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## RESEARCH ARTICLE

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### Key Points:

- For the first time, the effect of the ambipolar electric field is self-consistently included in the global multifluid MHD model
- The ambipolar electric field plays a significant role in driving ion loss from Mars. The ion mass loss can be enhanced by more than 50%
- The improved model matches best with MAVEN observations in comparison with previous models

### Supporting Information:

- Supporting Information S1

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## Importance of Ambipolar Electric Field in Driving Ion Loss From Mars: Results From a Multifluid MHD Model With the Electron Pressure Equation Included

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**Abstract** The multifluid (MF) magnetohydrodynamic model of Mars is improved by solving an additional electron pressure equation. Through the electron pressure equation, the electron temperature is calculated based on the effects from various electron-related heating and cooling processes (e.g., photoelectron heating, electron-neutral collision, and electron-ion collision), and thus, the improved model can calculate the electron temperature and the electron pressure force terms self-consistently. Model results of a typical case using the MF with electron pressure equation included model are compared in detail to identical cases using the MF and multispecies models to identify the effect of the improved physics. We find that when the electron pressure equation is included, the general interaction patterns are similar to those with no electron pressure equation. However, the MF with electron pressure equation included model predicts that the electron temperature is much larger than the ion temperature in the ionosphere, consistent with both Viking and Mars Atmosphere and Volatile EvolutionN (MAVEN) observations. Using our numerical model, we also examined in detail the relative importance of different forces in the plasma interaction region. All three models are also applied to a MAVEN event study using identical input conditions; overall, the improved model matches best with MAVEN observations. All of the simulation cases are examined in terms of the total ion loss, and the results show that the inclusion of the electron pressure equation increases the escape rates by 50–110% in total mass, depending on solar condition and strong crustal field orientation, clearly demonstrating the importance of the ambipolar electric field in facilitating ion escape.

## 1. Introduction

At Earth, there are two principal pathways to generate ionospheric outflows: Poynting flux and electron precipitation (Strangeway et al., 2005). Although both processes lead to an increase in ion scale height and ion upwelling, the former does so through Joule dissipation, while the latter does so through electron heating/ionization, which enhances the ambipolar electric field. The ambipolar electric field, also known as the electron pressure gradient force, plays an important role in driving ion acceleration along open magnetic field lines and forming a polar wind in the polar cap region (Axford, 1968; Banks & Holzer, 1968; Ganguli, 1996; Welling et al., 2015; Yau et al., 2007).

In comparison, Mars does not have a substantial internal planetary magnetic field on a global scale but has remanent crustal magnetic fields mostly located in the southern hemisphere (Acuña et al., 1998, 1999). Therefore, its interaction with the solar wind is mainly the ionosphere-atmosphere type of interaction, similar to that of Venus. However, the presence of the strong localized crustal magnetic fields significantly increases the complexity of the interaction, making its plasma environment and magnetic field topology unique in the solar system, akin to a mixture of Venus and Earth, with a globally induced magnetosphere (Bertucci et al., 2011) but with mini-magnetospheres (local regions in which both sides of magnetic field lines are connected to the planet) around strong crustal field regions (Mitchell et al., 2001; Nagy et al., 2004).

The understanding of the solar wind-Mars interaction has been greatly improved by the observations of Mars Global Surveyor (MGS, Brain, 2006; Mars Express, Barabash et al., 2007; and the ongoing Mars Atmosphere and Volatile Evolution [MAVEN] mission, Jakosky et al., 2015). The measurements made by the MGS magnetometer/electron reflectometer have shown spatially localized enhancements in electron fluxes over the strong crustal fields on both the dayside and night, indicating solar wind electron precipitation into the Martian upper atmosphere through the cusps of strong crustal fields (Xu et al., 2014). Recent observations by the Langmuir Probe and Wave (LPW) instrument (Andersson et al., 2015) onboard MAVEN revealed that the electron temperature ( $T_e$ ) of the daytime ionosphere above 180-km altitude is higher than predicted (Ergun et al., 2016), suggesting that the ambipolar electric field may play a more important role in driving ion loss from Mars.

Collinson et al. (2015) first provided an upper limit of  $\pm 2$  V of the total potential drop in the Martian ionosphere by examining the photoelectron spectra measured by the MAVEN Solar Wind Electron Analyzer instrument (Mitchell et al., 2016). They later found that there was a large ( $7.7 \pm 0.6$  V) parallel potential drop above the Utopia Planitia, a large impact basin with no significant crustal magnetic field (Collinson et al., 2016). Recently, Xu et al. (2018) made a more accurate estimate of the magnitude of the ambipolar electric field on Mars, by combining measurements from the SupraThermal and Thermal Ion Composition (McFadden et al., 2015) and Solar Wind Electron Analyzer. According to the new method, the field alignment potential has an average value ranging from 0 to 1.5 V, smaller than the energy required for planetary ionospheric ions to overcome gravity (2.1 eV for  $O^+$  and 4.2 eV for  $O_2^+$ ).

There also has been some numerical work to quantify the effect of the ambipolar electric field. Ergun et al. (2016) evaluated the effect using a one-dimensional Combined Photochemistry and Ion Tracing model, with prescribed electron temperature profile, and found that the ambipolar electric field from heated electrons can substantially increase ion outflow ( $O^+$ ,  $O_2^+$ , and  $CO_2^+$ ) in the present day. However, the effect has not been investigated on a global scale in a self-consistent manner. The ambipolar electric field is generally included in both global magnetohydrodynamic (MHD) or hybrid models, but the electron temperature is typically assumed to be constant (Brecht & Ledvina, 2010; Kallio et al., 2010) or adiabatic (Brecht et al., 2016; Brecht & Ledvina, 2014; Modolo et al., 2016) in the hybrid model or the same as the ion temperature in the MHD model (Dong, Bougher, et al., 2015; Ma et al., 2004; Najib et al., 2011). The latter assumption is reasonable inside the deep ionosphere, where the neutral density is so dense that collisions between ions (and electrons) and neutrals are frequent; as a result, both the ion temperature and electron temperature are tightly coupled with the neutral temperature. However, it is often not the case in other plasma regions such as the upper ionosphere, induced magnetosphere, magnetosheath, and in solar wind. To accurately calculate the electron temperature and electron pressure force, a separate electron pressure equation is needed in the model. As shown in Ma et al. (2011), the inclusion of the electron pressure equation in the Titan MHD model leads to a significantly improved agreement between the model field and Cassini magnetometer data in the ionosphere.

In this study, the multifluid (MF) MHD model is further improved by including an electron pressure equation to self-consistently calculate the electron temperature and the electron pressure gradient force. In addition, some chemical reactions such as dissociative recombination reactions (e.g.,  $O_2^+ + e \rightarrow O + O$  and  $CO_2^+ + e \rightarrow CO + O$ ) and electron impact ionization rates are dependent on the electron temperature. Thus, improvement of the model is expected to lead to a more accurate description of both the plasma interaction with the solar wind and the ion density in the ionosphere. The rest of the paper is organized as follows: A detailed description of the MFPe model (i.e., improved MF MHD model with electron pressure (Pe) equations included) is described in section 2. Model results are presented in section 3. We first present results from the MFPe model in section 3.1. Comparisons of MFPe model results with the multispecies (MS), and the MF models are provided in section 3.2. The effects of different forces and current distribution are discussed in section 3.3. A MAVEN case study is shown in section 3.4. Model results of ion escape rates are discussed in section 3.5. A brief summary and some discussion are presented in section 4.

## 2. Methodology: MFPe Model

The improved MF MHD model of Mars solves for the continuity, momentum, and pressure of the four ion fluids ( $H^+$ ,  $O^+$ ,  $O_2^+$ , and  $CO_2^+$ ), together with an electron pressure equation and magnetic induction

equation. The continuity, momentum, and magnetic induction equations are the same as in Najib et al. (2011), also listed below for completeness:

Continuity equations for each ion fluid:

$$\begin{aligned}\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{u}) &= S_i - L_i \\ S_i &= m_i n_i \left( \nu_{\text{ph},i} + \nu_{\text{imp},i} + \sum_{s=\text{ions}} k_{\text{si}} n_s \right) \\ L_i &= m_i n_i \left( \alpha_{R,i} n_e + \sum_{t=\text{neutrals}} k_{it} n_t \right),\end{aligned}\quad (1)$$

where  $\rho_i$  ( $i = 1$  to 4) are the mass densities of  $\text{H}^+$ ,  $\text{O}_2^+$ ,  $\text{O}^+$ , and  $\text{CO}_2^+$ , respectively, and  $S_i$  and  $L_i$  ( $i = 1$  to 4) are the mass production and loss rates, respectively, which calculated based on main chemical reactions in the ionosphere including ionization (with rates  $\nu_{\text{ph},i}$  and  $\nu_{\text{imp},i}$ ) of each neutral, charge exchange ( $k_{\text{si}}$ ) between the major neutral and ions and recombination reactions (with rates  $\alpha_{R,i}$ ).

Momentum equations for each ion fluid:

$$\rho_i \frac{\partial (\mathbf{u}_i)}{\partial t} + \rho_i (\mathbf{u}_i \cdot \nabla) \mathbf{u}_i = -\nabla P_i + \rho_i G + n_i q_i (\mathbf{E} + \mathbf{u}_i \times \mathbf{B}) + \rho_i \sum_{n=\text{neutrals}} \nu_{in} (\mathbf{u}_n - \mathbf{u}_i) + S_i (\mathbf{u}_n - \mathbf{u}_i). \quad (2)$$

The first three terms on the right-hand side of the momentum equation represent the forces exerted on the plasma, which are ion thermal pressure gradient force, gravity, and electromagnetic forces. The last two terms are ion momentum change due to ion-neutral collisions and chemical reactions, respectively.

