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Topside ionosphere of Mars: Variability, transient layers, and the role of crustal magnetic fields

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ABSTRACT

The topside ionosphere of Mars is known to show variability and transient topside layers. In this study, we analyzed the electron density profiles measured by the radio occultation technique aboard the Mars Global Surveyor spacecraft to study the topside ionosphere of Mars. The electron density profiles that we used in the present study span between 1998 and 2005. All the measurements are done from the northern high latitudes, except 220 profiles which were measured in the southern hemisphere, where strong crustal magnetic fields are present. We binned the observations into six measurement periods: 1998, 1999-north, 1999-south, 2000–2001, 2002–2003, and 2004–2005. We found that the topside ionosphere in the southern high latitudes is more variable than that from the northern hemisphere. This feature is clearly seen with fluctuations of wavelengths less than 20 km. Some of the electron density profiles show a transient topside layer with a local maximum in electron density between 160 km and 210 km. The topside layer is more prone to occur in the southern hemispheric crustal magnetic field regions than in the other regions. In addition, the peak density of the topside layer is greater in regions of strong crustal magnetic fields than in other regions. The variability of the topside ionosphere and the peak density of the topside layer, however, do not show one-to-one correlation with the strength of the crustal magnetic fields and magnetic field inclination. The results of the present study are discussed in the light of current understanding on the topside ionosphere, transient topside layers, and the role of crustal magnetic fields on plasma motions.

1. Introduction

The main layer of the Martian ionosphere has its peak at ~135 km altitude and has a density of ~10^{11} m^{-3} (e.g., Kliore et al., 1965; Bougher et al., 2001). These values, however, have a strong dependence on the solar zenith angle (SZA). At the altitudes of the main peak, the ionosphere of Mars is close to that predicted by the classical Chapman theory (Rishbeth and Garriott, 1969), mainly because the atmospheric composition of Mars is dominated by a single gas, i.e. CO_2. In addition, the ionization cross section of CO_2 is approximately uniform between 20 nm and 90 nm wavelengths, which are the primary ionizing radiation for the main layer (Fox and Yeager, 2006). The Chapman theory also predicts that the electron density (N_e) in the ionosphere above the main peak (called the topside ionosphere) should decrease exponentially (Rishbeth and Garriott, 1969; Withers, 2009).

However, the N_e profiles at and above the peak of the main ionospheric layer are often found to show deviations from the Chapman profiles (Hanson et al., 1977; Wang and Nielsen, 2003; Gurnett et al., 2008; Withers et al., 2012). For example, a change in the scale height with altitude was found in the ion density profiles measured by the retarding potential analyzer aboard Viking 2 spacecraft (Hanson et al., 1977), radio occultation (RO) profiles of the Mars Global Surveyor (MGS) (Ness et al., 2000; Withers et al., 2012), and in the ionospheric traces of the ionograms measured by the Mars Advanced Radar for Subsurface and Ionosphere Sounder (MARSIS) (Gurnett et al., 2008; Kopf et al., 2008) aboard the Mars Express spacecraft. The smaller plasma scale heights in some of these studies were interpreted as due to horizontal magnetic fields, but such changes in scale height were also observed in regions where magnetic anomalies are not present (Ness et al., 2000; Withers et al., 2012). Wang and Nielsen (2003) reported the observation of wavelike disturbances in the topside Martian ionosphere.

Some studies have shown that the crustal magnetic fields also control the movement of plasma thereby altering the shape of the electron density profiles in the Martian ionosphere. In regions of strong crustal magnetic fields, the scale heights are in fact smaller if the magnetic fields are horizontal (that impede the vertical motion of plasma) and become larger as the magnetic fields become vertical (that enhance the vertical motion of plasma) (Ness et al., 2000; Matta et al., 2015). Withers et al. (2005) have reported the presence of anomalous electron density profiles in regions of strong magnetic fields that show either an increase or a decrease in the electron densities of the topside ionosphere. MARSIS observations have also shown that the topside ionosphere of Mars is not

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always horizontally stratified but consists bulges of ionization in regions of strong magnetic fields (Gurnett et al., 2005; Duru et al., 2006; Andrews et al., 2014; Diéval et al., 2015; Venkateswara Rao et al., 2017). On some occasions, enhanced electron densities and elevated altitudes are observed in regions of strong crustal magnetic fields (Ness et al., 2000; Mitchell et al., 2001; Nielsen et al., 2007a, 2007b).

Apart from the above mentioned altitude variabilities, the vertical ionospheric traces of MARSIS ionograms revealed the presence of a layer in the topside Martian ionosphere between 180 and 220 km (Gurnett et al., 2008; Kopf et al., 2008; Zhang et al., 2015; Venkateswara Rao et al., 2017). The layer was found to be highly transient with timescales of a few tens of seconds to a few minutes and at times it completely disappears (Kopf et al., 2008). The SZA variation of the layer's occurrence shows that it is highest at sub-solar point (60%) and least near the terminator (5%) (Kopf et al., 2008).

Using MGS RO N_e profiles, the variability of the topside ionosphere has been studied until now either by considering individual profiles (Withers et al., 2005) or all the profiles together (Wang and Nielsen, 2003), irrespective of the measurement period. In this paper, we study the variability of the topside ionosphere by dividing the MGS RO N_e profiles according to their measurement period. Until now, the topside layer has been explored mostly by using MARSIS measurements. In these measurements, the topside layer appears at the low-frequency end of ionograms. However, this portion of the ionogram is frequently contaminated by the local plasma frequency lines which mask the appearance of the topside layer. In addition, when MARSIS passes over the regions of strong crustal magnetic fields the electron cyclotron lines further obscure the observation of topside layers in MARSIS ionograms. Therefore, from MARSIS ionograms it is difficult to study the relation between the topside layers' occurrence and the crustal magnetic fields. To overcome these limitations, in the present study we investigate the topside layers using the MGS electron density profiles. These profiles are further used to examine the role of crustal magnetic fields on the vertical variability of the Martian topside ionosphere.

