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Martian ionosphere observed by Mars Express. 2. Influence of solar irradiance on upper ionosphere and escape fluxes

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ABSTRACT

We present multi-instrument observations of the effects of solar irradiance on the upper Martian ionosphere and escape fluxes based on Mars Express measurements obtained over almost 12 years. It is shown that the variations in the upper ionosphere caused by solar irradiance lead to significant changes in the *trans*-terminator fluxes of low-energy ions and total ion losses through the tail. The observed dependence of the electron number density in the upper ionosphere at altitudes above 300 km on solar irradiance implies that the ionosphere at such altitudes was denser by a factor of ten during the periods of solar maxima in solar cycles 22–23. Correspondingly, the *trans*-terminator fluxes of cold ions and escape fluxes through the tail were also significantly higher. We estimate an increase of total ion losses through the tail during these solar maxima by a factor of 5–6.

1. Introduction

Direct interaction of solar wind with the Martian exosphere/ionosphere results in significant atmospheric losses (see e.g. Vaisberg, 1976, Lundin et al., 1989, 2008a, Barabash et al., 2007, Dubinin et al., 2011, Nilsson et al., 2011, Fraenz et al., 2015, Brain et al., 2015, Dong et al., 2015, Jakosky et al., 2015). These losses depend not only on the characteristics of solar wind but also on solar EUV flux. Indeed, escape fluxes observed by Phobos-2 during solar maximum (Lundin et al., 1989, Ramstad et al., 2013) occur approximately ten times higher than fluxes measured by Mars Express during solar minimum (Lundin et al., 2008a, Nilsson et al., 2011, Dubinin et al., 2011). The 3D-hybrid simulations performed by Modolo et al. (2005) have also shown a positive correlation between the solar activity and oxygen losses. This is probably not surprising since solar irradiance is an important energy supplier for the Martian ionosphere which is the main reservoir for ion escape forced by solar wind.

The Martian ionosphere was intensively studied over the two decades by the Mars Global Suveyor (MGS) and Mars Express (MEX) spacecraft (see e.g reviews by Haider et al., 2011, Orosei et al., 2015, Pätzold et al., 2016). Since the bulk of the ionosphere is created by photoionization by the solar EUV irradiance (10–90 nm) the main ionospheric peak at $\sim$ 130 km altitude and the density below $\sim$ 180 km determined by balance between photoionization and recombination follow well variations in the EUV flux (Mendillo et al., 2003, 2013, Breus et al., 2004; Zou et al., 2006, Withers et al., 2015). A similar trend is observed in the variations with solar irradiance of the ionospheric column density or total electron content (TEC), which is the electron density integrated over the height of the ionosphere, (Lillis et al., 2010, Dubinin et al., 2016). Elevated profiles of the ionospheric number density during solar flares were also reported (Mendillo et al., 2006, Gurnett et al., 2005, Nielsen et al., 2007, Haider et al., 2009, Mahajan et al., 2009). The positive response of the ionosphere at altitudes $\leq$ 250 km to solar activity as exposed in variations in the neutral scale height, in the main ionospheric peak and in TEC, was also discussed by Sanchez-Cano et al. (2016).

At altitudes above $\sim$ 180 km the ionosphere is no longer in photochemical equilibrium and diffusion and transport processes become dominant. However, as will be shown in this paper, solar irradiance remains to be important even in the upper ionosphere. Observations by Mars Express (MEX) supplemented by the EUV monitoring at Earth orbit and translated to Mars provide us information about this dependence over more than 12 years. We present multi-instrument observations of the influence of the solar irradiance on the Martian ionosphere and escape fluxes. We use data obtained by the ASPERA-3 and MARSIS

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experiments on Mars Express.

It is worth noting that some similar efforts were made in previous studies. Lundin et al. (2008b) have used the sensitivity of the Neutral Particle Imager (NPI) of the ASPERA-3 experiment onboard Mars Express to Lyman-α as a proxy of solar EUV fluxes. These authors have studied the response of ion escape to variations in the noise background of NPI based on 42 orbits selected from a 17 month period from December 2004 to June 2006 and have found that a decrease in the EUV flux by a factor of 2.5 leads to a decrease of outflow of ions with $E \leq 800$ eV also by a factor of 2.5. On the other hand, analyzing the ASPERA-3 data from May 2004 to November 2005 and using as a proxy the solar EUV flux at Earth scaled and shifted to Mars, Nilsson et al. (2010) did not find any clear correlation between the solar EUV flux and the ion escape rate. Simulations also provide us controversial results. Modolo et al. (2005) and Dong et al. (2014) have reported that loss rates increase by ~ 4.3 and ~ 2.5 times, respectively, from solar minimum to solar maximum while in simulations by Brecht et al. (2016) losses increase by more than 20 times.

2. Instrumentation

Mars Express was inserted into Mars orbit in February 2004 at the declining phase of solar activity of the solar cycle 23. Fig. 1 shows the data of the Solar EUV Monitor (SEM) on the Solar Heliospheric Observatory (SOHO) which measures EUV and soft X-ray solar irradiance in the band 0.1–50 nm. Solar fluxes from the SOHO spacecraft were scaled in the intensity to the distance of Mars and rotated to Mars position. Black and green symbols correspond to the mean and median values, respectively. Time intervals of the operation of MARSIS and IMA/ASPERA-3 in low energy mode are also given. The unusually weak solar cycle 24 followed the solar minimum which was reached in 2009. The solar irradiance in this band during the whole time interval of MEX operation in Mars orbit varies approximately from 0.6×10^{10} photons/cm^{2}s to 2×10^{10} photons/cm^{2}s.