The electric field  $\mathbf{E}$  is defined as

$$\mathbf{E} = -\frac{\nabla P_e}{en_e} - \mathbf{u}_e \times \mathbf{B}, \quad (3)$$

and the electron velocity is given by

$$\mathbf{u}_e = \mathbf{u}_+ = \frac{\mathbf{J}}{en_e}, \quad (4)$$

where  $\mathbf{u}_+$  is the charge averaged ion velocity.

$$\mathbf{u}_+ = \frac{\sum_i n_i q_i \mathbf{e}_i}{en_e}. \quad (5)$$

As a result, the electromagnetic forces acting on the plasma (the third item on the right-hand side of equation (2)) can be expressed as

$$\mathbf{F}_{EMo} = -\frac{n_i \nabla P_e}{n_e} + n_i e (\mathbf{u}_i - \mathbf{u}_+) \times \mathbf{B} + \frac{n_i}{n_e} \mathbf{J} \times \mathbf{B}. \quad (6)$$

The three terms on the right-hand side of the equation (6) correspond to partial electron pressure gradient force, motional electric force, and partial  $\mathbf{J} \times \mathbf{B}$  forces. It is important to note that the motional electric force only appears when the ions are moving across the magnetic field. The magnetic field is moving at charge averaged ion velocity ( $\mathbf{u}_+$ ), so the motional electric force on a particular ion depends on its relative velocity to  $\mathbf{u}_+$ . The shocked solar wind protons and planetary ions usually move at different speeds, with the former moving rapidly toward the planet and the latter nearly stationary. So their relative velocity to the charge averaged velocity (that is  $\mathbf{u}_i - \mathbf{u}_+$ ) are in opposite directions; as a result, solar wind protons and planetary ions “see” the motional electric field with opposite signs (Dubinin et al., 2018).

Magnetic induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left( \mathbf{u}_e \times \mathbf{B} + \frac{\nabla P_e}{en_e} \right). \quad (7)$$

The above equation includes the effect of the Hall term, assuming the magnetic field is frozen with electrons and the effect of ambipolar electric field. The diffusion term in the induction equation is neglected in the model, assuming that the plasma is perfectly conducting. We expect the magnetic diffusion term may be important in the ionosphere below the ionospheric peak region where the plasma is only partially ionized, which will be a subject of future study.

Ion pressure equation for each ion fluid:

$$\begin{aligned} \frac{\partial P_i}{\partial t} + (\mathbf{u}_i \cdot \nabla) P_i + \gamma P_i (\nabla \cdot \mathbf{u}_i) = & \sum_{i=\text{ions}} \sum_{n=\text{neutrals}} \frac{\rho_i \nu_{in}}{m_i + m_n} [2k(T_n - T_i) + (\gamma - 1)m_n u_i^2] \\ & + \sum_{i=\text{ions}} \nu_{ie} n_i n_e (T_e - T_i) 2k + \frac{(\gamma - 1)}{2} \sum_{i=\text{ions}} S_i u_i^2 + \sum_{i=\text{ions}} \left( \frac{S_i T_n - L_i T_i}{m_i} k \right). \end{aligned} \quad (8)$$

The pressure of each ion fluid is  $P_i$ . The terms on the right-hand side of the equation correspond to the energy exchange due to ion-neutral collisions, ion-electron collisions, and chemical reactions (last two terms), respectively.

Electron pressure equation:

$$\begin{aligned} \frac{\partial P_e}{\partial t} + (\mathbf{u}_e \cdot \nabla) P_e + \gamma P_e (\nabla \cdot \mathbf{u}_e) = & \sum_{n=\text{neutrals}} \nu_{ne} n_n n_e (T_n - T_e) 2k + \sum_{i=\text{ions}} \nu_{ie} n_i n_e (T_i - T_e) 2k + (\gamma - 1) \\ & \sum_{i=\text{ions}} N_i \nu_{ph,i} E_0 - \sum_{i=\text{ions}} n_i \alpha_{R,i} n_e T_e k - L_{e,R(CO_2)} - L_{e,V(CO_2)}, \end{aligned} \quad (9)$$

The electron pressure ( $P_e$ ) is new, relative to the earlier models (Ma et al., 2004; Najib et al., 2011). The right-hand side terms correspond to the energy exchanges due to electron-neutral collisions, electron-ion collisions, heating due to photoelectrons, and recombination reactions, respectively. Note that what is calculated here is the pressure equation of core thermal electrons, and  $T_e$  refers to the temperature of thermal electrons. The major heat source for thermal electrons is Coulomb heating from the superthermal electron population, while the main energy loss is due to  $\text{CO}_2$  collisional rotational and vibrational cooling (Matta et al., 2014; Sakai et al., 2016). The superthermal electron heating is included through superthermal photoelectron heating term (the fifth term on the right-hand of equation (9)).  $E_0$  is the approximate heating energy per photoelectron produced due to photoionization process. It is taken to be 1.0 eV in the calculation, estimated based on Sakai et al. (2016). As for the electron-neutral cooling, we take into account both elastic and inelastic electron-neutral collisions with major neutrals, with the latter including both  $\text{CO}_2$  rotational and vibrational cooling processes. The elastic electron-neutral collision rates ( $\nu_{ne}$ ) are taken from Schunk and Nagy (2009), while the  $\text{CO}_2$  rotational ( $L_{e,R(CO_2)}$ ) and vibrational ( $L_{e,V(CO_2)}$ ) energy loss rates are from Dalgarno (1969).

In summary, the improved MF MHD model solves for the mass density, velocity, and pressure of all the four ion fluids, as well as the electron pressure and magnetic field. As in our previous Mars MHD models, the above set of equations is solved using the Michigan BATS-R-US code (Toth et al., 2012), which uses an upwind finite volume scheme, based on the approximate Riemann solver, to ensure the conservation of state variables. In this study, we also used the local time stepping scheme, which allows different grid cells to select different time steps, thereby accelerating convergence and saving computing resources.

The simulation is done in the classic Mars-centered solar orbital (MSO) coordinate system, with the  $X$  axis pointing from Mars to the Sun, and  $Z$  axis perpendicular to Mars orbital plane, and  $Y$  axis completing the right-handed coordinate system, roughly in the direction antiparallel to the orbital velocity of Mars. The calculation domain covers a broad region of  $[-24, 8] R_M$  in  $X_{\text{MSO}}$  and  $[-16, 16] R_M$  in  $Y_{\text{MSO}}$  and  $Z_{\text{MSO}}$  directions, where  $R_M$  is the radius of Mars ( $R_M = 3,396$  km). This large computational domain is used to minimize numerical artifacts from the outer boundary. A nonuniform spherical grid is used with high radial resolution (5 km) near the inner boundary of 100-km altitude and gradually increases to 630 km near the downstream outer boundary. The angular resolution is fixed to  $3^\circ$  in both the longitudinal and azimuthal directions throughout the computational domain. The total number of cells is about 2.2 million.

**Table 1.**  
*Specific Parameters and Conditions Applied to the Cases Performed in the Study*

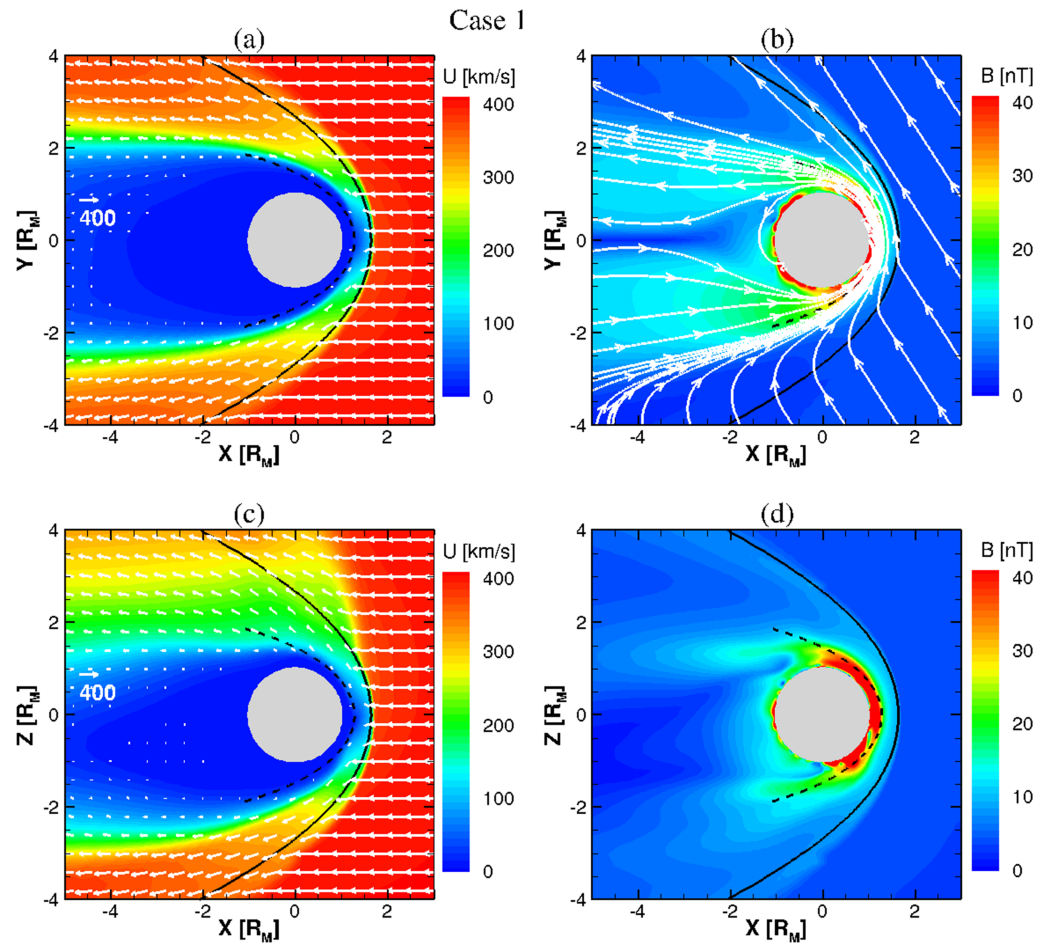
Cases	Solar EUV conditions	Crustal field	Solar wind density ( $\text{cm}^{-3}$ )	Solar wind velocity (km/s)	IMF (nT)
Case1	Solar max	Yes (dayside)	4	(−400,0,0)	(−1.6,+2.5, 0.0)
Case2	Solar max	Yes (nightside)	4	(−400,0,0)	(−1.6,+2.5, 0.0)
Case3	Solar max	No	4	(−400,0,0)	(−1.6,+2.5, 0.0)
Case4	Solar min	Yes (12-03-2014/08:43 UT)	10.4	(−310,9.3,11.2)	(0.3,−5.6,−1.0)

*Note.* Solar wind density, velocity, and IMF conditions for Case 4 are based on Solar Wind Ion Analyzer and magnetometer measurements during the inbound pass of Orbit 451. EUV = extreme ultraviolet; IMF = interplanetary magnetic field.

