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Martian ionosphere observed by Mars Express. 1. Influence of the crustal magnetic fields

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ABSTRACT

We present multi-instrument observations of the effects of the crustal magnetic field on the Martian ionosphere at different altitudes and solar zenith angles by Mars Express. Total electron content (TEC) at solar zenith angles $55^\circ \geq SZA \geq 105^\circ$ over the ionosphere with crustal sources increases with the strength of the magnetic field. A similar trend is observed in a dependence of the local electron density in the upper ionosphere on the crustal magnetic field. On the nightside, at $SZA \geq 110^\circ$, the opposite trend of TEC increase with decrease in the magnetic field value is observed. A dependence on the magnetic field inclination also varies between the day and night sides. TEC decreases for vertical field inclination at $90^\circ \geq SZA \geq 70^\circ$ and increases at $SZA \geq 110^\circ$. This effect becomes stronger for larger magnetic field values. A different dependence of the local electron densities in the upper ionosphere at small and high SZA is observed too. An ionospheric exhaust for vertical field inclination in the regions with strong crustal sources is probably caused by escape to space along open field lines which arise due to reconnection that is confirmed by the case studies. The existence of such localized ionospheric depressions is also observed by the in-situ plasma observations. In contrast, on the nightside downward plasma transport and electron precipitation along the field lines produce patches of enhanced ionization.

1. Introduction

The first detection of the Martian ionosphere with a peak value of the electron number density of about 10^5 cm^{-3} at an altitude of about 125 km was made by Mariner-4 using the method of radio occultation (Kliore et al., 1965). Later, similar measurements on other space missions to Mars have extensively sampled the Martian ionosphere (Kliore, 1992; Hinson et al., 1999; Pätzold et al., 2005). In particular, a lower-altitude density peak or shoulder at $h \sim 110$ km was also identified. The first in-situ ionospheric measurements were carried out by Viking-1 and 2 landers (Hanson et al., 1977) and provided us with the height versus density profiles of the main ionospheric species (O_2^+, CO_2^+ and O^+). Models of the ionosphere (see e.g. Shinagawa and Bougher, 1999; Krasnopolsky, 2002; Fox et al., 1993, 2004; Schunk and Nagy, 2009; Mendillo et al., 2011; Chaufray et al., 2014) have significantly increased our knowledge of the ionospheric structure and its dynamics.

The bulk of the ionosphere at Mars is created by the ionization of the major atmospheric neutrals CO_2. The main ionization process is photoionization by the solar EUV irradiance (10–90 nm). A lower peak at 90–100 km is produced by soft X-rays (≤ 10 nm). However, due to the photochemistry reactions, the dominant ion species at $h \geq 200$ km become molecular (O_2^+) and atomic (O^+) oxygen ions. A balance between photoionization and recombination determines the peak electron density at altitudes of about 130 km. At altitudes above ~ 180 km the ionosphere is no longer in photochemical equilibrium and diffusion and transport processes become important. Due to recombination of O_2^+ ions the ionospheric density rapidly decreases at the nightside.

The recent observations by Mars Global Suveyor (MGS) and Mars Express (MEX) spacecraft have strongly increased the database of the ionospheric measurements providing us a lot of new information. Reviews of these observations are given in Haider et al. (2011), Orosei et al. (2015), and Withers et al. (2015)).

In addition to the radio occcultation experiment, MEX carries the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS). The MARSIS radar has two modes of operation: the Active Ionospheric Sounder (AIS) mode (Gurnett et al., 2005) and the SubSurface (SS) mode (Picardi et al., 2005). In the AIS mode the radar transmits stepped pulses from 0.1 to 5.4 MHz. The remote ionospheric measurements are based on the reflection of the

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transmitted waves in the ionosphere where the wave frequency meets the local plasma frequency ($f_p \sim \sqrt{n_e}$, where n_e is the electron number density). Such a method allows to retrieve the altitude profile of the ionospheric electron number density down to the altitude of the main ionospheric peak ($h \sim 130$ km) (Gurnett et al., 2005; Morgan et al., 2008). The sounding measurements have shown that the electron density in the main ionospheric layer at $\sim$ 140 km is in reasonable agreement with the Chapman model while at higher altitudes ($\sim$ 200 km) a possible second layer probably associated with O^+ ions appears. Besides that, when the transmitted frequency passes through the local electron frequency, strong electrostatic oscillations at f_p are excited in the ionosphere and can be measured giving us an information about the local ionospheric density (Gurnett et al., 2005; Duru et al., 2008; Andrews et al., 2013).

In the subsurface (SS) mode of the MARSIS operation, the radar transmits wideband (1 MHz) pulses at four centered frequencies (1.3, 3, 4 and 5 MHz). Traversing the ionosphere the waves are distorted by a frequency-dependent change of the phases due to dependence of the wave speed on the frequency. The distortions depend on the total electron content $TEC = \int_0^\infty n_(z)\, dz$ which can be retrieved from the echo wave signal (Safaeinili et al., 2007; Mouginot et al., 2008).

Safaeinili et al. (2003) have analyzed the TEC data obtained from June 2005 to September 2006. Assuming that the signal distortion is caused mostly by the ionospheric content below 200 km where the approach of the photochemical equilibrium is valid, and using the Chapman model (Chapman, 1931) Safaeinili et al. (2003) have derived a mean scale height of 11 .5 km and the mean value of the peak number density of 2.1×10^5 cm^{-3} at the subsolar point (solar zenith angle $SZA = 0°$).

