bow shock: dynamic ram pressure, static particle pressure, and magnetic field pressure. However, the total momentum flux must be conserved. One can express this as:

$$\frac{B^2}{2\mu_0} + n_e k (T_e + T_i) + n_e m v^2 = \rho_{sw} v_{sw}^2$$

The left hand side represents the forms that the incident solar wind momentum can take between the bow shock and the planet. For lower altitudes the post shock dynamic pressure term is relatively small, and is usually dropped. This gives the standard representation:

$$\frac{B^2}{2\mu_0} + n_e k (T_e + T_i) = \rho_{sw} v_{sw}^2$$

The usual interpretation of this equation implies the total conversion of solar wind momentum to magnetic field pressure within the mantle region, which is then balanced by
static particle pressure at the ionopause. This explanation has several shortcomings. The solar wind momentum is not converted entirely to magnetic field pressure, the altitude where the particle and magnetic pressures coincide often misses the true ionopause by hundreds of kilometers, and the total momentum flux is rarely conserved.

Several studies have attempted to correlate magnetic field pressure to incident solar wind pressure. (Brace et al., 1980; Elphic et al., 1980). After correcting for a Newtonian pressure balance, this ratio is not one, but 1.5 to 2. (Figure 7) One should note that the magnetic field strength is the maximum measured within the Venusian magnetosheath. Where the magnitude drops below this maximum, the ratio of incident to field pressure is even greater than two. In many other theoretical models, all of the solar wind momentum is postulated to be converted to magnetic field pressure. This magnetic pressure then balances the particle pressure at the ionopause. Figure 8 from (Elphic et al, 1980) plots particle and magnetic pressure. We have added the incident solar wind pressure. As defined by Elphic et al (1980), "We identify the ionopause location as the position where the two pressure traces cross before entry into the ionosphere proper ". The ionopause is defined independently of the ion density. Stated simply, the location of this ionopause is not necessarily where the ions "pause". Cloutier et al. (1987) demonstrated that a discrepancy of hundreds of kilometers often exists between a pressure-balance ionopause and the true ionopause. Finally, even if one includes all the terms in the pressure balance equation, the ratio of solar wind pressure to post-shock pressure is nearly always greater than one.
Figure 7 Several studies have attempted to correlate magnetic field pressure to incident solar wind pressure. The solid line represents the equality of these pressures; the dashed line is the best fit. The points are PV observations. Note that the magnetic field strength is the maximum measured within the Venusian magnetosheath. Even with this maximum pressure, the solar wind pressure is 1.5 to 2 times greater. (from Brace et al., 1980).
3.2 Analysis of Pioneer Venus Observations

Thanks to Pioneer Venus, we can take a closer look. PV measured all of the required parameters: temperatures, densities, and velocities inside and out of the Venusian bow shock. Data was derived from the Orbital Plasma Analyser (OPA), Orbital Magnetometer (OMAG), Orbital Electron Temperature Probe (OETP), the Orbiter Retarding Potential Analyzer (ORPA), and the Orbiter Ion Mass Spectrometer (OIMS). Investigation of the conservation of momentum throughout the region, not just at the ionopause or at the location where the magnetic field is maximum, is possible. The known pressure terms were equated to the incident solar wind pressure. We determined that on average a "missing pressure" was necessary to ensure conservation of momentum. Moreover, this pressure characteristicly varied with altitude and solar wind pressure. Owing to the limitations of the instrumentation, individual orbits are insignificant. However, an average of a large ensemble of orbits should be representative.

3.2.1 Data Selection

Before carrying out this study various criteria had to be defined. First, some typical examples of orbit geometry and data selection is discussed. Not every orbit can be included; only a few per hundred are eligible. Newtonian pressure balance limitations require orbits of periapsis Solar Zenith Angle (SZA) less than 45°. As the spacecraft orbit precesses, this angle falls within the acceptable range approximately every one hundred orbits (Figure 9). This figure shows how the SZA at periapsis varies with orbit number. Each orbit has an inbound and an outbound portion. The orbits that pass closest to the subsolar point tend to sample
Figure 8 Plots of particle and magnetic pressure for orbits 173 & 185. Particle pressure is the heavy line, while the magnetic pressure is the thin line. We have added the incident solar wind pressure as a straight line. (from Elphic et al, 1980)
Figure 9  The dependence of periapsis SZA with orbit number. Only orbits with SZA less than 45° are considered.
Figure 10  The trajectory of the PV orbiter, in 3-dimensions, for a typical dayside orbit 175.
Figure 11  The trajectory of Pioneer Venus for orbit 175. The plane of the figure contains the spacecraft position and the sun-Venus axis. The distance units (Venus radii) are 6052 kilometers. The cross hairs represent 1/2 hour time intervals. The complete orbit is inset in the figure to demonstrate qualitatively when the spacecraft is outside the bow shock, within the ionosheath, or in the magnetotail behind the planet. The mean bow shock position as determined by Slavin (1979;1980) is also shown (dashed line).
the inbound ionopause at mid-latitudes and the outbound ionopause near the equator. (Figure 10) Because the inbound portion usually remains within the ionosheath, the spacecraft is able to monitor solar wind conditions only 20 - 40 minutes following periapsis.

Figures 10 and 11 illustrate this point. Figure 10 shows the trajectory of the PV orbiter, in 3-dimensions, for a typical dayside orbit 175. The same orbit is more conveniently shown, Figure 11, in solar cylindrical coordinates. Number orbit 175 has a periapsis SZA of 20 degrees. The plane of the figure contains the spacecraft position and the sun-Venus axis. The distance units (Venus radii) are 6052 kilometers. The complete orbit is inset in the figure to demonstrate qualitatively when the spacecraft is outside the bowshock, within the ionosheath, or in the magnetotail behind the planet. The mean bow shock position as determined by Slavin (1979;1980) is also shown. For at least SZA less than 45 degrees, the position of the bow shock should remain stable; the planet centered distance to this position varies by less than 10% over the course of a solar cycle. The subsolar values at Venus vary from 1.27 to 1.37 $R_V$ over the 11 year solar cycle according to Zhang et al. (1990). For orbit 175, PV crossed the bow shock 20-30 minutes after periapsis. Because timely solar wind data is essential in an intercomparison of solar wind, ionosheath and ionospheric data, one portion of each orbit must be ignored. We have reduced the available orbits to a small percentage, and of these, only half is admissible.

Figures 11 - 18 show 4 typical PV orbits accompanied by $\rho v_{sw}^2$ values calculated from OPA measurements. Orbit 127 (Figure 13) is a nightside orbit with periapsis SZA of approximately 100 degrees. This orbit does not meet our SZA
Figure 12 Dynamic pressure calculated from PV observations for orbit 175. The dashed line denotes the time of periapsis. Note the noisy nature of $pv^2$ after periapsis. This orbit was not accepted in the analysis.
Figure 13  Pioneer Venus orbit 127. The Periapsis SZA is on the night side, approximately 100°. The spacecraft spends most of the orbit in the unshocked solar wind.
Figure 14  Solar wind conditions for orbit 127. Relatively calm conditions exist since the spacecraft was almost exclusively outside the Venusian bow shock.
Figure 15  The trajectory of PV in solar cylindrical coordinates for orbit 420. The spacecraft crosses the shock about an hour after periapsis, remains outside the shock for 3 to 4 hours, and then returns to the magnetosheath for the duration of the orbit.
Figure 16  Plot of dynamic pressure vs. time for orbit 420. PV was in the post-shocked solar wind most of the time. This orbit was acceptable for the statistical study.
Figure 17  The comparison of orbit 175 to orbit 188 provides an example of the changes in geometry of the orbit. The trajectory of orbit 188 takes PV into the wake of the planet.
Figure 18 Dynamic pressure calculated from Pioneer Venus observations for orbit 188. This orbit was not included in the study owing to the transient nature of \( pv^2 \) following periapsis.
requirements of course, but it is a good example of undisturbed solar wind conditions. The trajectory takes the spacecraft within the bow shock for less than an hour and a half of the total orbit. Figure 13 shows \( \rho v_{2w} \) for this orbit. Except for an hour either side of periapsis, the total orbit is in the pre-shocked solar wind. In contrast, orbit 420 (Figure 14) crosses the bow shock about an hour after periapsis, remains outside the bow shock for 3 or 4 hours, and then returns to the magnetosheath for the rest of the orbit. As Pioneer Venus orbits the planet, the SZA at periapsis changes along with the geometry of the trajectory. Comparing orbit 175 to orbit 188 (Figure 16) provides an example of the changes in geometry of the orbit. Again, one can see the passage of the spacecraft into the preshocked solar wind. The trajectory of orbit 188 takes PV into the wake of the planet. Note the lack of data while the orbiter was behind the planet. Orbit 175 and 188 are also good examples of the transient nature of the solar wind. Although these two orbits do satisfy the SZA requirements (periapsis SZA approx 10 degrees for orbit 188), they were not included in the database owing to the noisy nature of the solar wind pressure after periapsis.

