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The morphology of the topside ionosphere of Mars under different solar wind conditions: Results of a multi-instrument observing campaign by Mars Express in 2010

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ABSTRACT

Since the internally-generated magnetic field of Mars is weak, strong coupling is expected between the solar wind, planetary magnetosphere, and planetary ionosphere. However, few previous observational studies of this coupling incorporated data that extended from the solar wind to deep into the ionosphere. Here we use solar wind, magnetosphere, and ionosphere data obtained by the Mars Express spacecraft during March/April 2010 to investigate this coupling. We focus on three case studies, each centered on a pair of ionospheric electron density profiles measured by radio occultations, where the two profiles in each pair were obtained from the same location at an interval of only a few days. We find that high dynamic pressures in the solar wind are associated with compression of the magnetosphere, heating of the magnetosheath, reduction in the vertical extent of the ionosphere, and abrupt changes in electron density at the top of the ionosphere. The first three of these associations are analogous to the behavior of the plasma environment of Venus, but the final one is not. These results reinforce the notion that changes in solar forcing influence the behaviors of all of the tightly coupled regions within the Martian plasma environment.

1. Introduction

Due to differences in planetary size, rotation rate, magnetic moment, and heliocentric distance, there is great diversity amongst the plasma environments of solar system bodies (Cravens, 2004; Witasse et al., 2008; Schunk and Nagy, 2009). Mars (Nagy et al., 2004; Russell, 2006) and Venus (Brace and Kliore, 1991; Luhmann et al., 1992), which lack significant internal magnetic fields, are characterized by induced magnetospheres formed through interactions between the upper atmosphere of the planet and the impinging solar wind plasma. An analogous process is also known to occur at Saturn's largest moon, Titan (Cravens et al., 2010; Luhmann et al., 2012).

The Martian system is particularly interesting because it contains a varied mixture of magnetic environments. This is caused by

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the presence of strong, spatially inhomogeneous, crustal magnetic field patches and the absence of any dipolar magnetic field produced in the planet's interior (Acuna et al., 1999). Magnetic field strength, local field direction and connectivity to the solar wind all vary on length scales that are less than a tenth of the planet's radius, circumstances that are not found anywhere else in the solar system.

The effects of the solar wind on the upper atmosphere of Mars are modulated by the intervening induced magnetosphere (Nagy et al., 2004; Russell, 2006). Many of the major features of ion outflow from the planet and plasma heating in the upper atmosphere are intricately coupled to the intensity and geometry of the draped field within the induced magnetosphere, conditions that are determined by solar wind dynamic pressure and orientation of the interplanetary magnetic field. The conditions in the impinging solar wind are hence highly important for governing the dynamics of the solar wind's interaction with the Martian upper atmosphere, as the induced magnetosphere it generates is constantly evolving in response to solar wind variations.

To date, the goal of obtaining a comprehensive understanding of how the ionosphere of Mars is affected by the solar wind has been impeded by the lack of appropriate and simultaneous information on the solar wind, magnetosphere, and ionosphere. In order to overcome this problem, we arranged for three dedicated campaigns of coordinated observations by several MEX instruments during the periods of March/April 2010, March/April 2012, and spring 2014. The objective of this paper is to investigate how the structure of the topside of the Martian ionosphere was influenced by solar wind and magnetospheric conditions during the first of these campaigns; the large-scale results of the observing campaigns will be reported elsewhere.

Mars was near opposition during these time intervals, and hence it was possible to infer solar wind conditions at Mars from observations closer to the Sun, such as data from the ACE, STEREO, Cluster, and THEMIS spacecraft. The MEX datasets selected for study are ionospheric electron density profiles obtained by MaRS, the Mars Express Radio Science Experiment, in situ electron densities measured by the MARSIS radar sounder, and in situ magnetospheric and solar wind conditions seen by ASPERA.

In the context of this work, the topside ionosphere is the region above about 180 km altitude. Transport processes are important in the topside ionosphere, but not at lower altitudes. Ions are produced by photoionization and, to a lesser degree, by impact ionization due to the precipitation of charged particles into the neutral atmosphere. The topside ionosphere is thought to be predominantly a mixture of O^+ and $O_2{}^+$ ions, though its composition is poorly-constrained by observations. Electron densities in the topside ionosphere generally decrease with increasing altitude, but a range of vertical structures is possible (Withers et al., 2012).

