Planetary and Space Science 128 (2016) 1–13

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Solar control of the Martian magnetic topology: Implications from model-data comparisons

D. Ulusen [a,*], J.G. Luhmann [a], Y. Ma [a], D.A. Brain [b]

[a] *Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA, USA*
[b] *Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA*

ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form
20 December 2015
Accepted 4 January 2016
Available online 13 April 2016

Keywords:
Mars
Plasma interaction
MHD models
Magnetic morphology
Crustal fields

ABSTRACT

One of the goals of the upcoming MAVEN mission to Mars is to investigate the effects of the crustal remanent fields on the solar wind plasma interaction and the upper atmosphere. The MGS Electron Reflectometer and magnetometer observations can be used to test the idea that, if the future data from the electron spectrometer (SWEA) are separated for the two prevalent interplanetary field orientations (Parker spirals 'toward' and 'away' from the Sun), one may be able to detect specific differences in the pattern of locations of open magnetic fields (where photoelectrons can escape from Mars' ionosphere into space), as well as patterns of photoelectrons in the Martian magnetotail. We use a pair of BATS-R-US MHD model results of the Mars–solar wind interaction, in a manner similar to that tested by Liemohn et al. in 2006 on Mars Express ELS electron data, to define these patterns of expected photo-electron detections on a global scale. Those cases have the strongest southern hemisphere crustal fields at noon or midnight, a matter of importance in such investigations because these patterns will be sensitive to the local time of those fields. We compare some MGS data-based maps of the time periods selected for their open field signatures in the pitch angle distributions and energy spectra, and separated by interplanetary field orientation inferred from Mars magnetosheath observations. This exercise illustrates the power (and necessity) of the global model comparisons as a means of interpreting the very complex Mars–solar wind interaction and its effects.

1. Introduction

Mars has no global magnetic field but a substantial atmosphere. Therefore the main plasma interaction is between the photo-ionized atmosphere and the solar wind, similar to a case of unmagnetized body interaction. In 1997, Acuna et al. (1998) discovered remanent crustal sources on the surface of Mars, accumulated mainly in the southern hemisphere around 180 East-longitude. These magnetic sources are strong enough to stand off the solar wind and complicate the interaction. They present a temporally and spatially variable obstacle to the solar wind as the planet rotates on its axis. The resulting effect can be global such as interaction boundary asymmetries or local such as transient particle events (aurora [e.g., Brain et al., 2006, or occurrence of special electron distributions at the solar wind interface such as temporary trapping (Ulusen and Linscott, 2008), or magnetosheath electron penetration (e.g. Mitchell et al., 2001) or electron conics (Ulusen et al., 2011) etc.) The physics that create many of these events are still under investigation.

Due to their nature, many of the particle events involve certain magnetic field configurations and exhibit distinct features. For instance, accelerated auroral electrons are observed in the vicinity of cusps (the presumed locations where external, draped fields of the magnetosheath connect to the crustal fields and become 'open') (Brain et al., 2006), while; trapped radiation is observed over closed field lines and exhibit distinct pitch angle distributions (PADs) as mentioned above (e.g., Brain et al., 2007). Therefore one observational approach to understanding the physics in these events is to use suprathermal electrons (energy range from 10 eV to a few hundred eV), which have a small gyro-radius relative to other scales and can act as tracers of magnetic topology (e.g. Brain et al., 2007).

Numerical models of the solar wind interaction with solar system bodies, such as MHD models, are potentially powerful tools and complementary to the observational approach in the 3D interpretation of the spacecraft observations. In the case of Mars interaction, the ion Larmor radius is comparable with the planetary length scale which imposes some limitations in the application of the MHD models to Mars. In such cases hybrid or kinetic approach is necessary to account

---

* Corresponding author. Tel.: +90 533 326 6079.
E-mail addresses: demetulusen@gmail.com (D. Ulusen), jgluhman@ssl.berkeley.edu (J.G. Luhmann), yingjuan@igpp.ucla.edu (Y. Ma), david.brain@lasp.colorado.edu (D.A. Brain).

http://dx.doi.org/10.1016/j.pss.2016.01.007
0032-0633/© 2016 Published by Elsevier Ltd.

for the separate motion of ions and electrons. However, in the literature it has been shown that MHD description of Mars interaction was successful even with the finite ion-Larmor radius limitation. The possible reason for this success of the model may be high wave activity and turbulence observed near Mars (e.g., Grard et al., 1989; Acun~a, 1998; Cloutier et al., 1999), which suggests a wide variety of wave particle interactions acting like pseudocollisions. Moreover, in this paper, the main focus is on the interaction region between 200 and 700 km altitudes inside Magnetic Pileup Boundary (MPB) at ~ 1100 km (Vignes et al., 2000). Below MPB, magnetic field strength increases significantly and therefore the ion gyroradius is reduced effectively. Furthermore, in the region of interest the ion temperature is notably decreased due to ion-neutral collision processes. Considering similar criteria and using the same approach, Ma et al. (2004) investigate the boundary asymmetries and atmospheric escape under different solar conditions at Mars. By comparing MHD model results with the auroral-like emissions reported from the Mars Express SPICAM instrument, Liemohn et al. (2007) showed that the main source of these emissions is solar wind electrons which have access to the upper atmosphere through open field lines. Using the same method they also show that atmospheric photoelectrons reported at high altitudes well above the ionosphere from the Mars Express ASPERA-3 electron instrument are the result of direct magnetic connectivity to the dayside ionosphere at the time of the measurements (Liemohn et al., 2006).