Similar to our previous Mars models (Ma et al., 2004; Najib et al., 2011), the inner boundary of the computation domain is set at 100-km altitude. Because the neutral densities near the inner boundary are very dense, the ion-neutral, electron neutral collisional rates are high, and as a result, the temperature of all the ion fluids and electrons are tightly coupled with the neutral temperature in this collisional dominant region. So, in the model, we set the temperature of all the ion fluids and electrons to be the same as the neutral temperature at the inner boundary ( $T_i = T_e = T_n$ ). At present, the neutral temperature is taken to be a constant at all altitudes in the model, 134 K for solar max and 117 K for solar min. In addition to set the lower boundary for  $T_e$  and  $T_i$ ,  $T_n$  is also used in the ion and electron pressure equations. In the ion pressure equations, it is used to account for ion-neutral collisional cooling effect and for newly generated ions through either ionization or charge exchange processes. In the electron pressure equation, it is used to account for electron-neutral collisional cooling effect. According to MAVEN observations, neutral temperatures are nearly constant or gradually increase with height, especially within the 150- to 180-km altitude range (Bougher et al., 2017). Thus, the assumption of a constant  $T_n$  will result in a slight underestimation of ion and electron temperatures at high altitudes. The strong ion-neutral collision also results in tight coupling of ions and neutral velocities. The effect of the neutral wind is currently neglected in the model, assuming  $U_n = 0$ . A reflective boundary condition is applied for the velocities of all ion fluid ( $\mathbf{u}_i$ ) to ensure near zero velocities of all the ion fluids at the inner boundary. The magnetic field vectors are fixed to be the same as the crustal field at the boundary. The crustal field model is taken from Morschhauser et al. (2014), under spring equinox conditions for nonevent cases or the actual configuration for Case 4 (see Table 1.).

In the current version of the model, the Martian atmosphere consists of three neutrals:  $\text{CO}_2$ , O, and H. For simplicity, we use the same 1-D neutral atmospheric profiles for solar max and solar min conditions as used in Ma et al. (2004). The chemical reaction rates are the same as used in Ma et al. (2004) and Najib et al. (2011). The only addition is the electron impact ionization, using Brain et al. (2010). Another improvement of the model is the use of Chapman function instead of  $\cos$  (solar zenith angle) to calculate optical depth (Ma et al., 2015).

To examine the importance of the ambipolar electric field, we run four cases (see Table 1. for specific parameters used in the run) for three MHD models: multispecies and single-fluid (MS), MF, and MFPe. Cases 1–3 are ideal cases, while Case 4 is a MAVEN event study, corresponding to 3 December 2014 (Orbit 451). For Cases 1–3, the solar wind condition is chosen to be nominal, with a density of  $4 \text{ cm}^{-3}$ , a velocity of 400 km/s, and thus a dynamic pressure of 1.07 nPa. The interplanetary magnetic field (IMF) follows the typical Parker spiral orientation of  $56^\circ$  at Mars with a magnitude of 3 nT, that is,  $(B_x, B_y, B_z) = (-1.6, 2.5, 0) \text{ nT}$ . For Case 4, the solar wind density, velocity, and the IMF conditions are based on 30-min averaged MAVEN Solar Wind Ion Analyzer (SWIA; Halekas et al., 2015) and magnetometer (Connerney et al., 2015) measurements in the solar wind before the inbound bow shock crossing of the orbit. For Cases 1–3, the photoionization rates and neutral profiles for solar maximum conditions are used, while for Case 4, we used solar minimum conditions to match with the actual extreme ultraviolet condition for the orbit. Also note that for Cases 1 and 2, the strong crustal field region is on the dayside and nightside, respectively, while in Case 3, the crustal field model is turned off to emphasize the effect of the ambipolar electric field. To directly compare with MAVEN observations, for Case 4, the Mars rotation axis is taken to be  $(-0.416, -0.09, 0.905)$ , and the subsolar latitude and longitude are set to be  $(131.9, -24.6)^\circ$  to match the actual conditions of Mars at the time when MAVEN was near periapsis on Orbit 451.

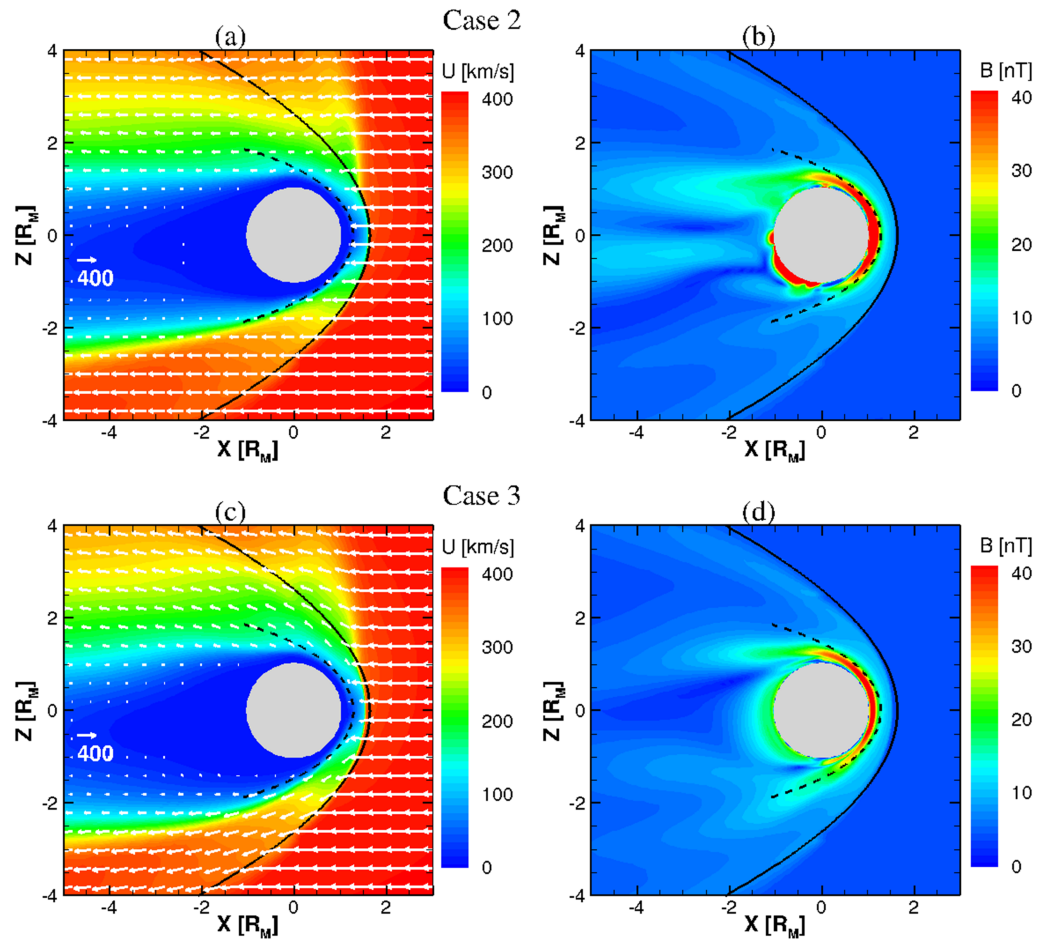


**Figure 1.** Contour plots of mass-averaged plasma flow speed (left panels) and magnetic field strength (right panels) in the XY plane (a and b) and XZ plane (c and d) for the multifluid magnetohydrodynamic model with electron pressure model for case 1. The white arrows show the projections of the plasma flow (left panels), and the white lines are projections of magnetic field lines (top right panel). The black solid lines and dashed lines are bow shock and induced magnetosphere boundary locations, respectively, from Vignes et al. (2000).

