THE SOLAR WIND INTERACTION WITH MARS: RESULTS OF THREE-DIMENSIONAL THREE-SPECIES MHD STUDIES


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ABSTRACT

The interaction of the solar wind with planets with no or only very weak intrinsic magnetic fields, such as Mars and Venus, involves their ionosphere/atmosphere system. Single-species MHD models, which incorporate some of the important mass-loading processes, have been useful in reproducing numerous observed features at these planets, such as the location of the bow shock, but they do have obvious limitations. Our present 3D MHD model uses three continuity equations in order to consider protons in the solar wind and the two dominant heavy ion species (O\(^+\) and O\(^{2+}\)) in the ionosphere, separately. We have used this model to study the interaction processes at Mars. The model results are in general agreement with the average observed bow shock shape and position and predict reasonable locations for the ionopause. The calculated oxygen escape flux down the tail was estimated to be about 3 \times 10^{25} \text{s}^{-1}, which is consistent with Phobos-2 estimates. We also studied the possible effect of the surface crustal magnetic field on the bow shock and the ionosphere of Mars.

INTRODUCTION

The Mars Global Surveyor (MGS) measurements have shown that Mars has no significant global intrinsic magnetic field. However, many local, small-scale, crustal, remnant magnetizations were found to be present (Acuña et al., 1998). An important consequence of the weak intrinsic field is a Venus-like interaction between the solar wind and the ionosphere/atmosphere. A well-defined bow shock has been observed around Mars. Acuña et al. (1998) found that the observed bow shock positions are variable, with a root-mean-square deviation about the average position near the terminator plane of about 0.5 Martian radius. Previous spacecraft observations at Mars show similar bow shock position variability, which is twice that observed at Venus. The electron reflectometer, carried on board the Mars Global Surveyor, indicates the existence of a dayside ionopause between the altitudes of about 200 and 800 km (Mitchell et al., 2000). The data of Mitchell et al. (2000) were obtained near solar minimum, when the ionospheric thermal pressure is low, therefore their ionopause positions of 200-800 km might be lower than those in the case of medium or high solar activity.

Studies of the solar wind interaction with unmagnetized bodies (such as Venus and Mars) have been carried out in the past using both semi-kinetic (e.g., Brecht, 1997) and single-species, ideal MHD model calculations (e.g., Murawski and Steinolfson, 1996; Bauske et al., 1998; Shinagawa and Bougher, 1999). The single species MHD calculations have, in general, considered the planet/moon as a perfectly conducting sphere. These model studies have been successful in predicting numerous observed features, such as the bow shock position. Semi-kinetic calculations have been especially useful in showing the lack of symmetry in the interaction processes. It has been argued that the use of semi-kinetic models is especially appropriate for Mars, where the ion gyroradius is of the same order as the planetary radius. However, it is important to note that the ideal MHD equations have been found to be successful even in such situations. The possible reason for this may be the fact that, as shown by the semi-kinetic code, and observed
by the Phobos-2 wave instrument (Grard et al., 1989), significant wave activity is present, leading to a wide variety of wave particle interactions, which in turn act as pseudo-collisions. A two-species ideal MHD model, to study the interaction of the solar wind with Venus was developed recently (Tanaka and Murawski, 1997; Tanaka, 1998), which for the first time used an actual, realistic ionosphere as the obstacle to the solar wind.

In order to study the solar wind interaction with the ionosphere of Mars, a multi-species, MHD model has been developed to include a more realistic ionosphere of Mars. The results from our two-species ideal MHD calculations of the solar wind interaction with Mars have been presented in the paper of Liu et al. (1999). The two ion species considered were the protons from the upstream solar wind and O$_2^+$ in the Martian ionosphere. The ionosphere observed by the Viking landers indicated that the major ions in the ionosphere consist of both O$_2^+$ and O$^+$ (Hanson et al., 1977). In the following section we present the results from our three-species ideal MHD simulation of the solar wind-Mars interaction, expanding the existing two-species model to include another major ion species in the Martian ionosphere, i.e. O$^+$. Later we also present the results from calculations in which a surface dipole field is added to the 3D three-species model, with the purpose of investigating the impact of the surface crustal magnetic field on the solar-wind Mars interaction.

THREE-SPECIES MHD SIMULATION

Model and Simulation Details

In our model we use the following conservative form of the classical, ideal MHD equations:

$$\frac{\partial W}{\partial t} + (\nabla \cdot F)^T = Q$$

(1)

The normalized conservative state vector (W) and flux tensor (F) are the same as those given in the paper of Nagy et al. (2000).

