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On the small-scale fluctuations in the peak electron density of Martian ionosphere observed by MEX/MARSIS

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ABSTRACT

We reported the small-scale fluctuations in the peak electron density of dayside Martian ionosphere observed by MEX/MARSIS. MARSIS is an ionospheric sounder that can measure the vertical electron density profile of the topside ionosphere. In the experiment the ionospheric critical frequency can be determined within the accuracy of 5 kHz, corresponding to a typical accuracy in electron density of 0.02%. As a space-borne remote sensing instrument, MARSIS can observe the ionosphere with a time resolution of 8 s, enabling one to study the horizontal variation of the ionosphere. Besides the normal variations of the peak electron density with respect to the solar zenith angles, small fluctuations in peak electron density is detected within single orbit of observation. The appearance of these fluctuations is relatively smooth and wavy, distinct from measurement errors which are random and noisy. The fluctuations do not exhibit a prevailing wavelength either in space or in time. The peak-to-valley amplitude of the fluctuation can reach 200 kHz in frequency, corresponding to a 10% variation in peak electron density. Over 38,000 peak values of electron density profiles were recorded, organized along each orbit. A mean variation of $\sim 6\%$ in the peak electron density is found. Fourier analysis of the data was performed with respect to the horizontal distance the spacecraft passes in one orbit. Resulting spectra generally follow a $-5/3$ power law in a double logarithm plot, suggesting a turbulence-dominated nature. Perturbations propagating from upper ionosphere and fluctuations in the neutral density are discussed as potential causes for this observation. This observation reveals a sensitive proxy to monitor the dynamics of neutral Martian atmosphere at ~ 130 km altitude.

1. Introduction

1.1. Background

Mars has a tenuous atmosphere composed mainly of CO_2. The atmosphere can be ionized by solar radiation and forms a thin ionosphere. Different from the complicated layers on the Earth, the stratification of Martian ionosphere is relatively simple. There are two steady layers in the ionosphere of Mars: the primary and upper layers (M2) peaking at ~ 130 km and the secondary and lower layers (M1) peaking at 115 km (Withers, 2009). Recently a transient third layer below M1 layer produced by micrometeorites was confirmed (Paetzold et al., 2005). The M2 layer with a typical electron density of $10^5\ cm^{-3}$ is ionized by solar EUV radiation with wavelengths of 20–90 nm (Schunk and Nagy, 2000). The solar irradiance penetrates the atmosphere of Mars at a zenith angle χ, ionizes neutral constituents along its path and produces an ionosphere.

The only *in situ* measurement of the Martian ionosphere was the Retarding Potential Analyzer (RPA) experiment on the Viking landers during their descent stages (Hanson et al., 1977). The data revealed the electron and ion density profiles in M2 layer peak and the topside ionosphere. *In situ* measurement is the most definite means to observe the ionosphere, however, its temporal and spatial coverage is poor. Most of our current understandings about Martian ionosphere come from remote sensing techniques. One important method is the radio occultation experiment facilitating the radio transmission from an orbiter around Mars. The basic idea of radio occultation experiment is to measure the Doppler shift of the radio waves from a spacecraft during its immersion and emersion at the limb of a planet, yielding its dependence on the altitude of transmission path, thereby obtaining the altitude profile of the electron and atmosphere density (Fjeldbo et al., 1965). Mariner 4, 6, 7, 9 and Viking 1, 2 are the early missions that

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systematically carried out radio occultation experiments. Their results constructed the basic frame of our understandings of Martian ionosphere. The background of Martian ionosphere, and the effect of global dust storms, was studied (see Zhang et al., 1990, for a review). Later, Mars Global Surveyor (MGS) greatly enriched the information of electron density profiles of Martian ionosphere by over 5000 electron density profiles, enabling people to investigate its variability and finer features (e.g. Hinson et al., 1999; Bougher et al., 2001). In the 21st century, Mars Express (MEX) mission performed high-accuracy radio science experiment that revealed the portion of ionosphere lower than the M1 layer and discovered a sporadic third layer produced by the ablation of micrometeoroids (Paetzold et al., 2005). Radio occultation method has good vertical resolution, and is able to measure the lower part of the ionosphere below the main peak. However, its time resolution is constrained by the period of orbit, and it has collapsed the horizontal variations of the ionosphere. Another restriction for Mars is that due to the geometric configuration of the Earth and Mars, radio occultation experiment can only observe the ionosphere regions with SZA 45–135°.