While the ionosphere at $h \le 200$ km is in photochemical equilibrium, deviations from the Chapman model become essential at larger altitudes. Duru et al. (2008) have shown that the ionospheric densities above $\sim$ 300 km varies with solar zenith angle not according to Chapman theory as $\cos(SZA)^{1/2}$ implying a dominance of horizontal transport processes over photochemistry. Since the ionospheric thermal pressure above 300 km is insufficient to endure the dynamic pressure exerted by the solar wind, the ionosphere occurs magnetized and dynamics of the upper ionosphere is controlled the by the solar wind (Shinagawa and Cravens, 1989; Dubinin et al., 2008).

The nightside ionosphere of Mars occurs highly variable. It is generally thought that plasma transport from the dayside and ionization of the atmosphere by precipitating electrons are the most important sources of the nightside ionosphere (Haider et al., 1992; Fox et al., 1993; Fillingim et al., 2010; Lillis et al., 2009, 2011). Analyzing the radio occultation measurements at the nightside of Mars made onboard MEX Withers et al. (2012a) have shown that transport from the dayside is a main source at $SZA \le 115°$ but at higher SZA electron precipitation probably dominates.

The existence of strong localized sources of crustal magnetic field at Mars (Acuna et al., 1999) introduces new important features. Analyzing the radio occultation measurements by MGS, Ness et al. (2000) have observed that scale heights of the electron number density were much larger above regions of locally vertical magnetic field. Ness et al. (2000) have assumed that reconnection between the crustal magnetic field and draping IMF may lead to penetration of solar wind electrons to low altitudes and heating of the ionosphere electrons. Increase in the electron temperature can decrease the efficiency of the dissociative recombination of the major ion species (O_2^+) and increase in the density scale height (Krymskii et al., 2003).

Nielsen et al. (2007) have reported about cases of the peak density enhancements in spatially limited regions with strong crustal magnetic field. Neither solar events or precipitation of energetic electrons were observed during these events. Nielsen et al. (2007) have suggested that plasma instabilities driven by solar wind interaction in minimagnetospheres of Mars might be responsible for electron heating and density enhancement.

Safaeinili et al. (2007) have observed that at the nightside ionosphere of Mars, TEC is higher over the region with vertical crustal magnetic field although the enhancements in TEC were also measured in the areas where there was no evident connection with crustal sources.

Analyzing MARSIS ionograms in AIS mode Němec et al. (2010) have observed that the occurrence rate of the nightside ionosphere is more than 4 times larger in regions with nearly vertical crustal magnetic field.

The measurements of low energy ions carried by the Ion Mass Analyzer (IMA) onboard MEX have shown that the dayside ionosphere over the regions with strong crustal magnetization occurs more inflated (Dubinin et al., 2012). These results were confirmed by the measurements of the local plasma density retrieved from the frequencies of electron plasma oscillations (Andrews et al., 2013). Andrews et al. (2015) have provided an empirical model of effects of the crustal magnetic field on plasma density in the topside ionosphere.

Cartacci et al. (2013) have analyzed variations of TEC in the nightside ionosphere based on MARSIS data from 2006 to 2011. To quantify the TEC variations they did not used average values as was done by Safaeinili et al. (2007) but 10th order polynomial fits. Cartacci et al. (2013) have also observed that the increase in TEC (positive δ (TEC)) was often related to the regions with vertical crustal fields.

Fillingim et al. (2010) and Lillis et al. (2011) have modeled effects of precipitating electrons into the crustal field area on the nightside. These studies have found a large variability in peak ionization rate between different geographic regions. According to Fillingim et al. (2010) ionization patches produced by the precipitating electrons with densities up to $\sim 3 \times 10^4$ cm^{-3} at an altitude of about 140 km appear.

In this paper we study properties of the Martian dayside and nightside ionosphere observed by MEX spacecraft by combining observations by the MARSIS radar and ASPERA-3 particle spectrometer. The measurements of the total electron content (TEC) provide us the information about the ionosphere near the main ionospheric peak. The in-situ measurements by MARSIS of the electron number density at altitudes from $\sim$ 300 km to $\sim$1400 km tell us about the characteristics of the topside ionosphere. These data are complemented by the measurements of low-energy ion and electron fluxes by ASPERA-3. We focus on effects of the planetary crustal magnetic field on the ionosphere of Mars.

2. Observations

2.1. Instrumentation

We use the MARSIS-TEC data from June 2005 to August 2010 derived using the method by Mouginot et al. (2008). Note also that Cartacci et al. (2013) have applied another method ('contrast method') of compensating the distortions in the phase shift caused by the Martian ionosphere. This method allowed processing the MARSIS data in the nightside ionosphere with an accuracy of 10% .

Local electron number densities can be derived by measuring the spacing between plasma frequency harmonics generated by distortion in the preamplifier due to the large amplitude of the emitted wave (Duru et al., 2008). Andrews et al. (2013) have developed a method for the automatic retrieval of local plasma density from a large data set of the MARSIS data in the AIS mode. In this paper, we use this database of local density derived from the observations between June 2005 and May 2014.