To summarize, we require orbits near the subsolar region where the spacecraft samples both ionospheric and undisturbed solar wind conditions almost simultaneously. Furthermore, the solar wind exhibits transient "gusts" - rapid fluctuations in density and/or velocity. During these times the ionosphere must react to such events. Because the ionospheric reaction time is uncertain and these events can be extremely short lived, relatively stable solar wind conditions are also a prerequisite. Figure 15 (orbit 420) shows an acceptable orbit. Notice how the solar wind pressure increases as PV crosses the bow shock into the solar wind approximately 20 minutes after periapsis. The solar wind conditions immediately following periapsis are relatively calm. However, as mentioned earlier, figure 11 and 17 (orbits 175 and 188) demonstrate orbits that were not
considered owing to the transient nature of the solar wind.

One final note about data screening. Dropouts in density, velocity, temperatures, and magnetic field exist. If one or more of these parameters are unknown, then none of the data at that altitude are used. For example, over a particular altitude range, the magnetic field, velocity, and temperatures is known, but the density is not. No relevance can be given to a comparison of the total pressure to incident solar wind pressure if the particle pressure can't be computed. The only points that are included in the analysis are those that involve simultaneous measurement of all the parameters. The one exception is when the spacecraft is above the ionopause; here the density falls below instrument thresholds and the thermal particle pressure is negligible.

3.2.2 Missing Pressure Analysis Results

Reiterating our premise, we add a missing pressure term to ensure a total momentum balance:

\[
\frac{B^2}{2\mu_0} + n_e k (T_e + T_i) + n_e m v^2 + P_{\text{missing}} = \rho_{sw} v_{sw}^2
\]

Knowing the other parameters, we can solve for this missing pressure term:

\[
P_{\text{missing}} = \rho_{sw} v_{sw}^2 - \frac{B^2}{2\mu_0} - n_e k (T_e + T_i) - n_e m v^2
\]
First, if solar wind conditions are acceptable, we determine the initial $\rho v^2$ of the solar wind. In the Newtoninan pressure balance approximation, the effective pressure applied by the solar wind to the ionosphere at a given SZA is:

$$P_{sw} = K \rho v^2 \cos^2(SZA)$$

where $\rho$ and $v$ are the solar wind density and velocity at preshock values. Assuming $K = 1$, we can make corrections to the incident pressure for changing SZA. Using the electron density data, we identify the ionopause altitude for each orbit. The ionopause is defined as the altitude where the density decreases by greater than a factor of 10 within a few kilometers. Figure 19 is a typical example. If a definitive, unique ionopause could not be identified, the orbit was excluded. This altitude is essential in determining where a dropout in particle density is acceptable and also provides information about the correlation between ionopause height and solar wind conditions.

We are concerned mainly with $P_{missing}$ inside the ionosphere. The missing pressure outside the ionosphere can be quite large, in some cases half of the total pressure is missing. In our estimates, a conservative approach was always taken; all parameters were chosen to minimize the missing pressure contribution. Ignoring the distinction between these two types of data can overestimate the average missing pressure within the ionosphere. Since the ionopause altitude can vary over 1000 kilometers, we must be able to limit the data to points below each individual ionopause. Although this is another restriction on the amount of data available, ionopause filtering gives a better representation of the missing pressure profile within the ionosphere.
Figure 19 Using the electron density data, we identify the ionopause altitude for each orbit. The ionopause is defined as the altitude where the density decreases by greater than a factor of 10 within a few kilometers. For orbit 423, the ionopause height is assigned a value of 340 km.
We tabulate the data for a large number of orbits over a variety of altitude ranges. This database can be sorted by solar wind conditions, ionopause considerations, SZA, and altitude range. Clearly, this analysis has implications beyond the scope of this thesis. We are concerned with the 'characteristic' curve of missing pressure for low, medium, and high solar wind dynamic pressures for application to the solution of the flow/field equations. Figure 20 shows the percentage of the missing pressure to total pressure for the three solar wind conditions. Figure 21 is the actual values these percentages represent for the average $p v^2_{sw}$ in each of the cases. On average, missing pressure exists for the full range of solar wind pressures. Although the total amount falls off rapidly in the low case, there is missing pressure at all altitudes down to 150 kilometers. For the high case and to some extent the intermediate case, a substantial amount of $P_{\text{missing}}$ extends to lower altitudes where it converges to zero over a relatively short altitude range.
Figure 20  Missing pressure profiles calculated from an analysis of PV data for three solar wind conditions: low, intermediate and high. This plot shows the percentage of pressure vs. altitude necessary to ensure conservation of momentum for the three cases.
Figure 21  Actual missing pressure for low, intermediate, and high solar wind conditions translated from the profiles of Figure 20.
4.0 Flow/Field Equations

4.1 Conservation relations

We simultaneously solve the coupled, non-linear, steady-state MHD equations to obtain profiles of ion density, vertical velocity and magnetic field. Conservation of mass is related by the mass continuity equation.

Continuity Equation:

\[ \nabla \cdot (\rho V) = \sum_i (p_i - l_i) m_i \]  \hspace{1cm} (1)

where \( \rho \) is the mass density defined by,

\[ \rho = \sum_i n_i m_i \]

\( V \) is the center of mass bulk flow velocity:

\[ V = \frac{\sum_i n_i m_i v_i}{\sum_i n_i m_i} \]

\( p_i, l_i, n_i, \) and \( m_i \) are the volume production and loss rates, the number density and the
mass, respectively, for each charged species \( i \). The summation extends over all charged species.

The conservation of momentum can be expressed as:

**Momentum Transfer Equation:**

\[
\nabla \cdot \left[ \rho \mathbf{v} \mathbf{v} + \mathbf{P} \right] = \mathbf{j} \times \mathbf{B} + \mathbf{F} 
\]  

(2)

where \( \mathbf{P} \) is the plasma pressure tensor, \( \mathbf{j} \) is the total electric current, and \( \mathbf{F} \) is the net force on the plasma given by

\[
\mathbf{F} = \rho \mathbf{g} - \rho \mathbf{v} \mathbf{v}_{in} - \left( \sum_i m_i \right) \mathbf{v} + \rho_c \mathbf{E} 
\]  

(3)

where \( \mathbf{g} \) is the local gravitational acceleration, \( \rho_c \) is the total charge density, and \( \mathbf{v}_{in} \) is the ion-neutral collision frequency. The corresponding energy conservation relation is:

**Energy Transfer Equation:**

\[
\nabla \cdot \left[ \frac{1}{2} \rho \mathbf{v}^2 + \frac{\gamma - 1}{\gamma - 1} \mathbf{P} \right] = \mathbf{j} \cdot \mathbf{E} + \mathbf{W} 
\]  

(4)
where $\gamma$ is the ratio of specific heats. $E$ is the electric field and $W$ is the sum of the work done by the forces on the plasma:

$$ W = F \cdot V + Q $$

(5)

where $Q$ is an independently specified external heating term. We have chosen to set this term to zero in an effort to obtain a self-consistent, stable, empirically acceptable solution to the equations without the requirement of the free parameter $Q$.