### 3. Simulation Results

#### 3.1. Results From the MFPe Model

The general interaction patterns, as predicted by the MFPe model, are shown in Figure 1, using Case 1 as an example. Across the shock, the plasma flow is slowed down and diverted around the obstacle, while the magnetic field piles up and wraps around, similar to the previous MS and MF model (Ma et al., 2004; Najib et al., 2011). Keep in mind that for the MF MHD models, the flow patterns are generally different for different ion fluids, and here the mass-averaged flow is shown. In this case, only the magnetic field contours provide a good indication for the bow shock locations. There is a clear asymmetry in the equatorial (XY) plane, especially for the magnetic field strength due to the IMF direction being the Parker Spiral. The quasi-perpendicular bow shock in the dusk side is slightly farther from the planet, compared with the quasi-parallel shock in the dawn sector, consistent with both MGS and MAVEN observations (Vignes et al., 2002; Gruesbeck et al., 2018). The bow shock locations also show a clear north-south asymmetry (Panel d), with the plasma boundary being slightly farther away from the planet in the southern hemisphere, where the crustal field is relatively strong. The same asymmetry is also observed by MAVEN, as found by Gruesbeck et al. (2018), who built a 3-D bow shock surface model, using over 1,000 MAVEN bow shock crossings. Compared to the previous observations (Trotignon et al., 2006; Vignes et al., 2000), both the bow shock positions and the induced magnetosphere boundary (IMB) positions predicted by the

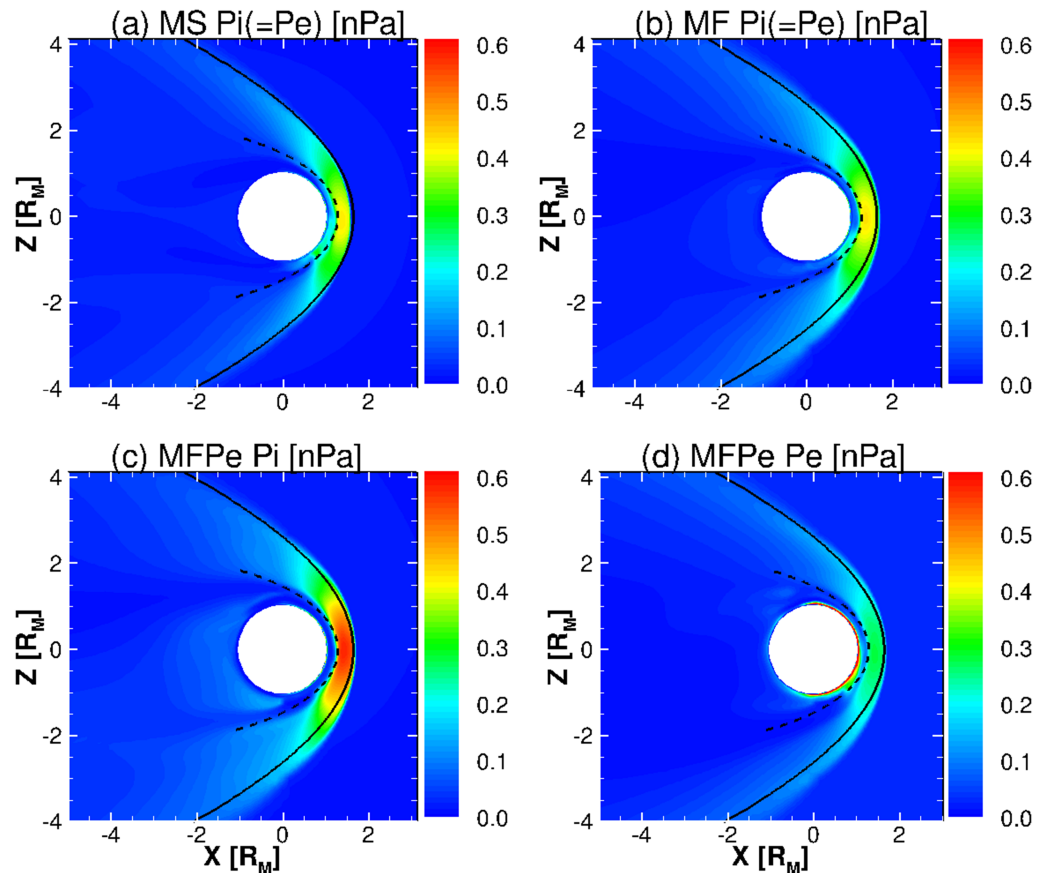


**Figure 2.** Contour plots of plasma flow speed (left panels) and magnetic field strength (right panels) in the  $XZ$  plane for the multifluid magnetohydrodynamic model with electron pressure model for cases 2 (upper panels) and 3 (bottom panels). The white arrows show the projections of the plasma flow (a and c). The black solid lines and dashed lines are bow shock and induced magnetosphere boundary locations, respectively, from Vignes et al. (2000).

model for Case 1 are slightly farther away from the planet. This is because (1) Case 1 is for solar maximum conditions and (2) the strong crustal field region faces toward the Sun.

For comparison, in Figure 2, we show the model results for the nightside crustal field case (Case 2) and the no crustal field case (Case 3) in the  $XZ$  plane in the same format. When the strong crustal field is located at midnight (Panel b), the model results match perfectly with the MGS observation of the bow shock and IMB boundaries. When the crustal fields are turned off (Panel d), the plasma boundaries, as predicted by the model, are slightly inward as compared with observations most notably near the subsolar region. The subsolar bow shock locations for the three cases are 1.69, 1.61, and 1.54  $R_M$ , respectively, which clearly demonstrate that the presence of crustal fields, especially when located on the dayside, helps to stand off the shocked solar wind.

It is also interesting to note that there is a large asymmetry in the  $XZ$  plane for all three cases along the convection electric field direction ( $+Z$ ) for the mass-averaged flow speed (Figures 1c, 2a, and 2c). This is because, in the current setup, the convection electric field  $\mathbf{E}_{SW} = -(\mathbf{V}_{SW} \times \mathbf{B}_{IMF})$  aligns with the  $Z$  axis in MSO, making the Mars Solar Electric coordinates the same as the MSO coordinates. The north-south asymmetry in the flow pattern is caused by the different motional electric field force acting on the plasma (equation (6)), which only arises when different ions move at different flow velocities. This term is especially important in regions where planetary ions and shocked solar wind protons coexist. As a result, the originally stationary planetary heavy ion fluids are accelerated in the  $+Z$  ( $+E$ ) direction, forming a heavy ion plume as observed by MAVEN (Dong, Fang, et al., 2015) and as predicted by test particle models (e.g., Fang et al., 2008). The plume extends



**Figure 3.** Ion and electron pressure distribution in the  $XZ$  plane using (a) multispecies (MS), (b) multifluid (MF), and (c,d) multifluid with electron pressure equation (MFPe) models for case 1. The black solid lines and dashed lines are bow shock and induced magnetosphere boundary locations, respectively, from Vignes et al. (2000).

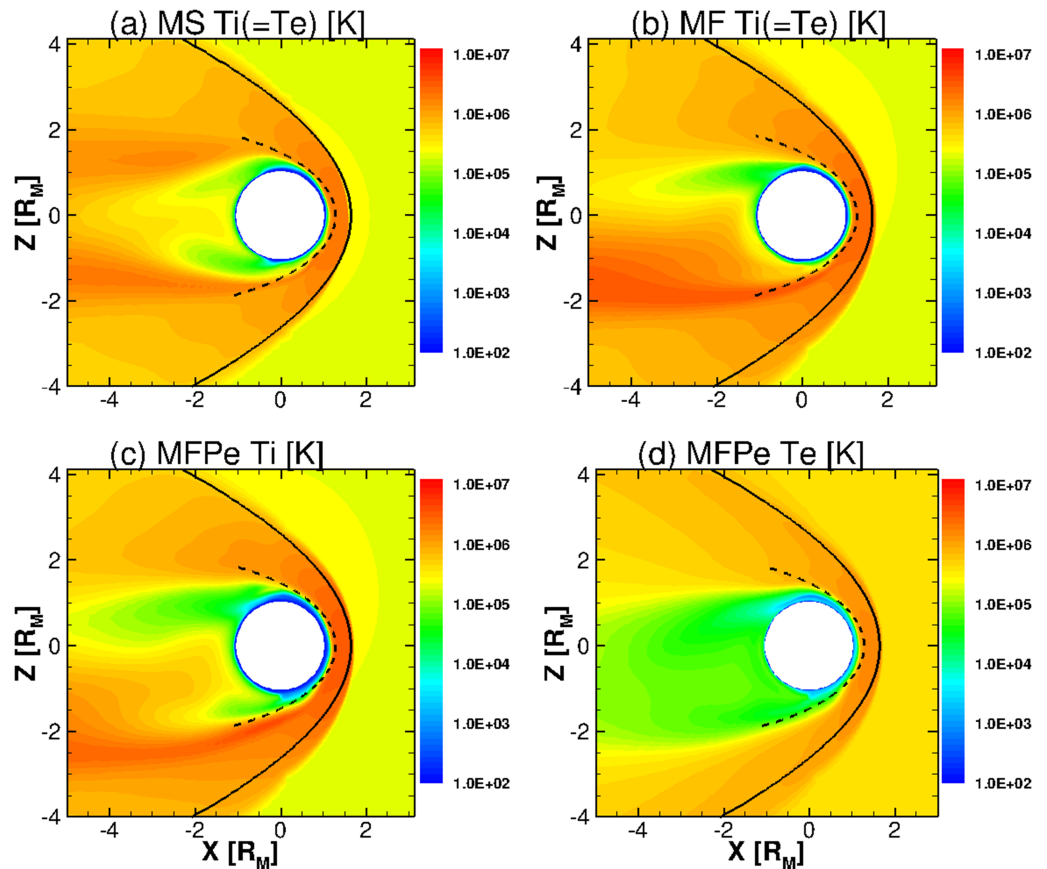
in regions even outside of the bow shock in the northern hemisphere, significantly disturbing the solar wind flow. In contrast, the shocked solar wind is accelerated in the opposite direction, and as a result, the plasma wake is shifted slightly downward in the negative  $Z$  direction. Similar feature is also observed by MAVEN (Halekas et al., 2018). It is also worth noting that there is only a small asymmetry of the bow shock locations in the  $XZ$  plane for Cases 2 and 3 (Panels b and d), with the bow shock location being slightly outward in the  $-Z$  direction due to the MF effect caused by motional electric field forces. This clearly demonstrates that the large north-south asymmetry of the bow shock locations in Case 1 is mainly caused by the presence of a strong crustal field in the southern hemisphere. This is also consistent with MAVEN results (Gruesbeck et al., 2018).