The source vector, Q, used is:

$$Q = \begin{pmatrix} 0 \\ S_2 - L_2 \\ S_3 - L_3 \\ (\rho_1 + \rho_2 + \rho_3) u - (\rho_1 + \rho_2 + \rho_3) v u - u (L_2 + L_3) \\ 0 \\ Q_6 \end{pmatrix}$$

(2)

where the source term of the energy equation, $Q_6$, is

$$Q_6 = (\rho_1 + \rho_2 + \rho_3) u \cdot g - \frac{1}{2} u^2 (L_2 + L_3) - (\rho_1 + \rho_2 + \rho_3) \nu u^2 - \frac{1}{\gamma - 1} \left( \frac{L_2 p}{32 \rho_1 + 2 \rho_2 + \rho_3} + \frac{L_3 p}{16 \rho_1 + 0.5 \rho_2 + \rho_3} \right) + \frac{1}{\gamma - 1} S_2 \frac{k m_2}{m_2} T_0 + \frac{1}{\gamma - 1} S_3 \frac{k m_3}{m_3} T_0$$

(3)

where $\rho_1$, $\rho_2$, and $\rho_3$ are the mass densities of the proton, O$_2^+$, and O$^+$, respectively, the protons are the major ion species in the upstream plasma, while O$_2^+$ and O$^+$ are the two major ion species in the Martian ionosphere, $p$ is the total thermal pressure of the plasma, $u$ is the plasma velocity, $B$ is the magnetic field vector, and the specific heat ratio, $\gamma$, was taken to be $5/3$, $S_2$ and $L_2$ are the O$_2^+$ mass source and loss rates, respectively, $S_3$ and $L_3$ are the O$^+$ mass source and loss rates, respectively, $m_2$ is the mass of O$_2^+$, $m_3$ is the mass of O$^+$, $\nu$ is the ion neutral collision frequency (taken to be $4 \times 10^{-10} \{[O] + [CO_2] \} s^{-1}$), $T_0$ is the temperature of the newly produced ions, and $g$ is the gravitational acceleration. Chemical reactions involving protons are neglected here.

The chemical reactions that we considered for the production and loss of O$_2^+$ and O$^+$ ions are:

$$CO_2 + h\nu \rightarrow CO_2^+ + e$$

(4)

$$O + h\nu \rightarrow O^+ + e$$

(5)

$$CO_2^+ + O \rightarrow O^+ + CO_2$$

(6)
where the photoionization rate of CO$_2$ is taken to be $7.3 \times 10^{-7}$ s$^{-1}$, the photoionization rate of O is taken to be $2.734 \times 10^{-7}$ s$^{-1}$, $k_1 = 9.6 \times 10^{-11}$ cm$^3$ s$^{-1}$, $k_2 = 1.1 \times 10^{-9}$ cm$^3$ s$^{-1}$, $k_3 = 1.64 \times 10^{-10}$ cm$^3$ s$^{-1}$, $k_4 = 7.38 \times 10^{-8}$ cm$^3$ s$^{-1}$ (Schunk and Nagy, 2000). In this model, we have made the assumption that $[e] \approx [O_2^+] + [O^+]$ (this assumption simplifies the source terms). The density distributions of atomic oxygen atoms and carbon dioxide molecules used are: $[O] = 3 \times 10^8 \exp(-h/140 \text{ km})$ cm$^{-3}$ and $[CO_2] = 1 \times 10^{10} \exp(-h/15.84 \text{ km})$ cm$^{-3}$, where $h$ is the altitude from the Martian surface. These neutral density profiles are consistent with Chen et al. (1978).

A computational domain defined by $-24R_M \leq x \leq 8R_M$, $-16R_M \leq y, z \leq 16R_M$, where $R_M=3396$ km is the radius of Mars, was used in the calculations, the inner boundary was taken to be 140 km above the Martian surface, and a non-uniform grid (with cell sizes ranging from 53 km to 6792 km) was used.

The inner boundary conditions are: $P_l = 0.3P_{sw}$, where $P_{sw}$ is the mass density of the undisturbed solar wind; the $O^+$ and $O_2^+$ densities were taken to be the photochemical equilibrium values; $B$ was set equal to zero and a reflective boundary was used for $u$; the sum of the electron and ion temperatures was assumed to be 3000 K.