4.1.1 Simplifying the Equations

Several approximations are necessary to simplify the coupled equations; we have too many unknowns. First, we assume charge neutrality so that the total ion concentration equals the total electron concentration. Therefore the total charge density, $\rho_c$, is zero and the electric force term in the momentum equation is excluded.

The total ion concentration $n$ is given by

$$ n = \sum_i n_i $$

and the average ion mass $m$ by

$$ m = \frac{1}{n} \sum_i m_i n_i $$

The average velocity of each species is assumed to be equal: the bulk flow velocity.
That is:

\[ V_i = V \]

for all species.

These are the basic equations and assumptions that are inherent in most treatments of a solar wind interaction with the ionosphere and atmosphere of a planet (Chen, 1978). What makes our approach unique is the approximations that further simplify the relations while maintaining a true representation of the dominant physical features of the interaction.

The coordinate system is defined such that local vertical is the z-axis. Horizontal refers to the direction tangent to the surface of the planet at a specific SZA, vertical perpendicular to that point, (local horizontal and vertical in the region) and the subsolar point refers to SZA=0°. The bulk motion of the plasma is directed radially downward towards the surface of the planet in the -z direction. We also include a horizontal component of velocity. This horizontal velocity is significant at high altitudes, and is essential in simulating a variety of solar zenith angles. The horizontal axis x is parallel to B, the magnetic field, at the ionopause. (horizontal velocity in the y, horizontal B in the x and vertical velocity in the -z direction)

Therefore:

\[ \mathbf{v} = v \hat{z} + v \hat{y} \]

\[ \mathbf{B} = B \hat{x} \]
We assume all vertical current densities are small in comparison to horizontal current densities; all horizontal gradients in all parameters are small in comparison to vertical gradients. By definition, all gradients are in the $\pm dz$ direction.

Our model assumes a steady state time-independent flow. The time-independent flow solution describes the state of the ionosphere where solar wind parameters are fixed during the time of iteration from the ionopause to the altitude where solar wind momentum is completely transferred to the neutral atmosphere. Cloutier et al. [1987] demonstrated that a one-dimensional steady state time-independent model of the solar wind interaction with Venus accounts for the observed magnetic field and overall ion concentration structure within the Venusian ionosphere. Transient events will occur so that the ionopause height and degree of magnetization of the ionosphere varies accordingly with time. The only limitation of a time-independent solution is that it does not describe such events, and therefore is not intended to do so. We require a stable, unique ionopause with the initial magnetization defined at that altitude. Our steady state assumption implies

$$\nabla \times E = 0$$

In turn, $E$ is given by

$$E = -v \times B$$

so that

$$E_y = -v_z B_x (\hat{z} \times \hat{x})$$
\[ E_z = -v_y B_x (\hat{y} \times \hat{x}) \]

and therefore

\[ \mathbf{E} = E_y + E_z \]

Since the bulk force due to the electric field is zero owing to the electrically neutral plasma, the remaining E-field effects are contained in the joule heating term:

\[ \mathbf{J} \cdot \mathbf{E} \]

which is taken from the energy transfer equation. The current density \( \mathbf{J} \) is given by Ampere's law:

\[ \mathbf{J} = \frac{1}{\mu_0} \nabla \times \mathbf{B} \quad (6) \]

Simplifying the joule heating term:

\[ \mathbf{J} \cdot \mathbf{E} = -\frac{1}{\mu_0} \left( \nabla \cdot (\mathbf{E} \times \mathbf{B}) \right) \]

\[ = -\frac{1}{\mu_0} \left( \mathbf{B} \cdot (\nabla \times \mathbf{E}) - \mathbf{E} \cdot (\nabla \times \mathbf{B}) \right) \]

\[ = +\frac{1}{\mu_0} \left( \mathbf{E} \cdot (\nabla \times \mathbf{B}) \right) \]

\[ = \frac{1}{\mu_0} \left( (E_y + E_z) \cdot \left( \frac{\partial B_x}{\partial z} \hat{y} - \frac{\partial B_x}{\partial y} \hat{z} \right) \right) \]
\[ \mathbf{J} \cdot \mathbf{E} = \frac{1}{\mu_0} E_y \frac{\partial B_x}{\partial z} \]  

(7)

Finally, the pressure term is assumed to be isotropic in the momentum and energy transfer equations; the tensor pressure simplifies to a scalar. This scalar pressure is conventionally represented as the sum of the thermal partial pressures: ion and electron.

\[ P = \sum_i P_i + P_e = n_e k (T_i + T_e) \]

However, the existence of another pressure (see Chapter 3) has been identified by a statistical analysis of PV data; an additional partial pressure term is required. This term is designated as \( P_m \): the missing pressure. The total particle pressure is now represented as the sum of thermal and missing pressure contributions:

\[ P_{\text{total}} = P_{\text{thermal}} + P_{\text{missing}} \]

With these definitions and assumptions, the conservation relations can be combined and simplified to obtain differentials in \( v_z \), \( n_i \) and \( \mathbf{B} \) as a function of altitude:
4.2 Flow/Field Differential Equations

\[ \text{dn}_i = \frac{[S_i \, dz - n_i \, dv_z]}{v_z} \quad (8) \]

\[ \text{dV}_z = \left[ \frac{B \, (w - v_z \gamma' \left( \frac{\partial T}{\partial z} + \frac{\partial P}{\partial z} \right) - \gamma' k T S - \frac{1}{2} S m |v|^2 \right]}{v_z} + F \left( \frac{\partial T}{\partial z} + \frac{\partial P}{\partial z} \right) - \rho v_z \, v_r \, \frac{dv_y}{v_y} \, \frac{dv_z}{v_z} \, S \left( k T + m |v|^2 \right) \right] \frac{dz}{v_z} \quad (9) \]

\[ \text{dB} = \frac{\mu_0}{B} \left[ F \, dz - dP_{\text{Total}} - \left( v_y^2 \, d\rho + v_z \rho \, dv_z + \rho v_z \left( \frac{v_y \, dv_y + v_z \, dv_z}{|v|} \right) \right) \right] \quad (10) \]

where

\[ P_{\text{Total}} = P_{\text{Thermal}} + P_{\text{Missing}} \]

\[ \frac{\partial T}{\partial z} = \frac{\partial t_c}{\partial z} + \frac{\partial t_i}{\partial z} \]

\[ T = t_i + t_c \]

\[ \gamma' = \frac{\gamma}{\gamma - 1} \]

\[ F = \rho g - \rho \nu v_{\text{in}} - \left( \sum_{i} m_i \right) v \]

\[ S_i = p_i - l_i \]

\[ S = \sum_i p_i - l_i \]
where

\[ E_y = \text{constant} \equiv (v_zB)_{\text{ionopause}} \]

\[ k = \text{Boltzmann constant} \]

\[ T_i, T_e = \text{Ion and electron temperature} \]

and

\[ v_{in} = 2.6 \times 10^{-9} \left(n_n + n_i\right) M_n^{1/2} \text{ S}^{-1} \]

(ion-neutral collision frequency taken from [Hanson, 1961])

These relations are numerically solved to give profiles of vertical velocity, magnetic field, and ion density. Clearly, since the unknowns outnumber the equations, more parameters must be specified. We are modelling Mars; the known parameters are constrained by observations or estimated from comparisons with Venus. Therefore, the elimination of all free parameters is paramount.
5.0 Results

5.1 Viking Simulations

We have further developed the flow/field model by removing the free parameter Q while demonstrating the need for a new pressure term from an analysis of Pioneer Venus data. Furthermore, we have included this pressure in the conservation relations and observationally constrained this term for varied solar wind conditions. Finally, in rederiving the differential equations, we have also incorporated horizontal velocities in an attempt to provide a quasi two-dimensional solution. The next step is to apply these modifications to Mars and determine whether a finite solution exists within observational constraints.