### 3.2. Comparison of MFPe With MS and MF Models

Figure 3 (and Figure 4) shows a comparison of the ion and electron pressure (and temperature) distributions in the  $XZ$  plane using three different models for Case 1. Both the MS and MF models solve only ion energy (pressure) equation and assume that the electron pressure (and temperature) are the same as the total ion pressure (and mean ion temperature; see Panels a and b). The MS model results also show some north-south asymmetry in the ionosphere and near the shock, which are mainly due to asymmetric distribution of the crustal fields but are less apparent compared with MF and MFPe models. The bow shock location, as predicted by the three models, also varies somewhat. The corresponding subsolar bow shock locations of MS, MF, and MFpe models are 1.58, 1.70, and 1.69  $R_M$ , respectively. The large difference between MS and the two MF models clearly show that the MF treatment results in a larger obstacle to the solar wind.

Because the MFPe model solves the electron pressure equation directly in addition to ion pressure equations, it is the only model that is able to reproduce different ion and electron pressures (and temperatures) of the



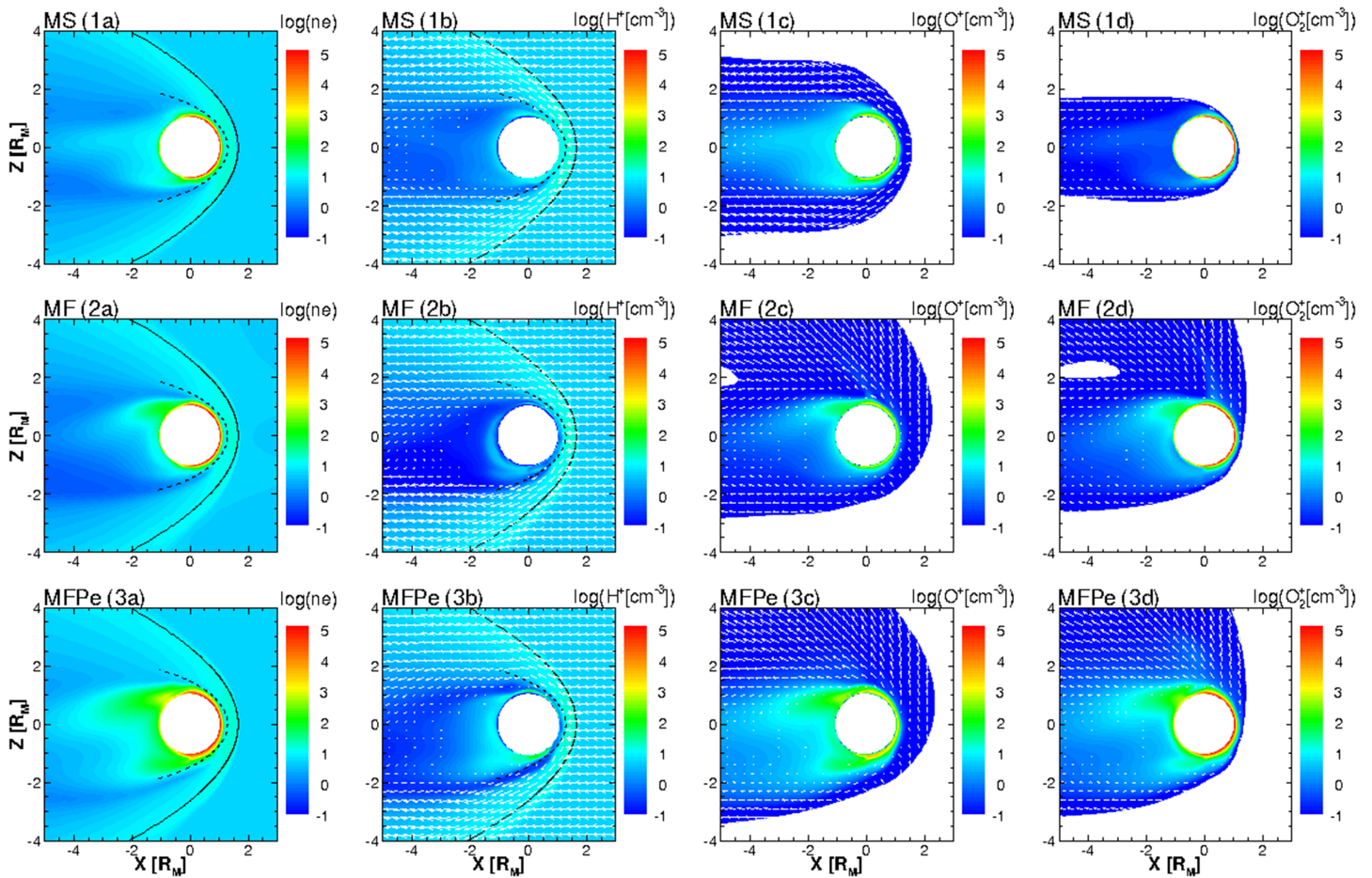


**Figure 4.** Ion and electron temperature distribution from the three models for case 1, in a format similar to Figure 3.

three models. As predicted by the MFPe model, the ion and electron temperatures are different in both the ionosphere, where the electron temperatures predominate, and in the magnetosheath region, where the ion temperatures are relatively high. The pressure (and temperature) distributions in the XY plane are quite symmetric (not shown) for all three models but show significant asymmetric patterns in the XZ plane due to crustal fields. In addition, regions of strong crustal magnetic field in the dayside feature with higher electron pressure (see Figure 3d), consistent with MAVEN observations (Flynn et al., 2017). It is worth noting that even though the MFPe model predicts higher electron pressure (temperature) than the MF model in the ionosphere, the two MF models result in very similar bow shock locations.

Figure 5 shows density distributions of electrons and three ions ( $H^+$ ,  $O^+$ , and  $O_2^+$ ) in the XZ plane using three different models for Case 1. All the density patterns show clear asymmetric distribution in north-south direction. The asymmetry in the MS model is the least, which is mainly due to asymmetric crustal field distribution. Both the MF and MFPe models show larger asymmetry, especially for planetary ions ( $O^+$  and  $O_2^+$ ), with a plume-like structure forming in the northern hemisphere consistent with MAVEN observations (Dong, Fang, et al., 2015). The ion plume is formed mainly due to the pickup process of planetary ions at high altitude; as a result, the densities of heavy ions are largely enhanced in the northern hemisphere (along +E direction).

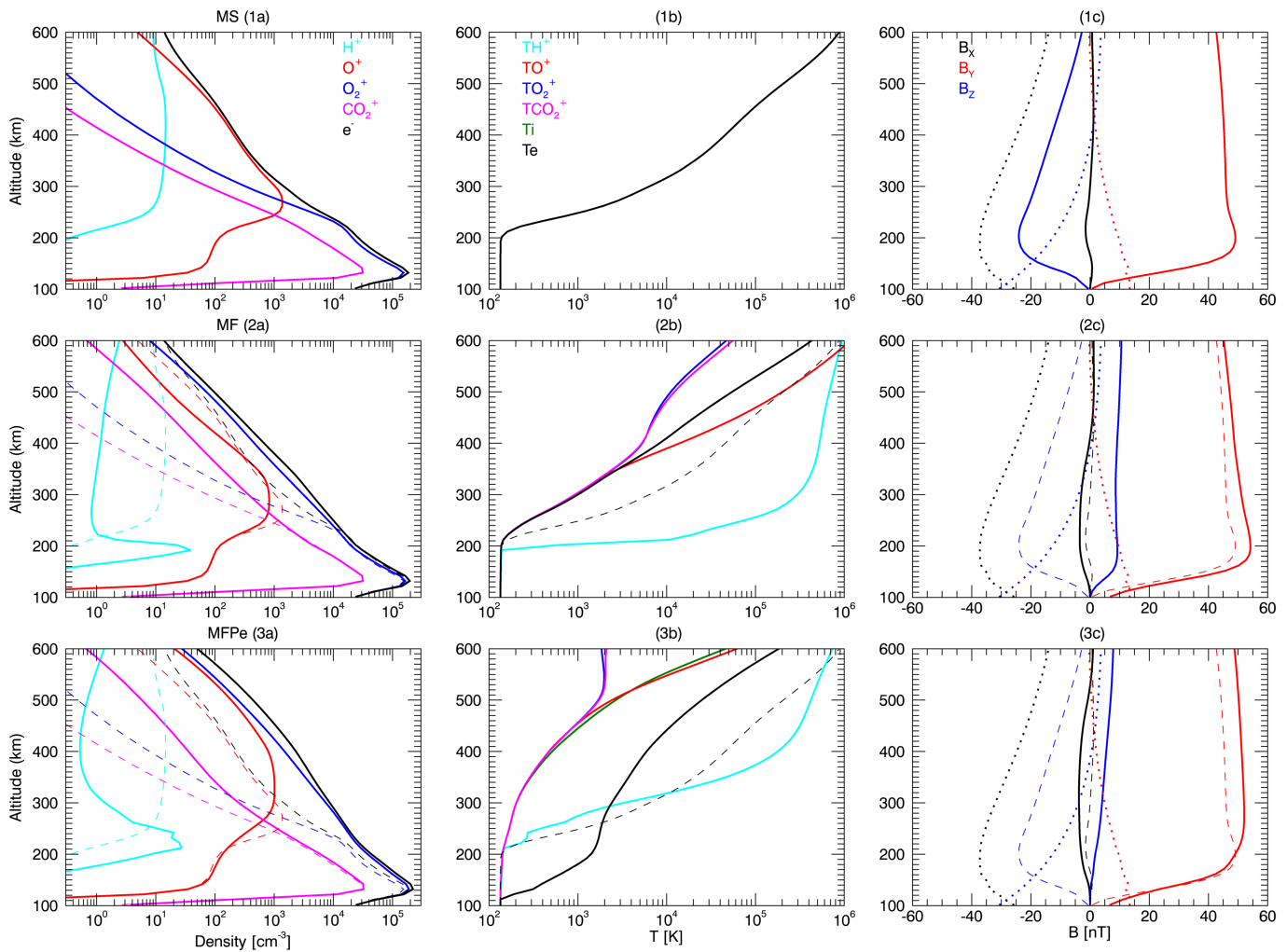
There is also a clearly higher concentration of electrons,  $O^+$  and  $O_2^+$  ion particles in the tail region as predicted by the MFPe model, due to the upwelling of ions in the ionosphere caused by larger electron pressure gradient force (details to be discussed in the next section). Flow vectors are also plotted for each of the three ions, which clearly show that protons have a very different flow pattern, compared to heavy ions ( $O^+$  and  $O_2^+$ ) for both the MF and MFPe models. The shocked solar wind proton flow diverts around the planet after the shock, while planetary ions are mostly moving along the convection electric field direction, especially in the northern hemisphere.