The upstream solar wind plasma temperature used is $3.5 \times 10^5$ K. The IMF (Interplanetary Magnetic Field) was assumed to be a Parker spiral in the X-Y plane with an angle of 56 degrees and a magnitude of 3 nT and the solar wind velocity was selected to be 500 km s$^{-1}$. Three basic cases are examined in this three-species MHD model for the solar wind-Mars interaction: (1) nominal $P_{sw}$ case ($n_{sw} = 4$ cm$^{-3}$), (2) low $P_{sw}$ case ($n_{sw} = 2$ cm$^{-3}$), and (3) high $P_{sw}$ case ($n_{sw} = 8$ cm$^{-3}$). The parameters of the nominal $P_{sw}$ case correspond to a sonic Mach number of 7.2 and Alfvénic Mach number of 15.3.

Results

In Figure 1 we plot various calculated parameters along the subsolar line, for the low pressure case (upper panel), the nominal case (middle panel) and high pressure case (lower panel). We show the distributions of the kinetic (ram) pressure of the solar wind ($P_{sw}$), the thermal pressures of protons ($P_1$), molecular oxygen ions ($P_2$), and atomic oxygen ions ($P_3$), and the magnetic pressure ($P_B$) along the Sun-Mars line on the dayside. The region where the magnetic field peaks is called the magnetic barrier, and it is supported by the thermal pressure of ionospheric plasma. We define ionopause as the location where the ionospheric thermal pressure balances the sum of the magnetic pressure and the shocked solar wind thermal pressure. The calculated subsolar ionopause and bow shock locations are listed in Table 1. The calculated subsolar bow shock position for the nominal case is about 1.65 $R_M$, approximately the same as the two-species MHD model result (Liu et al., 1999), which is in very good agreement with the observed MGS values (Vignes et al., 2000). Like the two-species model results showed, both the bow shock and the ionopause locations moved out slightly (about one grid point) from the planet when the solar wind pressure was decreased. It is clearly shown in Figure 1 that when the solar wind dynamic pressure is increased, the peak value of the magnetic field in the magnetic barrier increases, and the magnetic barrier becomes more compressed. The larger the solar wind kinetic pressure is, the deeper the magnetic field penetrates into the ionosphere, and larger portion of the ionosphere is

<table>
<thead>
<tr>
<th>Density of upstream solar wind plasma (cm$^{-3}$)</th>
<th>Upstream solar wind kinetic pressure (nPa)</th>
<th>Ionopause altitude (km)</th>
<th>Bow shock location ($R_M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.8</td>
<td>680</td>
<td>1.74</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>590</td>
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<tr>
<td>8</td>
<td>3.2</td>
<td>465</td>
<td>1.57</td>
</tr>
</tbody>
</table>
Fig. 1. The distributions of kinetic pressure of the solar wind ($P_{\text{sw}}$), thermal pressure of proton ($P_1$), thermal pressure of $O_2^+$ ($P_2$), thermal pressure of $O^+$ ($P_3$), and magnetic pressure ($P_B$) along the Sun-Mars line on the dayside for the low pressure case (upper panel), the nominal case (middle panel) and high pressure case (lower panel).

Here we present some results from the nominal case of our model. The 3D configuration of magnetic field magnitude is shown in Figure 2. The solar wind flows from positive X to negative X. We can easily see the formation of bow shock, magnetic barrier and magnetotail. In Figure 2, the white lines show the draping IMF (interplanetary magnetic field), while the red lines show the magnetic field slipping over the body.

Figure 3 shows the density distribution of $O_2^+$ and $O^+$ around Mars in the equatorial plane and the X-Z meridian plane. The maximum value of $O_2^+$ density on the dayside is of the order of $10^5$ cm$^{-3}$, which is consistent with the Viking Lander measurements (Hanson et al., 1977). The maximum $O_2^+$ density in the wake region is of the order of $10^3$ cm$^{-3}$, which is in reasonable agreement with the few radio occultation observations (Zhang et al., 1990). As magnetized and compressed. Similar results were obtained by Tanaka (1998) for Venus. Our model calculations also show that, similar to the subsolar bow shock, the terminator bow shock moves towards the planet when solar wind density and/or ram pressure increases. The terminator bow shock is located at approximately 2.7 Mars radii for our nominal case.
we know, there is basically no photoionization on the night side, and the formation of the nightside ionosphere is due to the day-to-night plasma transport, which will be discussed later. The calculated total O\(^+\) flux flowing down the tail and escaping from the planet is approximately \(2.61 \times 10^{26} \text{ s}^{-1}\). The maximum value of O\(^+\) density on the day side is of the order of \(10^3 \text{ cm}^{-3}\), which is also consistent with the Viking Lander measurements (Hanson et al., 1977). The maximum O\(^+\) density in the wake region is about 65 cm\(^{-3}\). The total O\(^+\) flux flowing down the tail and escaping from the planet is estimated to be approximately \(0.45 \times 10^{25} \text{ s}^{-1}\). Therefore, the total oxygen ion flux, including both O\(^+\)\(_2\) and O\(^+\), is approximately \(3.06 \times 10^{25} \text{ s}^{-1}\) and is in good agreement with the estimate based on the local flux measurements by the ASPERA instrument carried aboard Phobos 2 (Lundin, 1989). We also calculated the oxygen fluxes at the terminator plane: the O\(^+\)\(_2\) flux is about \(5.15 \times 10^{25} \text{ s}^{-1}\); the O\(^+\) flux is about \(0.54 \times 10^{26} \text{ s}^{-1}\). Therefore, the total oxygen flux at the terminator plane is about \(5.69 \times 10^{25} \text{ s}^{-1}\). Recalling the escape oxygen flux of \(3.06 \times 10^{25} \text{ s}^{-1}\), this means that about 50% of the oxygen ions which cross the terminator escape from the tail, while the other 50% flow down into the ionosphere.