2. Radio occultation technique and data

The data used in the present study are the electron density profiles measured by the radio science experiment on MGS spacecraft through radio occultation technique (Bougher et al., 2001). Radio occultation is a remote sensing limb sounding technique that is used for measuring physical properties like temperature and electron density of a planet's atmosphere and ionosphere, respectively (Kliore et al., 1965; Hinson et al., 1999; Withers et al., 2014). It relies on the detection of a change in the frequency of radio signal as it passes through a planet's atmosphere or ionosphere. In radio science, S and X band signals are generally used for ionospheric probing. Ionospheric plasma, being a dispersive medium, refracts the radio signal traversing through it from the transmitter to the receiver. As a result, the time at which the receiver receives the signal gets delayed and this delay is inversely proportional to the square of the transmitted frequency (Lawrence et al., 1964). A time series of frequency residuals gives the corresponding bending angles as a function of impact parameter (Healy, 2001). It is assumed that the ionosphere is spherically symmetric. Once the bending angles are obtained, the corresponding refractive indices are calculated using the Abel transform. Implementing the radio occultation technique requires a telemetry system onboard the spacecraft and a receiver either in the ground station or in another satellite. In MGS radio science experiment, the receiver is at the Earth's ground station and it is a one way single frequency technique with a transmitter having ultra stable oscillator on board the spacecraft (Withers et al., 2014).

MGS was put into Martian orbit in 1997 and during its lifetime it periodically measured several thousand electron density profiles of the Martian ionosphere. The data span from 1998 to 2005 with several consecutive days of measurements in each year. The number of profiles in each year varies from 32 profiles in 1998 to as many as 1524 profiles in 2005. In the following, we grouped the observations by considering continuous data from different years or data with small gaps as one group. In this way, the N_e profiles are separated into six groups; 1998, 1999-north, 1999-south, 2000–2001, 2002–2003, and 2004–2005. Among these, the observations in 2000 and 2001 are continuous and similarly in 2004 and 2005 and hence they are combined. The observations in 2002 and 2003 are separated by 80 days, but they are considered as one set as there is not much flux difference between the two. 1998, 1999-north, 1999-south data sets are not combined as we intend to make a comparison between the 1999-north and 1999-south data sets. Table 1 gives the observational summary of the MGS N_e profiles. As shown in Table 1, all the data were obtained within a restricted latitude and solar zenith angle (SZA) range, but covering all longitudes. In the entire MGS data set, the SZA varied between 71° and 89°. Most of the data were obtained from northern high-latitudes (60.64° N - 85.48° N) near the terminator, except for 220 profiles in May 1999 which were obtained from southern high-latitudes (64.60° S - 69.00° S). In addition, there are 43 profiles in 1999 that were obtained from northern high latitudes.

Among others, the two most important parameters that affect the electron densities in the Martian ionosphere are the solar flux and the SZA. Fig. 1 shows the measurement periods of the MGS N_e profiles plotted over the F10.7 cm solar flux corrected for the Martian orbit. The average fluxes during the MGS measurement periods lie between 43.09 sfu and 64.80 sfu (sfu, solar flux units). Among these measurement years, the fluxes are highest in 2000–2001 and least in 2004–2005. The distribution of SZAs during each measurement period is shown in Fig. 2. As mentioned before, all the measurements are taken between SZA values of 71° and 89°. Among these, the observations in 1998 and 1999-north correspond to a narrow SZA range, while those in other years are made in relatively wide SZA range. The highest altitude in each profile is highly variable. To make all the results consistent, we restricted the topside altitude to 210 km. To study the topside ionosphere, the lower boundary is set at ~145 km (Wang and Nielsen, 2003).

3. Results

In Fig. 3 we show a N_e profile obtained on 29 May, 1999 to describe the characteristic features that we are going to study further. In Fig. 3, we can note that the density of the topside ionosphere decreases gradually. Superimposed on this gradual decrease, there are several fluctuations whose vertical scales (the difference in altitude between two consecutive enhancements in density) vary from a few kilometers to less than 20 km. In the subsequent section, these fluctuations will be quantified and studied under 'vertical variability of the topside ionosphere'. In Fig. 3, we can also note the presence of a topside layer (a local maximum in density) above 175 km. A local maximum is considered as a topside layer when the difference between the peak density of the layer and the background profile is $> 1.0 \times 10^{10}\,\mathrm{m}^{-3}$. The local maximum above 175 km in Fig. 3 satisfies this criterion and is considered as a topside layer. All the other enhancements do not satisfy this criterion. This layer will be further studied in section 3.2. In the following, we will make a detailed study of the variability of the topside ionosphere and the topside layers.

3.1. Vertical variability of the topside ionosphere

To quantify the vertical variability of the topside ionosphere, we designed a 30th order linear-phase finite impulse response filter with hamming window (Programs for Digital Signal Processing, IEEE Press, New York, 1979. Algorithm 5.2). We applied it on each individual N_e profile in high-pass mode with a cutoff of 20 km which allows only the fluctuating part of each profile. In Fig. 4 we show two topside N_e profiles, along with their filtered outputs, obtained on 10 May, 1999 and 17 March, 1999, respectively. By observing the original profile and the filtered output of Fig. 4a, we can note that there are fluctuations in the topside ionosphere with vertical wavelengths of a few km superposed on a profile whose density decreases gradually. Similarly, Fig. 4b also