**Figure 5.** Electron and ion density distributions in the XZ plane using three different models for case 1. The black solid lines and dashed lines are bow shock and induced magnetosphere boundary locations, respectively, from Vignes et al. (2000). The white regions are areas where the corresponding densities are less than  $0.01 \text{ cm}^{-3}$ . The white arrows show flow vectors of corresponding ions.

Figure 6 shows altitude profiles of ion and electron densities and temperatures, as well as magnetic field along the subsolar line for the three different models for Case 1. As can be seen from the figure, densities below 200 km are very similar for MS and MF models, as this is below the exobase, a photochemistry-dominated region. The densities of the MFPe model differ from the two other models even at low altitude ( $\sim 140$  km), especially for  $\text{O}_2^+$  and electron densities, due to the fact that some of the chemical reaction rates depend on electron temperature. Below the exobase, both the MS and MF models predict that ion and electron temperatures are about the same as neutral temperature due to the tight coupling between ions and neutrals (note that in Panels 1b and 2b, Ti and Te are the same), while Te from the MFPe model is much higher than the neutral temperature because of photoelectron heating (see Panel 3b). Given that the dissociative recombination rate of  $\text{O}_2^+$  is proportional to  $(1/\text{Te})^{0.56}$ , with higher electron temperature predicted by the MFPe model, the loss rate of  $\text{O}_2^+$  decreases, and the  $\text{O}_2^+$  density and the total ion density increase. The peak electron density for the MS and MF models is  $\sim 1.85 \times 10^5 \text{ cm}^{-3}$ , and for the MFPe model, it is  $2.21 \times 10^5 \text{ cm}^{-3}$ , about 20% higher. The peak altitude of electron densities of all the models remains the same.

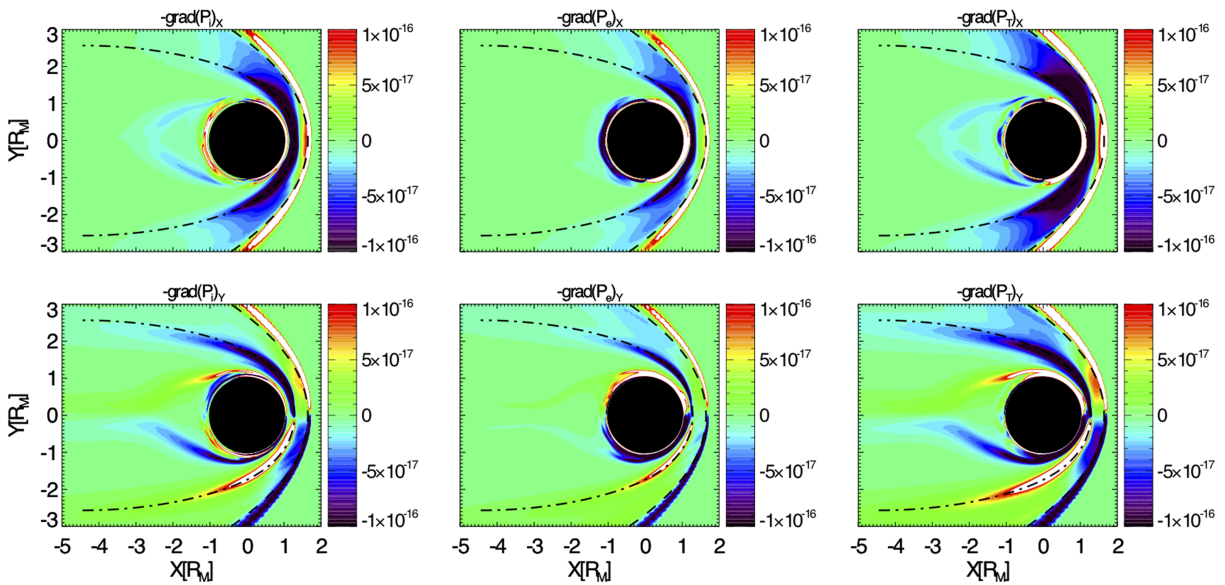
At high altitude, the three models differ from each other significantly. Density differences between the MS and the two MF models (MF and MFPe) result from the decoupling of the velocities of the shocked solar wind proton and planetary ions in the MF treatment (see in Figures 5 and S1 in the supporting information). When we examined the velocity profiles, we found that the proton velocity is very different, compared with the velocities of heavy ions between 200- and 700-km altitude range for the two MF models. The MF/MFPe models predict significant acceleration toward the planet of the protons right below the IMB, which is likely due to



**Figure 6.** Plasma properties along the subsolar line for multispecies (MS), multifluid (MF), and multifluid magnetohydrodynamic model with electron pressure (MFPe) models for case 1. Results from MS model are also plotted in dashed lines in the middle and lower panels for easy comparison. The solid lines in the right panels show the induced magnetic field, while the dotted lines are the crustal magnetic field (1c–3c).

the tension force exerted by the curved magnetic field. Such acceleration is not seen in the MS model, because in the single fluid momentum equation, the ion pressure gradient force counterbalances the magnetic tension force. As the proton flux is roughly a constant and the charge reactions between  $H^+$  and neutral particles is negligible above exobase, the proton density decreases below IMB in the MF models due to the acceleration. While the proton density increases rapidly around the exobase ( $\sim 200$ -km altitude), the proton-neutral collision becomes important and significantly slows down the proton flow below the exobase. Both MF and MFPe models predict higher densities of heavy ions at high altitude, due to the ion and electron pressure gradient forces. The MFPe model also predicts higher densities of heavy ions at high altitude than the MF model, due to larger electron pressure gradient force (or ambipolar electric force) in regions between 110- to 230-km altitude. Also note that ion temperatures at high altitude for the MFPe model is somewhat less than that of the MF model. This is likely due to the fact that at high altitude, heating of the planetary ions mostly come from the shocked solar wind in the sheath and MPB regions. As the total heat flux from the solar wind is about the same, larger density in the MFPe model results in less heating per ion at high altitude.

The major component of the magnetic field in all three models is  $B_y$ , due to draping of the magnetic field. However, there are noticeable differences in  $B_x$  and  $B_z$  components in the three models.



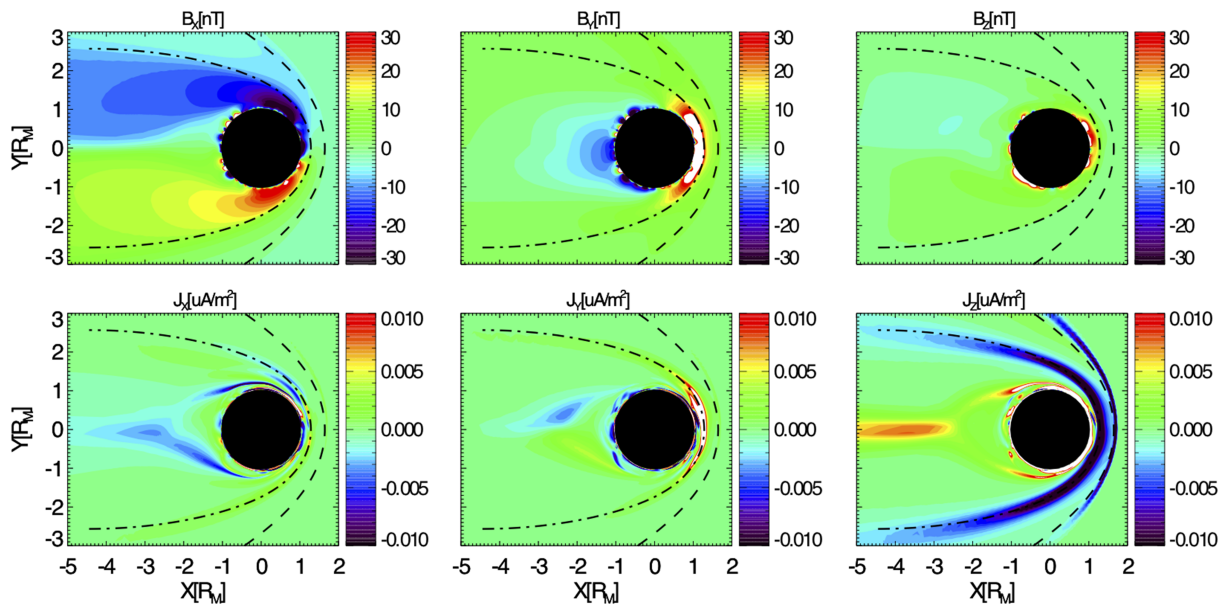
**Figure 7.** Pressure gradient forces in the X (top panels) and Y direction (bottom panels) for ion, electron, and total pressure in the equatorial (XY) plane for the multifluid magnetohydrodynamic model with electron pressure model for case 1.