The plasma speed in the vicinity of Mars is displayed in Figure 4 (upper panel). The arrows show the direction of the plasma velocity. On the dayside, the flow in the ionosphere is generally upward. At increasing solar zenith angles the topside ionospheric flow drapes poleward and nightward, which is followed by downward (towards the planet) and outward (away from the planet) flow in the wake region as mentioned above. This shows that the formation of the Martian nightside ionosphere is a result of the transport of ionospheric plasma from the dayside to the nightside. Figure 4 (upper panel) shows that a stagnation point in the central tail is located at about 1.5 \(R_M\). Beyond this region the flow is tailward. Figure 4 (upper panel) also indicates the "tail boundary", which represents the transition from a hot, rapidly flowing magnetosheath plasma to a cooler, more slowly flowing medium. We can see that the terminator radius of the Martian tail is about 1.5 Mars radii, which is significantly greater than the Venus tail terminator radius of only about 1.2 Venus radii (Luhmann et al., 1991). This difference is consistent with the Phobos 2 observations (Luhmann et al., 1991).

The magnetic field intensities near Mars in the equatorial plane and meridian plane are displayed in Figure 4 (lower panel). On the dayside, the magnetic field increases monotonically to a peak downstream of the bow shock, but eventually vanishes on the downstream side of the ionopause, creating a diamagnetic region (also cf. Figure 1). In the magnetic barrier, the peak magnetic field intensity is about 40 nT. The magnetic barrier is strongest and thinnest at the subsolar point and becomes weaker and thicker at the terminator, similar to the situation at Venus (Tanaka and Murawski, 1997). The asymmetry in the X-Y plane results from the tilted upstream magnetic field. In Figure 4 (lower panel) we can clearly see that the magnetotail has a two-lobe structure, and there is a central current sheet. The terminator bow shock occurs at approximately 2.7 Martian radii.
Fig. 3. The density distribution of O$^+_2$ (upper panel) and O$^+$ (lower panel) around Mars in the equatorial plane and the X-Z meridian plane for the nominal case.

THREE-SPECIES MHD SIMULATION WITH SURFACE MAGNETIC DIPOLE FIELD

Model and Simulation Details

Recently the Mars Global Surveyor has provided a new, very low, upper bound on the global magnetic field at Mars, indicating that the intrinsic field is negligible. However, it found the presence of strong localized crustal magnetic fields (Acuña et al., 1998, 1999; Connerney et al., 1999). Sources with equivalent surface dipole magnetic moments as large as $1.3 \times 10^{17}$ ampere$^{-2}$ meters were detected (Acuña et al., 1999).

In addition to the solar wind-induced magnetic field, the magnetic field of crustal origin and effects of the rotation of Mars might play an important role in determining the structure and dynamics of the Martian ionosphere and solar wind interaction. It is also expected that at solar maximum the ionospheric thermal pressure exceeds the average solar wind dynamic pressure most of the time. Under such conditions, the solar wind magnetic field would be effectively shielded by the ionosphere of Mars, and the crustal magnetic field might become a dominant magnetic field below the ionosphere.

In order to study the impact of the localized crustal magnetic field sources on the solar wind-Mars interaction, we ran a three-species model calculation in which we added a surface dipole field source in our three-species MHD model. A dipole with a moment of $2.6 \times 10^{20}$ G cm$^3$ was added at 45°S (latitude of 45° in the southern hemisphere) on the surface. The assumed dipole moment we used for this, so-called Case 4, leads to ionospheric magnetic fields of the same magnitude as the largest fields observed by the magnetometer on MGS (cf. Acuña et al. (1999)).
Fig. 4. The plasma speed and magnetic field intensity around Mars in the equatorial plane and the X-Z meridian plane for the nominal case. The arrows show the direction of the plasma velocity.