The low-altitude data for Mars consists of Viking 1 and 2 observations as they passed through the Martian ionosphere enroute to a soft landing on the planet surface. Fortunately, the solar wind conditions were different for each encounter. Luhmann (1987) speculates that Mars may behave like Venus under high solar wind conditions. Luhmann refers to this condition (when the incident dynamic pressure of the solar wind is larger than the greatest ionospheric pressure of the planet) as an "over" pressure state. This comparison enables estimation of parameters at Mars from those at Venus in an "over" pressure state. Although the conditions at Mars are expected to be predominantly "over" pressure, we chose to use the high-pressure curve for the missing pressure for Viking 2 and the intermediate curve for Viking 1. The intermediate case reflects calmer conditions of Viking 1 as compared to the more turbulent observations of the higher solar wind conditions of Viking 2. Also note from the missing-pressure profiles of Chapter 3 (Figures 20 and 21), that no data exists above 300 km for the high dynamic
pressure curve. This means that the ionopause was always located at or under 300 km for these cases. In the Viking 2 case, where the ionopause is identified at 300 km, the high-pressure curve is appropriate. Since the ionopause altitude was greater than 300 km for Viking 1, using the intermediate curve for this case is also consistent with observations.

The data taken along the spacecraft trajectory represents a vertical profile that describes the various ionospheric parameters with radial distance. Unlike orbital spacecraft that have large horizontal velocities near periapsis, the Viking landers give a truer representation of a vertical profile. Between 350 and 100 km, the variation in the spacecraft parameters (SZA and latitude) is only 7-8 degrees. Since the ionospheric parameters are not expected to change significantly over these SZA variations, the data basically describe vertical profiles of the measured parameters at an approximate SZA. The SZA for both Viking landers at 120 km was 45°.

We solved the model at the subsolar point (SZA=0°) for both Viking 1 and 2 solar wind conditions. Each case was then solved at a solar zenith angle of 45 degrees; the angle at which both landers descended through the ionosphere. Other SZA can be modelled, but SZA's of 0° and 45° were chosen to be representative. The results are presented here. The differentials (equations 8-10) in ion densities, vertical velocity, and magnetic field are solved as a function of altitude in the ionosphere of Mars. Other variables must be eliminated before a solution can be attained. We specify plasma temperatures, missing pressure, horizontal velocity, neutral densities, and initial values to model Viking results. We attempt to match the ionospheric environment of both spacecraft by modifying these parameters for solar zenith angle (SZA) and solar wind conditions.
As discussed earlier, we have eliminated the heating term (Q) by deriving the flow field equations with a missing pressure term that is defined by solar wind conditions. Previously, the heating term and plasma temperature profiles were adjusted to maximize agreement with observations while maintaining a finite solution. Because of the model's sensitivity to these variables, an iterative method of modifying their values was used to produce acceptable results. In this treatment we maximized the integrity of the missing pressure profile. Given the initial solar-wind pressure, the missing pressure profile followed the percentage profiles at Venus for either a high, intermediate, or low solar wind case. Likewise, the plasma temperature (T_e and T_i), horizontal velocity, and neutral density profiles were defined before run-time based upon Mars observations or extrapolations from Venus. Summarizing, we have minimized the run-time variable specification to two initial values: magnetic field and vertical velocity. Next, we will discuss how the other parameters were determined, and then four specific solutions of the model.

5.1.1 Model Input Parameters

The horizontal velocity is assumed to be zero at the subsolar point (symmetry in the flow about the subsolar point). The horizontal velocity profile at other SZA was assumed to follow those calculated at Venus and were taken from Theis et al, (1984); McGary (1988); and Cloutier (1979). (See Figure 22) The neutral densities are from Viking measurements (Nier and McElroy, 1977) and are shown in figure 23. With the exception of neutral oxygen, the important constituents are defined. Viking did not measure oxygen owing to spacecraft contamination (McElroy, 1977). Unfortunately, oxygen plays a vital role in the chemistry of the Martian ionosphere.
Figure 22  Horizontal velocities used in the SZA of $45^\circ$ simulations. This profile is based upon horizontal velocities at Venus. (Theis, 1984; McGary, 1988)
Figure 23  Neutral atmosphere derived from Viking observations
Other models (Chen et al., 1978; Fox and Dalgarno, 1979; and Hanson et al., 1977) provide a fit from photochemical equilibrium considerations. The atomic oxygen number densities used in these models are chosen to fit measured [CO$_2^+$] densities by the relation:

$$[O] = \frac{k_3}{k_1 + k_2} \frac{[O^+]_e}{[CO_2]^n} n_e$$

where

$$k_1 = 1.6 \times 10^{-10}$$

$$k_2 = 1.0 \times 10^{-10}$$

$$k_3 = 1.9 \times 10^7 (300/T_e)^5 (cm^3 s^{-1})$$

These values are adjusted for the best agreement between model results and Viking 1 ion densities. Our model uses a profile based upon these findings.

Chemistry plays a vital role in any model of the Martian ionosphere. Total ion production rates were taken from Fox and Dalgarno [1979]. Table 1 contains the reaction rate coefficients for the ion-neutral and dissociative recombination reactions used in our calculations. Only the ions O$^+$, O$_2^+$, and CO$_2^+$ are considered because they are chemically dominant and are the only ions that can be compared to observations.
### Chemical Reactions in the Martian Ionosphere

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate Coefficient ( (\text{cm}^3 \text{s}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>( \text{CO}_2^+ + \text{O} \rightarrow \text{CO} + \text{O}_2^+ )</td>
<td>( K_1 = 1.6 \times 10^{-10} )</td>
</tr>
<tr>
<td>R2</td>
<td>( \text{CO}_2^+ + \text{O} \rightarrow \text{CO}_2 + \text{O}^+ )</td>
<td>( K_2 = 1.0 \times 10^{-10} )</td>
</tr>
<tr>
<td>R3</td>
<td>( \text{O}^+ + \text{CO}_2 \rightarrow \text{CO} + \text{O}_2^+ )</td>
<td>( K_3 = 9.4 \times 10^{-10} )</td>
</tr>
<tr>
<td>R4</td>
<td>( \text{CO}_2^+ + \text{e} \rightarrow \text{CO} + \text{O} )</td>
<td>( K_4 = 3.8 \times 10^{-7} \left( \frac{300}{T_e} \right) )</td>
</tr>
<tr>
<td>R5</td>
<td>( \text{O}_2^+ + \text{e} \rightarrow \text{O} + \text{O} )</td>
<td>( K_5 = 1.6 \times 10^{-7} \left( \frac{300}{T_e} \right)^{0.35} )</td>
</tr>
<tr>
<td>R6</td>
<td>( \text{CO}_2^+ + \text{NO} \rightarrow \text{CO}_2 + \text{NO}^+ )</td>
<td>( K_6 = 1.2 \times 10^{-10} )</td>
</tr>
<tr>
<td>R7</td>
<td>( \text{CO}_2^+ + \text{O}_2 \rightarrow \text{CO}_2 + \text{O}_2^+ )</td>
<td>( K_7 = 5.0 \times 10^{-11} )</td>
</tr>
<tr>
<td>R8</td>
<td>( \text{O}^+ + \text{O}_2 \rightarrow \text{O} + \text{O}_2^+ )</td>
<td>( K_8 = 2. \times 10^{-11} )</td>
</tr>
<tr>
<td>R9</td>
<td>( \text{O}_2^+ + \text{NO} \rightarrow \text{O}_2 + \text{NO}^+ )</td>
<td>( K_9 = 4.4 \times 10^{-10} )</td>
</tr>
</tbody>
</table>