### 3.3. Effect of Different Forces and Current Distribution

To better understand the MFPe model results of the flow and field patterns, we also calculated the major forces included in the model. According to the ion momentum equations, five different forces are exerted on each ion fluid: ion pressure gradient force, gravity, partial electron pressure gradient force, and motional electric force and partial  $\mathbf{J} \times \mathbf{B}$  forces. As the gravity force is relatively small compared with the other forces except at very low altitudes, it is neglected in the discussion below. Also, the other forces are all different for different ions. For simplicity, we will sum up the different forces for all the ions and discuss their total effects. Please note that the sum of the motional electric force is zero, so there are only three forces left: ion pressure gradient force, electron pressure gradient force (ambipolar electric field force), and the  $\mathbf{J} \times \mathbf{B}$  force.

We first examine ion and electron pressure gradient forces. The ion and electron pressure forces have a similar effect on the plasma, as shown in Figure 7. Across the shock, both forces dominate with positive X components and away from subsolar region with substantial positive Y components in the top side and negative Y components in the bottom, meaning that the forces are pointing outward to slow down the solar wind plasma flow. The ion pressure gradient force is somewhat larger than the electron pressure gradient force near the shock. In the magnetosheath region, forces are also dominated by the ion pressure gradient force, mainly in the negative X direction and away from the subsolar region with negative Y components in the top side and positive Y components in the bottom, compressing the plasma toward the planet. While in the ionosphere, the electron pressure gradient force is the dominant one, which acts together with the ion pressure gradient force to push against the shocked solar wind. The pressure gradient force in the Z direction is negligible near the equatorial plane. The ion pressure gradient force predicted by the model is consistent with that derived from MAVEN plasma observations (Halekas et al., 2017).

Figure 8 shows the three components of the total magnetic field (top panels) and electric current (bottom panels) formed around Mars due to plasma interaction in the equatorial plane. The total magnetic field is the sum of the crustal field and induced magnetic field (or perturbations of the magnetic field). Except in regions very close to the planet, magnetic field is dominated by the induced magnetic field. The magnetic field pattern is consistent with the draping pattern observed by MGS (Crider et al., 2004) and MAVEN (Connerney et al., 2015; Halekas et al., 2017). The  $B_x$  component shows a clear bipolar signature, and there is significant enhancement of the  $B_y$  component inside the IMB due to the slowdown of the solar wind plasma flow. The  $B_z$  component is relatively small in most regions, except close to the planet, due to the presence of localized crustal magnetic fields.



**Figure 8.** Magnetic field components and current system in the equatorial ( $XY$ ) plane for the multifluid magnetohydrodynamic model with electron pressure model for case 1.

The electric current is calculated using the curvature of the magnetic field. As shown in Figure 8 (bottom right panel), the currents are mainly flowing in the  $Z$  direction. They are mainly distributed in four regions: bow shock, induced magnetosphere, ionosphere, and tail current sheet. The currents are flowing in a negative  $Z$  direction, near the bow shock and inside the induced magnetosphere, meaning that they both enhance the  $B_Y$  component. The currents induced in the ionosphere and the tail region are flowing in the opposite direction. As the ionosphere is a highly conducting region, the main effect of the current induced in the ionosphere is to counter the penetration of the magnetic field to lower altitude. The tail current sheet is formed due to the draping of the magnetic field lines (see upper left panel of Figure 8).

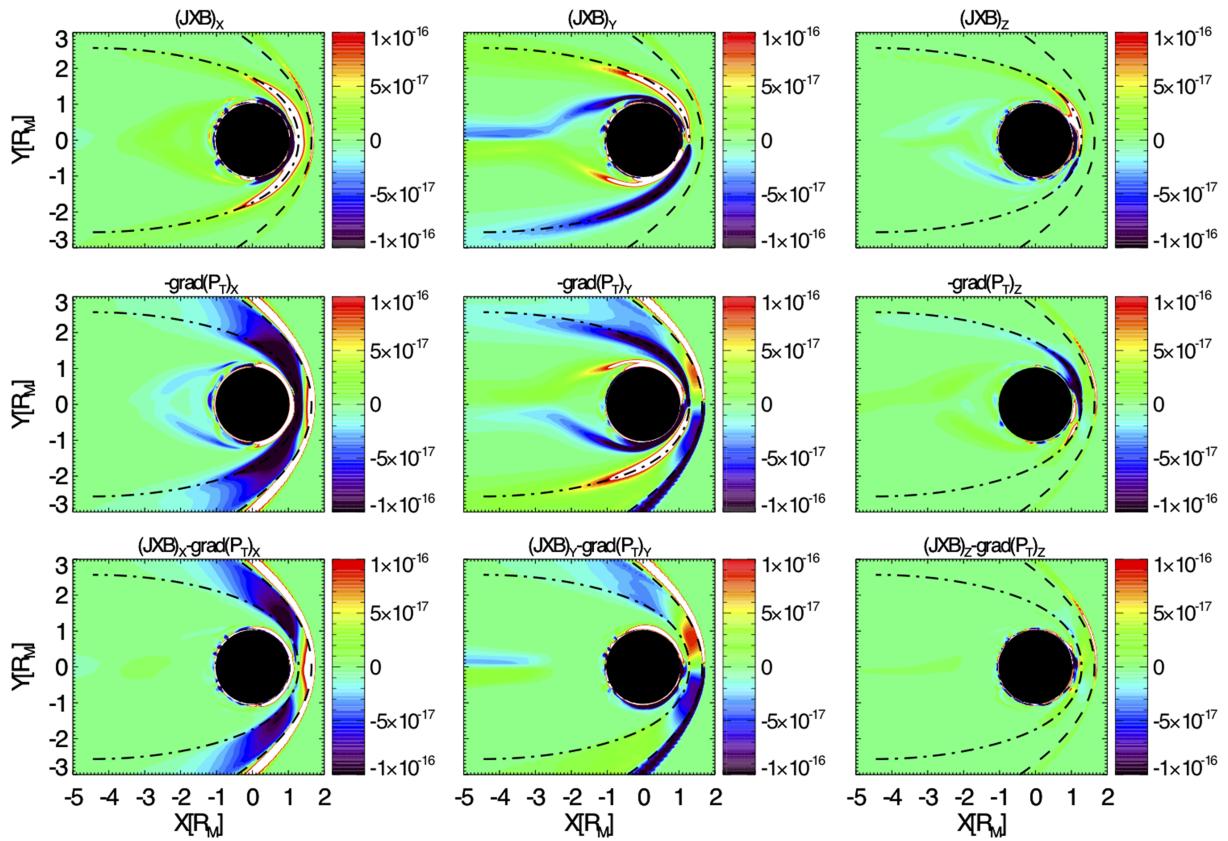
The  $\mathbf{J} \times \mathbf{B}$  force, total (ion + electron) pressure gradient force, and their sum are shown in Figure 9. Near the shock, the  $\mathbf{J} \times \mathbf{B}$  force is in the same direction as the total pressure gradient force, and they act together to slow down the plasma across the bow shock. However, inside the induced magnetosphere, the  $\mathbf{J} \times \mathbf{B}$  force is pointing outward, opposite to the total pressure gradient force, and the two forces roughly cancel each other out near the subsolar region. The net force of the two diverts the shocked solar wind around the obstacle. The  $\mathbf{J} \times \mathbf{B}$  force patterns predicted by the model are also consistent with MAVEN observations (Halekas et al., 2017).

### 3.4. Comparison With MAVEN Observations

We also conducted a case study using the three models in order to show their differences as well as how they compare with plasma observations. The case study is for 13 December 2014, Orbit 451. The solar wind condition during this time period is relatively quiet. We first calculated the average solar wind condition using SWIA measurements before the inbound bow shock crossings and used that as the input parameters of the model runs, as listed in Table 1. for Case 4.

Figure 10 shows the data-model comparison using three MHD models. As shown, the  $O_2^+$  density profiles near periapsis are all well reproduced by the three models. But the second peak of  $O_2^+$  density during the outbound trajectory is best reproduced by the MFPe model. The MFPe model also agrees the best with  $O_2^+$  density at high altitude.