The Ion Mass Analyzer (IMA) which is a part of the ASPERA-3 instrument (Barabash et al., 2006) measures the composition, energy and angular distribution of ions with energy ≤ 30 keV. A new patch uploaded on May 1, 2007 expanded the energy range down to ~ 10 eV. In many regions in the Martian space (e.g. in the ionosphere, in the optical

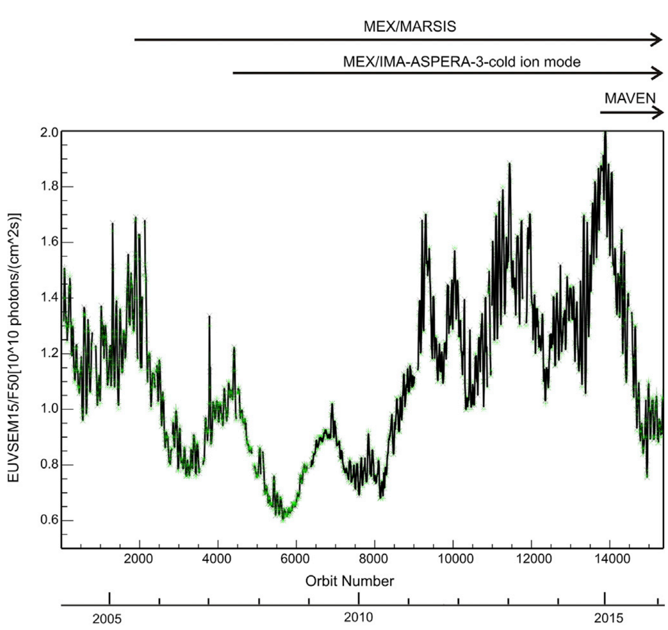

Fig. 1. Solar EUV flux (0–50 nm) measured by SEM/SOHO at the Earth orbit and translated to Mars position during the MEX mission. Black and green lines correspond to the mean and median values, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

planetary shadow), IMA is able to detect ions with lower energies because of a negative spacecraft potential providing us information about motions of the cold ionospheric plasma (Dubinin et al., 2008, Fraenz et al., 2010, 2015). The measurements of ions with low energies ($E/q \leq 50$ eV/q) are carried out without an elevation scanning that decreases the field-of-view of the instrument to $4^\circ \times^\circ 360^\circ$ as compared to $90^\circ \times^\circ 360^\circ$ for the measurements of the higher energy ($E > 50$ eV/q) ion component.

MEX also carries the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS). In the Active Ionospheric Sounder (AIS) mode the radar transmits electromagnetic pulses from 0.1 to 5.4 MHz and detects the waves reflected from the ionosphere which allows to retrieve the altitude profiles of the electron number density (Gurnett et al., 2005). Besides that, when the transmitted frequency passes through the local electron frequency strong electrostatic oscillations at this frequency are excited and provide us information about the local electron number density (Gurnett et al., 2005, Duru et al., 2008). Andrews et al. (2013) have developed a method for the automatic retrieval of local plasma density from the MARSIS data. In this paper we use this database of the local electron number density derived from the MARSIS observations from June 2005 to June 2014.

3. Observations

3.1. Variations in upper ionosphere with EUV

Fig. 2 shows a map of the local electron number density measured by MARSIS at 80°–90° solar zenith angles (SZA) at different EUV flux levels. It is observed that at all altitudes sampled by MARSIS the density increases with increase in solar activity. Fig. 3 depicts how the electron density varies with solar EUV flux at different altitudes. Dotted lines are

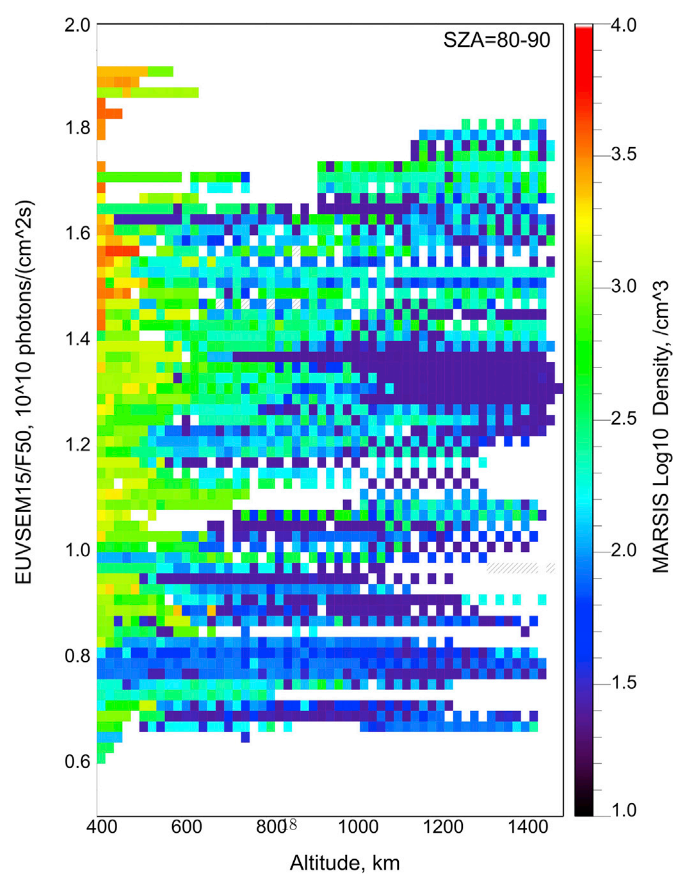

Fig. 2. Map of the local electron number density inferred from the MARSIS data as a function of altitude and solar irradiance near the terminator plane (SZA $= 80^o - 90^o$).