Table 1
As discussed in Chen et al., (1978); Johnson, (1978); Fox and Dalgarno, (1979); Luhmann et al., (1987); Mantas and Hanson, (1985); Hanson and Mantas, (1988), solar extreme ultraviolet (EUV) heating alone cannot account for ion and/or electron ionospheric temperatures at Mars or Venus. At the distance to Mars, the solar EUV energy flux in the wavelength range 1026 - 15 Å is approximately $5 \times 10^{11}$ eV cm$^{-2}$ s$^{-1}$ (Mantas and Hanson, 1985). About half of this energy is converted to photoelectron kinetic energy in the process of absorption of the solar EUV photons by the neutral atmosphere (Mantas and Hanson, 1979). Most of these primary photoelectrons (approximately $8 \times 10^9$ cm$^{-2}$ s$^{-1}$ ) have sufficient energy to excite or further ionize the neutral atmosphere which produces an additional $3 \times 10^9$ cm$^{-2}$ s$^{-1}$ secondary photoelectrons. By analyzing the incident energy flux and the energetics of the reactions within the ionosphere, one can predict temperature profiles based upon solar EUV heating alone. Of the field-free planets Venus and Mars, the actual temperatures are much hotter than these predictions. To account for observations at Mars, Chen et al. (1978) imposes a heat flux of $3 \times 10^{10}$ eV/cm$^2$ at their upper ionospheric boundary. Based upon further EUV and photoelectron flux analysis, Hanson and Mantas (1988) conclude that the solar wind provides a substantial direct or indirect energy source to the topside Martian ionosphere.

If this topside energy source is the solar wind, a correlation between electron and ion temperatures with solar wind conditions may exist. PV observations at Venus show that $T_e$ and $T_i$ take on representative structures in cases of high solar wind conditions (Luhmann et al., 1987). (cf. Figure 24) Viking ion temperatures resemble Venusian $T_i$ during times when solar wind dynamic pressure is greater than Venusian particle pressure. Assuming Mars behaves like Venus under solar wind conditions of $\rho v_{sw}^2 > nk(T_e + T_i)$, we adopt an initial electron temperature
Figure 24 Comparison of Viking ion temperature profiles with the Venus high dynamic pressure ion temperature profile. The dashed lines show the results of models with solar EUV heating alone. (Cravens et al., 1979; Chen et al., 1978) (from Luhmann et al., 1987)
profile similar in structure to those observed at Venus during extreme solar wind conditions. Because Viking 1's entry was at a time of relatively low solar wind pressure, we adopt an electron temperature profile similar to, but cooler at higher altitudes than Viking 2. The cooler temperatures correspond with the behavior of $T_e$ at Venus with decreasing solar wind dynamic pressure. These electron temperature profiles are also consistent with those derived by observation (Hanson and Mantas, 1988), and those calculated from theoretical energy considerations (Chen et al., 1978).

Using the data from Viking, the boundary conditions are specified at 280 km in the model. The initial values of $[O^+]$, $[O_2^+]$, and $[CO_2^+]$ are from Figure 25. With the neutrals, chemical reactions, horizontal velocities, missing pressure curve, plasma temperatures, and initial ion densities defined, the initial magnetic field strength and vertical velocity are provided at run-time and the equations are integrated downward.

5.1.2 Run-time Parameters

The initial value of the magnetic field serves two purposes. It defines the beginning value of magnetic field strength for the iteration, but also defines the magnitude of the incident solar wind pressure. As stated before, the total of all the ionospheric pressure terms (B,P,Missing P) must equal this incident pressure.
Figure 25  Plots of observed Viking ion concentrations.  
(from Hanson et al., 1977)
\[ \frac{B^2}{2\mu_0} + n_e k(T_e + T_i) + n_e m v^2 + P_{\text{missing}} = \text{Total} \]

Because all of the parameters are now specified, we can solve for the total and therefore \( P_{\text{missing}} \). Recall that whether the simulation is designated as a high, intermediate or low solar wind momentum case, \( P_{\text{missing}} \) is a predetermined percentage of the total pressure based upon the statistical study (Section 3.1).

\[
\text{Total} = \frac{\frac{B^2}{2\mu_0} + n_e k(T_e + T_i) + n_e m v^2}{(1 - \% \text{ missing})}
\]

Where \( \% \text{ missing} \) is simply a number obtained from the designated missing pressure profile at the altitude where the iteration begins. (e.g. Figure 21). So, the initial magnetic field is the final parameter that determines the total solar wind pressure, and the magnitude of the missing pressure at the top of the ionosphere. The initial downward vertical velocity is arbitrarily set between 10 and 20 m/s to provide a stable solution and the best fit to ion concentrations.

We choose to solve the model at two solar zenith angles: 0° and 45°. We have included horizontal velocity in our derivation; these two locations provide contrasting results while also serving a logical purpose. We selected 45° because of the spacecrafts' trajectory; therefore, the subsolar point provides a baseline, since by definition of flow symmetry, the horizontal velocities are zero here. Simply stated, we solve the equations with the same set of inputs twice: once with the horizontal velocities defined at 45° by previous Venusian studies, and the second with all horizontal velocities set to zero. One
point should be addressed here. We have purposely kept the initial conditions constant in order to highlight the differences between these two solutions. The initial ions, neutrals, and plasma temperatures may not vary appreciably (approximately 10%) over this solar zenith angle range (McGary, 1989; Theis et al., 1984). However, the effective solar wind dynamic pressure impinging upon the top of the ionosphere and therefore the initial magnetic field would vary considerably. Because of the Newtonian pressure approximation,

\[ k \rho v^2 \cos^2 (\text{SZA}) \]

the effective solar wind dynamic pressure and therefore magnetic pressure and missing pressure should vary as the square of the cosine of solar zenith angle. A dynamic pressure that requires magnetization of the ionosphere to 40 nT at the subsolar point would likely require a lower magnetization pressure at SZA of 45°. By keeping the initial parameters constant, we are actually simulating two different pre-shock solar wind conditions. We present the results in two parts, a Viking 1 and a Viking 2 simulation.

### 5.2 Viking 1 Results

Since the incident solar wind pressure of Viking 1 is estimated to be 1/2 that of Viking 2, we assume the intermediate solar wind missing pressure curve from the analysis of PV data (cf. Figures 20 & 21). Figure 26 shows the percentage of the total pressure represented by the missing pressure term. The translation of this curve into actual pressure is presented in Figure 27. The ion and electron
Figure 26  Percentage of missing pressure, over the altitude range of the calculations, used as an input to the model for the Viking 1 simulations. This profile is from the intermediate solar wind case at Venus.
Figure 27. Translation of missing pressure (figure 26) to actual pressures. The initial magnitude is determined by the incident solar wind dynamic pressure.
Figure 28  Plasma temperatures used in the Viking 1 simulation. $T_i$ was measured, $T_e$ above 200 km was measured. Below 200 km, $T_e$ was extrapolated from electron temperatures at Venus during an "over" pressure state.
Figure 29 Plots of observed Viking ion temperatures. The Viking 1 curve is lightly dashed in (b) for easy comparison. (Hanson et al., 1977)
temperatures are given in figure 28. The ion temperatures are from Viking 1 measurements (figure 29) and the electron temperatures above 200 km are from Viking (Hanson and Mantas, 1988). Below 200 km they resemble those in other models (Chen, 1978; Fox And Dalgarno, 1979). The initial values of \([\text{O}^+]\), \([\text{O}_2^+]\), and \([\text{CO}_2^+]\) were taken from observations (Figure 25). The two run-time parameters, initial vertical velocity and magnetic field, are defined for Viking 1. To provide a stable solution and a best fit, the downward vertical velocity was arbitrarily set to 12 m/s. The initial magnetic field is 35 nT.