The three models predict slightly different locations of the bow shock, and the observed shock locations for both inbound and outbound passes are best reproduced by the MFPe model. The  $U_Y$  and  $U_Z$  profiles by all three models match well with SWIA observations, but for the  $U_X$  component, the MFPe model results agree best with SWIA observations. As for the magnetic field, there are some discrepancies in all three components

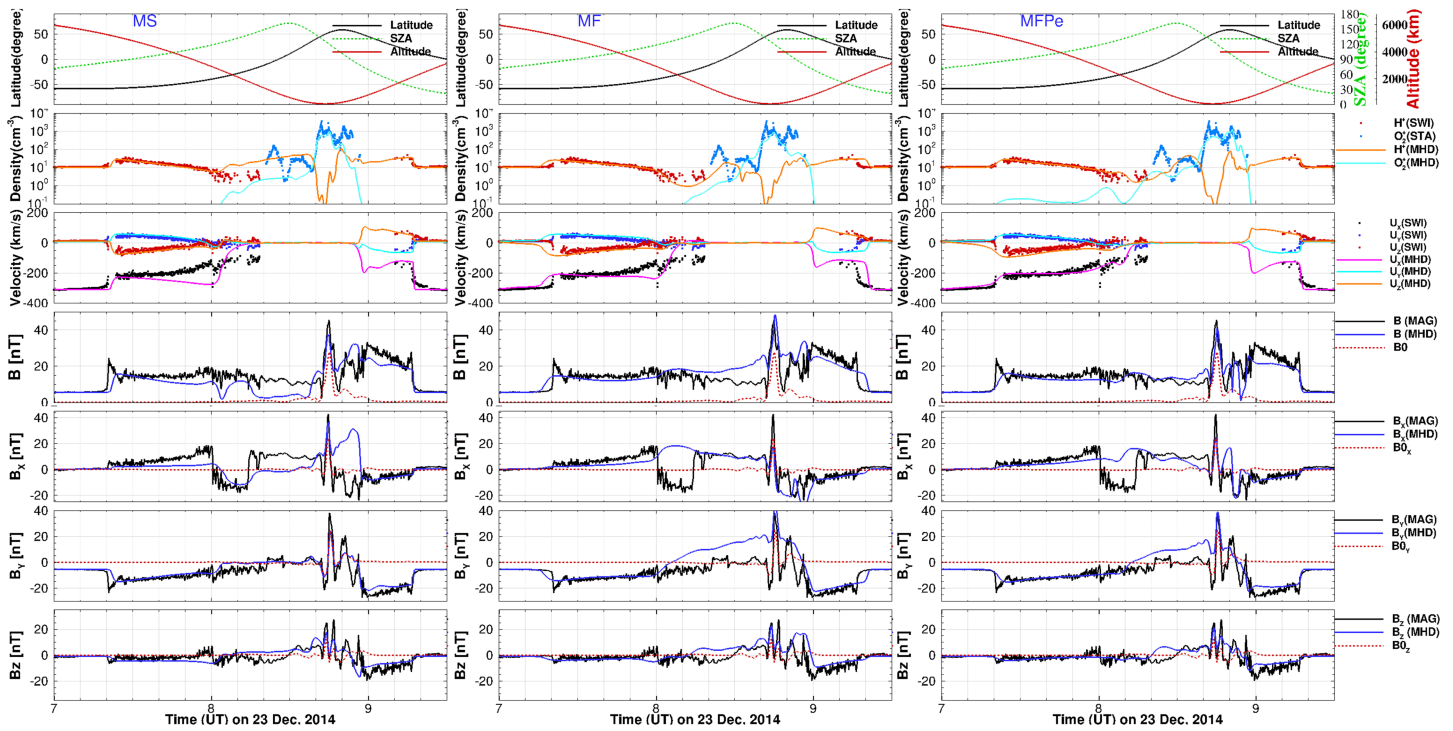


**Figure 9.** 2-D plot of the  $J \times B$  force (top panels) and total pressure gradient force (middle panels) and the total of the two forces (bottom panels) in three directions in the equatorial ( $XY$ ) plane for the multifluid magnetohydrodynamic model with electron pressure model for case 1.

and field magnitude for all three models, which are likely due to the fact that the IMF condition is highly variable, while such variations of the IMF are neglected in the steady-state runs. In comparison, the  $B_Y$  component agrees best with the MS model, but the observed magnitude of the field is best matched by the MFPe model. In general, we find that the MFPe model matches best with the relevant MAVEN plasma observations. We did not compare model results with  $T_e$  measured by the LPW instrument, because no LPW data are available for this particular orbit. But the electron temperature in Figure 6(3b) are qualitatively similar to MAVEN LPW observations as shown in Ergun et al. (2015). More direct comparison with LP measurements will be done in future work.

### 3.5. Escape Rates

We also examined ion escape rates for all the cases. The ion escape rates are integrated through the  $6 R_M$  spherical surface. The results are listed in Table 2. The total escape rates of the MF models are generally similar or larger than the corresponding MS model results. However, the main escaping ions, as predicted by the two MF models, are different. The MF model predicts that more heavy ions ( $O_2^+$  and  $CO_2^+$ ) are lost from the planet, while the MS model favors the loss of the light  $O^+$  ions. The escape rates predicted by the MFPe model are the highest, especially for heavy ions. The total escape rates increased by 38–177% when using the MFPe model, as compared with corresponding MS model results in total number density, which corresponds to 67–265% increase in total mass loss. Compared with corresponding MF model results, the increase is between 37% and 71% in total number density and 50–108% in total mass loss. Also, it is interesting to compare different cases. Comparison between Cases 1 and 2 shows the effect of crustal field orientation on the total ion loss rates. All three models predict lower total ion loss rates when the strong crustal field is facing toward the Sun. However, when comparing Cases 2 and 3, we found that both the MS and MF models predict that the escape rates are the largest when the crustal field is turned off, while for MFPe model, the escape rates for Case 3 are actually smaller than those of Case 2, meaning that under some weak crustal field



**Figure 10.** Comparison with Mars atmosphere and volatile EvolutionN for case 4 using multispecies (MS), multifluid (MF), and multifluid magnetohydrodynamic model with electron pressure (MFPe) models. The first panel in each case show Mars atmosphere and volatile EvolutionN trajectory information (latitude, solar zenith angle, and altitude). Second panel compares magnetohydrodynamic model results with proton density observed by solar wind ion analyzer and O<sub>2</sub><sup>+</sup> density observed by SupraThermal and thermal ion Composition. Third panel compares model results with plasma velocity vectors as observed by solar wind ion analyzer. The last four panels compare model results with magnetometer observations for the strength and the three components of the magnetic fields.

configurations, when taking into account the ambipolar electric field, the ion escape rates could be larger than without crustal field. Also note that Cases 1–3 are for solar max. For Case 4, the MAVEN event case, we are using solar minimum conditions, so the escape rates are the smallest of the four cases, indicating that solar extreme ultraviolet is one of the main factors controlling the total ion loss rate.

The total ion loss rates predicted by the MFPe model for the four cases are between  $3.5 \times 10^{24}$  and  $1.3 \times 10^{25} \text{ s}^{-1}$ , much larger than previous MS and MF model predictions, which clearly demonstrated the importance of ambipolar electric field in driving ion loss from Mars. The predicted ion loss rates by the

**Table 2**  
Escape Rates for the Four Cases With Three Different Models

Cases	Model	O <sup>+</sup> ( $\times 10^{24}/\text{s}$ )	O <sub>2</sub> <sup>+</sup> ( $\times 10^{24}/\text{s}$ )	CO <sub>2</sub> <sup>+</sup> ( $\times 10^{24}/\text{s}$ )	Total number ( $\times 10^{24}/\text{s}$ )	Total mass (kg/s)
Case 1 (with B <sub>0</sub> dayside)	MS	3.97	0.25	0.03	4.25	0.12
	MF	3.30	1.97	0.25	5.53	0.21
	MFpe	5.74	3.34	0.07	9.15	0.34
Case 2 (with B <sub>0</sub> nightside)	MS	4.37	0.17	0.02	4.55	0.13
	MF	5.19	2.26	0.23	7.67	0.28
	MFpe	7.89	4.72	0.04	12.6	0.47
Case 3 (no crustal field)	MS	6.72	0.67	0.06	7.45	0.22
	MF	5.98	1.32	0.18	7.49	0.25
	MFpe	6.95	3.21	0.13	10.3	0.37
Case 4 (MAVEN case study)	MS	1.67	0.39	0.03	2.09	0.07
	MF	1.26	0.69	0.09	2.04	0.08
	MFpe	1.08	2.27	0.14	3.49	0.16

Note. MS = multispecies; MF = multifluid; MFpe = multifluid magnetohydrodynamic model with electron pressure; MAVEN = Mars Atmosphere and Volatile EvolutionN.

new model are in the same range as the estimated escape rates between  $2 \times 10^{24}$  and  $3 \times 10^{25} \text{ s}^{-1}$  when the low energy ions are included using Phobos and Mars Express data at different times (Fränz et al., 2010; Lundin et al., 1990; Lundin et al., 2008; Nilsson et al., 2011; Ramstad et al., 2013). The new model results are also consistent with theoretical predictions (Cravens et al., 2017).

#### 4. Summary and Discussion

The MF MHD model of Mars is improved by solving an additional electron energy equation. With the electron energy equation, the electron temperature is calculated based on the effects from various electron-related heating and cooling processes (e.g., photoelectron heating, electron-neutral collision, and electron-ion collision), and thus, the improved model is able to calculate the electron temperature and the electron pressure force terms self-consistently. The general interaction patterns, as predicted by the MFPe model, are similar to those of the MF model. Comparison of the first three cases clearly showed that the presence of the crustal fields, especially when located on the dayside, helps to stand off the shocked solar wind, consistent with MAVEN observations.

Model results of a typical case using the MFPe are compared in detail to both MS and MF models with identical input conditions to identify the effect of the improved physics. The model with electron pressure equation predicts that the electron temperature is much larger than the ion temperature in the ionosphere, consistent with both Viking and MAVEN observations.

Different plasma forces act together during the interaction process. We compared the major forces considered in the MHD model: the ion and electron pressure gradient forces and the  $\mathbf{J} \times \mathbf{B}$  force. Using our numerical model, we also examined in detail the relative importance of different forces in the plasma interaction region. Across the shock, the ion pressure gradient force is the main force to slow down the solar wind. In the induced magnetosphere, the ion pressure gradient force and the  $\mathbf{J} \times \mathbf{B}$  force counterbalance each other in the subsolar region. While in the ionosphere, the electron pressure gradient force is the dominant one.

All three models are applied to a MAVEN event study using identical input conditions derived from MAVEN observations. The improved MFPe model matches best with MAVEN observations. Finally, the ion escape rates are calculated for all the cases, and we found that the inclusion of the electron pressure equation increases the escape rates predicted by the model by 50–110% in total mass, compared with MF model, which clearly demonstrates the importance of the ambipolar electric field.

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