In Section 2, we discuss the expected response of the plasma environment of Mars to changes in the solar wind. In Section 3, we establish the overarching solar wind and magnetospheric conditions that pertain to the March/April 2010 campaign. In Section 4, we introduce observations of the ionosphere by radio occultations (Section 4.1) and local radar sounding (Section 4.2) that are relevant to our three case studies. In Section 5, we synthesize observations spanning the upstream solar wind, the magnetosphere, and the ionosphere for the three case studies. In Section 6, we summarize our conclusions.

2. Expected response of the plasma environment of Mars to changes in the dynamic pressure of the solar wind

The plasma environment of Mars, which encompasses the planet's magnetosphere and ionosphere, has been reviewed by Nagy et al. (2004), Brain (2006), and Withers (2009). Here we summarize some of its key features. Upstream of the bow shock (typical subsolar altitude, 2000 km), the plasma population is the undisturbed solar wind: supersonic, cool, and low density. The magnetosheath lies inside the bow shock. Plasma in the magnetosheath originated from the solar wind, but is subsonic, hotter, more dense, and more turbulent. The inner boundary of the magnetosheath is the “magnetic pileup boundary” (MPB), which typically occurs at an altitude of 850 km (subsolar point). “The MPB clearly separates two very different regions: a magnetosheath with low amplitude and turbulent magnetic fields and a region of high pile-up fields, the Magnetic Pile-up Region (MPR), where the solar wind is piled-up and draped around the ionosphere” (Nagy et al., 2004). Within the MPR, the plasma composition is dominated by planetary ions, unlike the proton-dominated solar wind. However, the electron population within the MPR is of solar wind origin (Mitchell et al., 2001). The inner boundary of the MPR is the “photoelectron boundary” (PEB), which typically occurs at an altitude of 400 km. As explained by Mitchell et al. (2001), “Above the boundary, electron energy spectra are consistent with solar wind electrons that have been shocked and then modified by impact with exospheric neutrals (Crider et al., 2000). Below the boundary, electron energy spectra exhibit a broad feature from 20 to 50 eV, which likely results from a blend of unresolved photoionization peaks that have been predicted by published models of ionospheric photoelectrons at Mars (Fox and Dalgarno, 1979; Mantas and Hanson, 1979). A second feature at ~500 eV results from oxygen Auger electrons (Mitchell et al., 2000).” Below the PEB, electrons and ions are derived from the ionization, primarily by photoionization, of neutral atmospheric species. This region is the ionosphere. The upper boundary of the ionosphere is sometimes very sharp. Duru et al. (2009) analyzed in situ electron densities measured as a novel and unexpected byproduct of the MARSIS radar sounder. They reported very sharp gradients in electron density in which electron densities dropped to very low values in about 18% of the orbits studied. Where these sharp gradients occur, we assume that they coincide with the PEB.

Previous work on the effects of high dynamic pressure in the solar wind on the plasma environment of Mars has used MGS MAG/ER, MEX ASPERA, and MEX MARSIS to show that high dynamic pressure compresses the magnetic pileup boundary (Crider et al., 2003; Dubinin et al., 2006; Opgenoorth et al., 2013) and has used MGS MAG/ER to show that high dynamic pressure compresses the photoelectron boundary (Crider et al., 2003; Brain, 2006), Escape rates are also enhanced by high solar wind dynamic pressure (Lundin et al., 2008; Nilsson et al., 2010; Edberg et al., 2009, 2010; Kaneda et al., 2007).

Not known from observations are the effects of the dynamic pressure of the solar wind on either the altitude and occurrence probability of the abrupt changes in electron density observed by MARSIS or the vertical structure of the topside ionosphere as observed by radio occultations. However, numerical simulations have started to investigate this topic. In a series of magnetohydrodynamic simulations, Ma et al. (2014) found that the altitude of the top of the ionosphere (defined in this case by a density of $100\ \text{cm}^{-3}$) did not change during a period of high dynamic pressure, but did rise by several hundred kilometers upon return to normal dynamic pressures at the end of the compression phase. The recovery timescale was more than one hour. They also reported that the topside electron density profile was characterized by large fluctuations with altitude during, but not after, the period of high dynamic pressure. In the context of this work, such density profiles are said to be “disturbed”.

Analogy to Venus, which is also a non-magnetized planet and whose plasma environment was studied comprehensively by the Pioneer Venus Orbiter mission, is useful for setting expectations