Figures 30 - 35 represent the solution of the model for these input parameters. Figure 30 shows the ion densities as a function of altitude. The data taken from Viking 1 is superimposed on the graph. These calculated ion densities are from the simulation at SZA of 45° which included horizontal velocity. The ions from the subsolar solution are basically the same and are not shown. Because ion densities are the only empirically constrained parameter calculated by the model, we fit ion concentrations as well as possible. Noting again that neither the temperature profiles, nor the missing pressure curve was "tweaked" or otherwise adjusted in achieving this solution. Also, since the heating term \((Q)\) has been eliminated, there are no other global free parameters to adjust. However, neutral oxygen was chosen to bring \([\text{O}_2^+]\) in closest agreement with observations. The only other parameters that can be adjusted to provide a stable solution and a best fit are the initial magnetic field and the initial downward velocity. Consequently, \([\text{O}^+]\) has the largest discrepancy, primarily between 180 and 220 km. \([\text{CO}_2^+]\) fits well with the possible exception of altitudes above 220 where the empirical scale height may be changing. Overall, agreement exists between model densities and observations.
**Figure 30** Ion concentration profiles for Viking 1. Solid lines show model calculations. The measured values $\text{O}^+$ (triangles), $\text{O}_2^+$ (solid circles), and $\text{CO}_2^+$ (circles) are shown for comparison.
Figure 31 Downward vertical velocity calculated for Viking 1 at SZA 45°.
Figure 31 shows the calculated vertical velocity versus altitude at SZA of 45°. An interesting bulge exists near 220 km. Other than this feature, the velocity remains fairly stable until it becomes accelerated to 90 m/s near 150 km. At first glance, this may seem a bit odd. The vertical velocity increases with decreasing altitude below 180 km. One might expect the flow speed to decrease in this region since the collision frequency between ions and neutrals becomes significant here. The collisional interaction could stagnate the flow by converting flow energy into thermal energy, but as explained by Cloutier et al. (1987) and Stewart (1989) the flow is cooled by heat exchange with the neutrals in the collisionally dominated region. In cooling the ions, the ion temperature decreases with altitude providing a pressure gradient that not only maintains the downward flow but accelerates it. This pressure gradient coupled with the missing pressure gradient that also exists at these altitudes, if large enough, could actually accelerate the flow to the maximum flow rate of Mach 1. In the Viking 1 case, the missing pressure and hence pressure gradient is considerably smaller than the high solar wind case resulting in the acceleration of the vertical velocity to only 90 m/s. This flow speed only slightly modifies the ion density profiles (Figure 30). Notice the change in scale height near 170 km in the \([O_2^+]\) profile.

Figure 32 demonstrates the effects from the inclusion of horizontal velocities. The solid line is the 45° solution and the dashed line is the subsolar solution. Note that the bulge between 240 and 200 km seems to be attributable to these velocities. Besides this difference, the subsolar solution goes a few kilometers lower into the
Figure 32 Results from the inclusion of horizontal velocities. The solid line is the 45° solution and the dashed line is the subsolar case. Note that the bulge between 240 and 200 km seems attributable to these velocities.
ionosphere with a slightly smaller maximum velocity. With these notations aside, the curves are relatively identical.

The calculated magnetic field (Figure 33) for SZA of 45° shows a distinct structure that can be explained in terms of the current equation (10). Over the altitude range of the ionosphere, several terms of this equation exchange dominance. If all non-collisional terms were small, one might expect a constant magnetic field profile until the collisionally dominated lower edge of the ionosphere. Increasing ion-neutral collisions represented by the drag force (-ρvυn dz) would reduce the magnetic field to zero effectively releasing the magnetic field from the plasma. The remaining structure in the magnetic field can be explained by the interaction of the other terms. The dip in magnetic field is a result of a departure from hydrostatic equilibrium driven by convection. The initial decrease in B is due to a larger pressure gradient than required to balance the weight of the ionosphere over this altitude range. This pressure gradient is created by the compression of the ionosphere at high altitudes by the small downward vertical velocity. As noted in Figure 33, for a brief period the ionosphere is in hydrostatic equilibrium. Finally, the -ρg term dominates as the weight of the ions exceeds the upper pressure gradient. This gravity term will, in turn, drive currents to increase B. The interaction between chemistry and convection can be visualized by noting the behavior of the particle pressure compared to magnetic pressure terms in the momentum plot (Figure 35). The total deviation of the magnetic field depends on both the magnitude of the gradients involved and the intensity of the magnetic field itself. Examining equation (10) reveals that changes in B are inversely proportional to the strength of B. For larger values of B, the same gradients produce lesser effects on the structure within the ionosphere.
Figure 33 Calculated magnetic field magnitude for Viking 1. The structure is determined by the dominant terms in the current equation (10).
Figure 34 The contrasts in magnetic field profiles between the subsolar point and 45°. The horizontal term in the magnetic differential equation opposes the current, driven by the pressure gradient (\(-d\bar{P}\)), which acts to reduce B below 240 km. The field is maintained longer and therefore has a greater relative minimum than the case of zero horizontal velocities. (Solid = 45°, Dashed = 0°)
A significant difference exists in the magnetic field profiles between the subsolar point and 45°. The horizontal term in the magnetic differential equation opposes the current, driven by the pressure gradient (-dP), which acts to reduce B below 240 km.. Examining Figure 34, (solid = 45° and dashed = 0°), the field is maintained longer and therefore has a greater relative minimum than the case of zero horizontal velocities.

Plotting the various terms in the ionospheric momentum equation provides some insight into the solution. Owing to small differences, only the momentum terms from the 45° simulation are depicted. In Figure 35, P denotes total ionospheric static thermal pressure n_e k(T_e + T_i), B denotes magnetic field pressure (B^2/2u_o), M denotes the missing pressure, G is the weight of the ionospheric plasma above the point of measurement, and k represents the kinetic flow pressure (pv^2). The total ionospheric momentum flux is shown. This total remains constant, except for the additions of gravity, until it is exchanged with the neutral atmosphere below 170 km. Below this altitude the total begins to dissipate as momentum is transferred to the neutral atmosphere by ion-neutral drag. The total pressure is converging with the weight of the ionospheric column indicating that the excess pressure of the solar wind has been transferred to the neutral atmosphere. Note that the missing pressure term is small, a tenth of the total pressure. In this particular simulation, it is only a minor contributor to the total momentum of the system.

5.3 Viking 2 Results

Finally, we will discuss a Viking 2 type simulation. This is a high solar wind
Figure 35 Profiles of the various ionospheric vertical momentum fluxes. P denotes total ionospheric static thermal pressure \( n_e k(T_e + T_i) \), B denotes magnetic field pressure \( B^2/(2\mu_0) \), M denotes the missing pressure, G is the weight of the ionospheric plasma above the point of measurement, and k represents the kinetic flow pressure \( (pv^2) \). The total ionospheric momentum flux is shown in bold. Note that the total incident solar wind pressure is transmitted to the neutral atmosphere at the lower edge of the ionosphere.
Figure 36 Percentage of missing pressure, over the altitude range of the calculations, used as an input to the model for the Viking 2 simulations. This profile is based upon the high solar wind case at Venus (Figure 20).
Figure 37 Translation of missing pressure (Figure 36) to actual pressures. These are the values of $P_{\text{Missing}}$ in the Viking 2 simulations.
dynamic pressure case, with the ion densities reflecting the more turbulent nature of the interaction. The appropriate percentage of missing pressure per altitude was used. The percentage of the total pressure near 280 km is 26%, as presented in Figure 36, compared to the intermediate case of 14%. This curve is based upon the statistical analysis of the high solar wind cases from PV data (Figures 20 and 21). From this statistical analysis, we determined that, during episodes of high dynamic pressure, the missing pressure was a substantial contributor to the overall momentum budget. These percentages translate to an initial actual missing pressure of $4.1 \times 10^{-10}$ dynes cm$^{-2}$ at the top of the ionosphere, a factor of four greater than the Viking 1 simulation. (Figures 37 and 24) The initial downward velocity was set to 10 m/s, and the initial magnetic field increased to 40 nT.