**Results**

Figure 5 shows the magnetic field intensity around Mars in the X-Z meridian plane for Case 4. As a consequence of the surface dipole, the bow shock position on the side of southern hemisphere (the hemisphere in which the dipole is added) moves farther away from the planet surface noticeably. Also, by comparing Figure 5 with Figure 4, the distribution of magnetic field intensity in the X-Z meridian plane becomes fairly asymmetric on the night side for Case 4, while it is originally quite symmetric for the case without crustal field (cf. Figure 4). The small figure in Figure 5 shows the magnetic field intensity near the surface magnetic field source on a different scale. The white dashed line indicates the altitude of 400 km. At the altitude of 400 km, the magnitude of the magnetic field is about 800 nT.

Figure 6 shows the altitude profiles of the calculated electron densities for case 1 (nominal $P_{SW}$ case without crustal magnetic field) and case 4 (nominal $P_{SW}$ case with crustal magnetic field source on the surface) along the line with a solar zenith angle of 45° in the southern hemisphere on the dayside. For case 1, the peak electron density is about $7.4 \times 10^4 \text{ cm}^{-3}$ and for case 4, the peak electron density is about $1.58 \times 10^5 \text{ cm}^{-3}$. Above about 200 km the scale height of the electron density for case 4 is higher than that for case 1 at the solar zenith angle of 45°. The small apparent change in the altitude of the peak densities should not be considered to be significant, because the size of the grids, even in these ionospheric regions is about 53 km. Nevertheless the results indicate that the crustal magnetic field inhibits vertical diffusion and thus have a significant effect on the structure of the ionosphere, as well as the interaction with the solar wind.
Fig. 5. The magnetic field intensity around Mars in the X-Z meridian plane for Case 4. The small figure shows the magnetic field intensity near the surface magnetic field source on a different scale. The white dashed line indicates the altitude of 400 km.

We also ran two cases (Case 5 and Case 6) with the crustal dipole field added at the subsolar point and the southern terminator point, respectively. The dipole field strength used in these two cases is the same as that used in Case 4. For Case 5, the location of the subsolar bow shock is about 1.77 \( R_M \); compared with the results of Case 1, the bow shock moved out approximately 0.12 \( R_M \). For Case 6, the terminator bow shock moved out approximately 0.2 \( R_M \), compared to that of Case 1.

**CONCLUSION**

The large-scale solar wind interaction with the Martian ionosphere is numerically simulated in the framework of a three-dimensional, three-species MHD model. The impinging solar wind is represented by \( \text{H}^+ \) ions, and the ionosphere is assumed to consist of \( \text{O}_2^+ \) and \( \text{O}^+ \) ions.

The model results show the essential properties of the bow shock, magnetosheath draping, magnetic barrier, formation of ionopause, and a double-lobed magnetotail whose polarity is related to that of the draped magnetosheath field. Our model results for nominal solar wind pressure case show reasonable agreement with the measured bow shock positions (Vignes et al., 2000). The calculated ionopause location was defined as the altitude, where the sum of the \( \text{O}^+ \) and \( \text{O}_2^+ \) pressures becomes equal to the sum of the magnetic and the shocked solar wind \( \text{H}^+ \) pressure. The calculated subsolar ionopause altitudes are at 465, 590, and 680 km for the high, nominal and low pressure cases, respectively. These values fall well within the ionopause altitudes estimated from the electron fluxes observed by the MGS ER (Mitchell et al., 2000). The calculated oxygen escape flux (including both \( \text{O}_2^+ \) and \( \text{O}^+ \)) down the tail is approximately \( 3.06 \times 10^{25} \text{ s}^{-1} \) and is in good agreement with Phobos 2 observation (Lundin, 1989).

The modeled localized, single, surface magnetic dipole field results in changes in the shape and location of the bow shock, and the electron density profile in the ionosphere. The complicated magnetic field surface morphology of Mars suggests the possibility that some of the observed bow shock position variability could be explained by the changing orientation of locally magnetized regions as the planet rotates. Our model results show that the crustal
The altitude profiles of the calculated electron densities for case 1 and case 4 along the line with a solar zenith angle of 45° in the southern hemisphere on the dayside.

magnetic field can also have a significant effect on the ionospheric structure.

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