In this study we compare the magnetic topology inferred from the BATS-R-US MHD model of the Martian plasma interaction with the open and closed field magnetic topology inferred from Mars Global Surveyor (MGS) Electron Reflectometer (ER) electron distributions. We compare maps of particular types of electron distributions with the model field topology, focusing on the strong field regions in the southern hemisphere, to see if the open and closed fields found in the model resemble those inferred from the MGS electron observations. We further separate the distributions according to the inferred prevailing IMF direction to investigate whether IMF dependence on the patterns can be seen. This work is in part to prepare for the upcoming MAVEN mission where a more complete instrument and different orbital sampling will be available for such studies.

Section 2 introduces the model briefly, with the cases we analyzed in this work. Section 3 includes the detailed analysis of the model results. Section 4 introduces the data and Section 5 presents the results of model-data comparisons. Section 6 summarizes the paper findings.

2. Model summary

Only a brief overview of the single fluid 3D MHD model of the Mars plasma interaction is included here, as details can be found in Ma et al. (2004). In the model, the Martian atmosphere is spherically symmetric and consists of CO_2, O and H (Nier and McElroy, 1977; Hanson et al., 1977; Fox, 2003; Kim et al., 1998; Bougher et al., 2000). The ionosphere is represented by four species: H^+, ${O_2}^+$, O^+ and ${CO_2}^+$. Solar photoionization depends on both Solar Zenith Angle (SZA) and altitude. In the model this ionization rate is assumed to be zero on the nightside (Schunk and Nagy, 2000). The system of MHD equations solved in the model has only a single momentum equation assuming all species have the same velocity.

The computational domain is defined in spherical coordinates confined by $-24\,R_M < x < 8R_M$, $-16R_M < y$, $z < 16R_M$ (R_M=3396 km is the radius of Mars). This nonuniform spherical grid structure allows angular resolution of 2.5° and a graduated radial grid with a radial resolution of 10 km in the lower ionosphere. The inner boundary is at 100 km altitude. At this boundary ${O_2}^+$ and O^+ densities were assumed to be the photochemical equilibrium value. The sum of the electron and ion temperatures at the inner boundary was taken as 268 K for solar max and 117 K for solar min and the pressure was set accordingly. A reflective boundary was used for velocity, resulting in near zero velocities at the inner boundary. The effects of the crustal magnetic fields of Mars are incorporated into the model as a 60° spherical harmonic expansion representation of the observed remanent fields (Arkani-Hamed, 2001). The MHD equations are solved using a modified version of the BATS-R-US code (Block Adaptive-Tree Solar wind Roe-type Upwind Scheme), details of which can be found in Powell et al. (1999) and Toth et al. (2012).

Table 1
MHD model cases analyzed in this work.

Case #	SW_Bdir	SW_min/max	C_f
Case 1	EB	Max	NC (0)
Case 2	WB	Max	NC (0)
Case 3	EB	Max	DC (180)
Case 4	WB	Max	DC (180)
Case 5	EB	Min	NC (0)
Case 6	WB	Min	NC (0)
Case 7	EB	Min	DC (180)
Case 8	WB	Min	DC (180)

In this paper, we analyze the model results for a number of different cases. The summary of these cases is listed in Table 1 and associated features are explained below.

1. The IMF was assumed to be a Parker spiral in the X–Y plane with an angle of 56° and a magnitude of 3 nT (SW_Bmag). We considered two IMF directions (SW_Bdir). When the IMF has a $+y$ component we call it Eastward IMF (EB), when it has $-y$ component we refer to it as Westward IMF (WB). These two orientations represent the average conditions for undisturbed solar wind at Mars.
2. The solar wind velocity (SW_vel) was selected to be 400 km/s for both solar maximum and solar minimum.
3. The solar wind density around Mars (SW_den) was set at $4\,\text{cm}^{-3}$ for all the cases used here.
4. We considered two orientations for crustal fields: One with the strong southern hemisphere crustal magnetic field (C_f) centered on the dayside at the noon meridian at 0 E (DC) and the other with these fields centered on the nightside at 180 E (NC). These are considered to represent the extremes of the solar wind interaction with the crustal magnetic fields.
5. Solar flux used for solar maximum and minimum is F79050N and F74133, respectively (Schunk and Nagy, 2002).

3. Model analysis

Figs. 1 and 2 show the model results obtained for solar maximum and solar minimum cases in Table 1, respectively. In all panels, the magnitude of the total magnetic field is plotted in Mars Orbital coordinate system (MSO), where $+x$ points at the Sun in the Mars orbital plane, $+y$ is in the opposite direction with the Mars orbital velocity, and $+z$ completes the right-handed system. The color scale indicates magnetic field magnitude in nT. The plots are grouped into columns, first according to the plane in which the data are presented (xy or xz plane) and then according to the crustal fields' location with respect to the Sun (NC: crustal fields are on the nightside, DC: crustal fields are on the dayside). The first two rows indicate the IMF direction in the model (EB: Eastward IMF, WB: Westward IMF). The plots in the last row show the magnitude of the crustal fields calculated from the Cain model for reference. (For this plot the degree of the coefficients in the Cain spherical harmonic model is taken up to 50 (Cain et al., 2003).). In these figures, we can analyze the global features of the interaction