The ion concentration for the three dominant species [$O^+$], [$O_2^+$], and [$CO_2^+$] from the SZA of 45° simulation are shown in Figure 38. The solid lines are the calculated values, while the symbols designate the data from Viking 2. Note the large drop-out in density in [$O_2^+$] as well as [$CO_2^+$] between 175 and 200 km. The model produces a similar feature at approximately the same altitude range. Below this range, the ions will once again be determined by photochemical processes and the densities will recover to photochemical equilibrium values. There seems to be one physical explanation for such a feature: a large downward velocity. The flow speed must be sufficient to remove ions by convection faster than the chemical loss rate at that altitude. This produces a relative maximum above the region of highest velocity. Note the model velocity in Figure 39 approaches 560 m/s. This peak velocity is larger than the Viking 1 simulations owing to a much greater
Figure 38 Ion concentration profiles for Viking 2. Solid lines show model calculations. The measured values \([\text{O}^+\)] (triangles), \([\text{O}_2^+\]) (solid circles), and \([\text{CO}_2^+\]) (circles) are shown for comparison. Note the large drop-out in density of \([\text{O}_2^+\]) as well as \([\text{CO}_2^+\]) between 175 and 200 km. The model produces a similar feature at approximately the same altitude range. Below this range, the ions will once again be determined by photochemical processes and the densities will recover to photochemical equilibrium values.
Figure 39 Calculated downward vertical velocities for Viking 2. The peak velocity is greater than the Viking 1 simulations owing to a much greater missing pressure gradient, presumably due to an increased energy input from the solar wind.
missing pressure gradient, presumably due to an increased energy input from the solar wind. In this case, the velocity substantially modifies the structure of the ion density profiles.

The large downward velocity is driven by the pressure gradient in both the thermal pressure and the missing pressure. These gradients maintain and accelerate the flow through the increasing constriction of the background neutral population mimicking the decreasing area of flow through a nozzle. Re-writing the numerator of the differential velocity equation (9) assists in the demonstration of this assertion. Equations (11) - (16) are the terms grouped according to five classifications: collisions, gravity, pressure gradients from temperatures and densities, and horizontal velocities.

\[
\frac{B}{E_y} \left( -\rho V_z^2 v_{in} \right) - \rho V_z v_{in} \tag{11}
\]

\[
\frac{B}{E_y} \rho g V_z + \rho g \tag{12}
\]

\[
- \left( nk \frac{\partial T}{\partial z} + \frac{\partial P_m}{\partial z} \right) \left( \frac{B}{E_y} V_z \gamma' + 1 \right) \tag{13}
\]

\[
- \frac{1}{2} \frac{B}{E_y} Sm |V|^2 - Sm V_z \tag{14}
\]

\[
- \frac{B}{E_y} \gamma' kTS - \frac{s}{V_z} kT \tag{15}
\]

\[
- \rho \frac{V_z}{|V|} V_y \frac{\partial V_y}{\partial z} \tag{16}
\]

Figure 40a shows the competition between these factors for the determination of the
downward vertical velocity profile (Figure 39). This competition reduces to two terms, the collisional term (11) and the pressure gradient terms (13) from ion cooling through heat exchange with the neutrals and the missing pressure term. Note from Figure 40 that the other four terms are relatively negligible throughout the model’s altitude range. Near 170 km the pressure gradients begin to accelerate the flow. The momentum loss from the collisional drag force lags slightly behind, resulting in a net increase in the downward flow velocity. The flow accelerates until the pressure gradient can no longer overcome the loss of momentum from collisions. The drag force dominates below this altitude causing the velocity to turn-over and rapidly decrease. This in turn leads to the reduction of the drag force because it is directly proportional to the velocity. The final result is a stable solution with all parameters approaching zero.

The location of the velocity increase is dependent upon a large number of variables including neutral density, ion density, and flow velocity. More importantly, the magnitude of the missing pressure and it’s gradient are crucial in determining the altitude of the upturn in velocity. Recall that the missing pressure profile was from an average of many observations at Venus; the integrity of the curve was maintained when extrapolated to Mars. The noteworthy point is that the high velocity layer, accompanied with a ledge in ion densities, can be produced by adding the missing pressure term independent of an additional heating term (Q).

The vertical velocity profile for the subsolar simulation (no horizontal velocity effects) is shown in figure 40b. The velocity profile from 45° is also shown for comparison. Like the case for Viking 1, only greater, the acceleration of the ions occurs lower in the ionosphere and with a smaller relative maximum in the 0° SZA case. The effect on the ion distribution is presented in Figure 41. Note that the location of the ion
Figure 40a  Plot of the relative importance of the terms (11) - (16) in the differential velocity equation (9). The pressure gradient term accelerates the flow through the ever constricting background neutrals until the momentum loss due to collisions causes a turnover in the velocity profile. The two dominant terms (collisions and dP) are labelled.
ledge is 10 km lower in the subsolar case owing to the delay in the velocity feature. This results in the calculated ion densities for SZA of 45° (solid lines) agreeing with observations better than the subsolar simulated ion distribution (dashed lines).

The magnetic field (Figure 42) for the subsolar point is similar in structure to the previous simulations. The currents driven by departures from hydrostatic equilibrium modify the magnetic field, but not to the same extent as Viking 1. This is primarily because of the larger magnitude of the magnetic field. The reason is clear when one examines the differential in B (equation 10), which is inversely proportional to the magnetic field strength. The larger magnetic field is more resistive to perturbations driven by pressure gradients. Figure 43 demonstrates the contrasts between the 45° and 0° simulations. A difference is evident, but not to the same extent as Viking 1. The horizontal velocities maintain the field longer, but the higher relative vertical velocities near 170 km drives larger ohmic currents via the collisional drag force (-ρvv_in) that reduce the magnetic field at a greater rate. (Figure 40b same as above).

Finally, the ionospheric momentum profile is given by Figure 44. This figure is from the 45° simulation. Once again, the total remains constant except for additions from gravity. Near 175 km, the total begins to be transferred to the neutrals via the ion-neutral collisional drag force, until it approaches the weight of the ionosphere above. Note the emergence of the dynamic pressure (k) at these altitudes. Also, one sees that the missing pressure term is considerable; it is larger than the thermal pressure above 210 kilometers. In this simulation, the missing pressure makes up a large portion of the total ionospheric momentum budget.
Figure 40b  Results from the inclusion of horizontal velocities. The solid line is the 45° solution and the dashed line is the subsolar case. The acceleration of the ions occurs at a lower altitude with a smaller relative maximum in the subsolar case.
**Viking 2 Ions (SZA 0 and 45)**

![Graph showing ion concentration and altitude](image)

**Figure 41** Viking 2 ion concentrations for both cases. The delay in the peak velocity results in better agreement between observed and calculated ion densities for the 45° case (solid line).
Figure 42 Plot of calculated magnetic field magnitude versus altitude. The relative minimum is less pronounced than in the Viking 1 case.
Figure 43 Demonstration of the contrasts between the calculated magnetic field magnitude for 45° and the 0°.
Figure 44  Plot of the various terms of ionospheric vertical momentum flux versus altitude for Viking 2.
6.0 Discussion and Conclusions

The solar wind interaction with Mars, based upon information from the recent Phobos mission, appears to be dominated by the ionosphere of the planet and not an intrinsic magnetic field. These observations reinforce the stance taken by several researchers (Dessler, 1968; Cloutier et al 1969; Vaisberg, 1976; Cloutier and Daniell, 1979; Russell, 1979; Luhmann et al, 1987; Hanson and Mantas, 1988; Stewart, 1989; Shinagawa et al., 1989; Riedler et al. 1989; Yeroshenko et al., 1990; Schwingenschuh et al., 1990). While a complete lack of intrinsic field has not been ruled out, attempts to further understand the solar wind/ionospheric coupling at Mars are justified. One such effort has been presented here.

The energetics of a solar wind interaction with an ionosphere of a planet are still somewhat of a mystery. Most authors agree that solar wind energy deposition into the ionosphere must occur. (Chen et al., (1978); Johnson, (1978); Fox and Dalgarno, (1979); Luhmann et al., (1987); Mantas and Hanson, (1985); Hanson and Mantas, (1988); Cloutier et al., 1987) This conclusion is based upon the high electron and ion temperatures present in both the Venusian and Martian ionospheres discussed in Chapter 5. Heating by solar EUV alone is inadequate: an additional energy source is required. A feedback mechanism between solar wind energy deposition and ionospheric conditions must also occur. The ionospheric parameters (e.g. temperatures, magnetic fields, ionopause height) must respond to changing solar wind conditions through this mechanism.

Although the most plausible explanation for sources of the required energy involve wave-particle interactions (Cloutier et al., 1987), the details are beyond the scope of this
work. We have addressed the volume heating term (Q) in the energy conservation equation. Many models (Chen, 1987) assume an energy input profile that generically accounts for solar wind "heating". The flow/field models (Cloutier et al., 1987; McGary, 1987; Stewart, 1987) include an independently specified heating profile. This heating term, however, is only loosely constrained.

Understanding that the heating term requirement actually pointed to the possibility that the flow/field equations had excluded a pressure or momentum term has resulted in the elimination of the remaining free parameter of the model. This realization led to the identification of a new partial pressure through the PV momentum analysis. This study therefore provides another observationally defined input that further empirically constrains the model. Note that the independent heating term and this new pressure term are unrelated; the addition of Q simply produced some of the physical effects necessary for a stable and accurate solution to exist. Contrary to the heating term, which only appears in the energy equation (4), the pressure term contributes to both the momentum and energy equation (2 and 4). Another noteworthy point is that the missing pressure produced stable, empirically acceptable results at Mars, thereby removing all dependence upon an independently specified heating term. Given the fine balance between competing parameters, there was no assurance that the inclusion of this previously ignored pressure would have an appreciable effect on the solution, let alone the right combination of effects to allow the reduction of Q to zero.

The results of the Mars model show good agreement with Viking ion densities, the principal empirical constraint. For the high solar wind case, the model produces a ledge in [O_2^+] and [CO_2^+] densities near 180 km. This feature is reminiscent of the bump in [O_2^+] densities observed at Venus. The predicted magnetic fields within the ionosphere
of Mars were also shown to be similar in structure to those at Venus. The horizontal velocity effects were small, but not negligible, especially in the magnetic field profile for the lower solar wind case. The acceleration in downward velocity from collisional effects was also delayed between sza of 0° and 45°, producing variations in the altitude and structure of the ion ledge.

As demonstrated, the identification of the source of the missing pressure is not essential to its incorporation in the model, but a candidate does exist. The possibility that the missing pressure is actually the contribution from a distribution of suprathermals is intriguing. The dependence of the missing pressure on solar wind conditions could be explained in terms of suprathermals. Whatever the source, be it wave-particle interaction etc., the driving force most probably comes from the solar wind. Larger solar wind dynamic pressures would logically result in more energy available for the production of either more suprathermals, hotter suprathermals, or both. The existence of suprathermals at Venus was first verified using the OIMS by Taylor et al. (1980) and later the (ONMS) by Kasprzak et al. (1982). Taylor et al. define suprathermals as ions with energies greater than 20 eV. Neither of these instruments were designed to accurately detect or qualitatively describe the suprathermal ion population of Venus, but the evidence of their existence is overwhelming. Figure 45, from Kasprzak et al. (1982), shows a typical response of OEFD, OETP, OIMS, and ONMS as the instruments encounter suprathermals in the Venusian ionosphere. Brace et al. (1980) tried to establish a static balance between solar wind pressure and the ionopause magnetic field pressure; a "slight" imbalance (up to a factor of two) apparently exists. While attempting to explain this inconsistency, the authors state that the effect played by suprathermal ions (Taylor et al., 1980) is not yet clear. The authors do not exclude the possibility that the suprathermal pressure is a significant contributor to the total pressure of the ionosphere.
Figure 45 A typical response of OEFD, OETP, OIMS, and ONMS as the instruments encounter suprathermals in the Venusian ionosphere. (Orbit 403) (from Kasprzak et al., 1982)
The existence of suprathermals within the Earth's magnetosphere is well documented (Axford and Hines, 1961; Dungey, 1961; Shelley et al., 1972; Ghelmetti et al., 1979; Lundin et al., 1982; and Sauvaud and Delcourt, 1987). Various regions, from the foreshock down to the ionosphere, support populations of suprathermals with densities and energies of both solar-wind and ionospheric origin. A considerable amount of data has been accumulated that confirms the presence of ionospheric suprathermals throughout the terrestrial magnetosphere (Delcourt et al., 1989). In the upstream foreshock region particle densities typically range from 3 - 20 cm\(^{-3}\) with energetic particles having energies of 1 to several hundreds of keV. The magnetosheath number densities can increase to 1 X 10\(^6\) m\(^{-3}\). These particles have thermal energies of a few keV with suprathermal energies up to several hundred keV. Within the magnetosphere the thermal energies range from 1 eV in the plasmasphere to 1 keV near the magnetopause.

These observations have motivated analysis of the suprathermal ionospheric ion transport under the effect of large-scale magnetospheric convection (Delcourt et al., 1989; Moore et al., 1985; and Sauvaud and Delcourt, 1987). While these studies feature the solar wind as the primary energy source, any conclusions about suprathermal populations of Venus and Mars based upon terrestrial analogies should be drawn cautiously owing to the inherent differences between a magnetospheric and a purely ionospheric interaction.

Kramer (1991) has developed a Monte-Carlo simulation of a distribution of suprathermals interacting with ionospheric fields in a background neutral atmosphere. Although a discrepancy at lower altitudes exists, the results are promising because of the qualitative agreement between Kramer's model and the statistical analysis of PV
observations reported in this study. Research in progress (L. Kramer, 1991; private communication) may reconcile the differences, possibly owing to particle scattering from flux ropes at lower altitudes.

The model is highly sensitive to the volume heat input \( Q \): a fine balance exists between a reasonable solution and instability. Likewise, the model appears to be as sensitive to the missing pressure profiles. If the suprathermals are the source, they must produce a stable model that matches observations while independently satisfying the range of values determined by the statistical analysis of Pioneer Venus data.

A final note about the possible connection between the missing pressure and suprathermal pressure. Hanson and Mantas (1988) have recently extracted information from Viking measurements regarding suprathermals within the ionosphere of Mars. The data were delayed owing to an original lack of confidence in their validity coupled with the sophisticated nature of the required analysis. Recent success (Mantas and Hanson, 1985) in comparing actual RPA currents with expected currents calculated from theoretical considerations reduced their reservations and encouraged the development of techniques to extract the data. Hanson and Mantas demonstrate that not only does a suprathermal population exist at Mars, but they pervade the ionosphere.

While this pervasiveness is relevant to this study, even more significant is the partial pressure contribution from the suprathermals. Recall that the initial values of the missing pressure at 280 km for the Viking 1 and 2 simulations were \( 1.2 \times 10^{-10} \) and \( 4.1 \times 10^{-10} \) dynes \( \text{cm}^{-2} \) respectively. The measured suprathermal pressure at 280 km was \( 4 \times 10^{-10} \) dynes \( \text{cm}^{-2} \) (Hanson and Mantas, 1988). This evidence is circumstantial; the same suprathermal pressure that agrees in magnitude with our missing pressure disagrees in
structure at lower altitudes. The importance lies in the relative consistency between suprathermal observations (at both Venus and Mars) and the independently identified missing pressure, providing some intriguing possibilities for future research.
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