This paper is organized in the following order: the first section is an introduction to the background of our topic. In the second section the data of MARSIS observation on the ionosphere is introduced, including ordinary observations and featured phenomenon—the fluctuations in the peak electron density. The details of data processing are also described. In the last section we propose the potential cause of this observation and try to discuss the physical insights and potential applications of our observations.

1.2. Chapman's formation theory of ionosphere applied to Mars

Chapman (1931a,b) developed a theory to describe the generation of an ionosphere purely due to photoionization process. This theory was used widely to describe the profile and behavior of the Martian ionosphere (e.g. Zhang et al., 1990; Breus et al., 1998; Rishbeth and Mendillo, 2004; Nielsen et al., 2006; Withers, 2009). A steady photochemical layer is maintained by the equilibrium between the production rate and loss rate of electrons, mathematically $P{=}L$. The primary photochemical reactions that produce the electrons include

$$CO_2 + h\nu \rightarrow CO_2^+ + e \tag{1}$$

$$CO_2^+ + O \rightarrow O_2^+ + CO \tag{2}$$

The reaction rate of Eq. (2) is very large (e.g. Withers, 2009), so the main ion species around peak altitude of Martian ionosphere is O_2^+, although the most abundant neutral molecule in the atmosphere is CO_2. In Chapman's theory of ionosphere formation, the production rate from photoionization process is (Schunk and Nagy, 2000)

$$P = I\eta\sigma^a n \tag{3}$$

where I is the local radiation intensity, η is the absorption efficient, σ^a is the absorption cross-section, n is the neutral density. The production rate is proportional to the solar radiation flux and the density of neutral reactant. The loss process at the ionosphere peak is mainly the dissociative recombination reaction of electrons with O_2^+ ions

$$O_2^+ + e \rightarrow O + O \tag{4}$$

Thus the loss rate is

$$L = kn_e^2 \tag{5}$$

if the densities of electron and O_2^+ are equal, where k is the reaction rate of dissociative recombination reaction. Under the situation of the reactions above and a neutral atmosphere exponentially decreasing with altitude, the electron density profile with altitude is

$$n_e = n_m \exp\left(0.5\left(1 - \frac{z-z_m}{H} - \exp\left(-\frac{z-z_m}{H}\right)\right)\right) \tag{6}$$

where n_m and z_m are the peak electron density and the peak altitude of local ionosphere, H is the scale hight of the neutral atmosphere. n_m depends on the solar zenith angle of the local point as

$$n_m = n_0/\sqrt{Ch} \tag{7}$$

where Ch is the Chapman grazing incidence function describing the absorption of incident solar radiation as it passes an atmosphere. Ch can be well approximated by (sec χ) if $\chi < 85^\circ$, where χ is the solar zenith angle. n_0 and z_0 are the density and altitude of the ionospheric peak at the subsolar point ($\chi = 0$).

1.3. Description of MARSIS

The Mars Radar for Subsurface and Ionospheric Sounding (MARSIS) on MEX is the first topside sounder working on a planet other than the Earth. Its designed purpose is to observe the subsurface structure and the electron density profile of Martian ionosphere (Picardi et al., 1999). The physical components of the radar include a 40-m tip-to-tip dipole antenna, a 7-m monopole antenna and corresponding electronics. The dipole antenna is arranged parallel to the surface of the Mars and perpendicular to spacecraft orbit, while the monopole antenna point downward to the surface. The radar has two modes in nominal missions: the subsurface sounding mode and the active ionospheric sounding (AIS) mode. In AIS mode, only the dipole antenna is utilized. The basic principle of this mode is based on the dispersive nature of the propagation of radio waves in a plasma. The relation between the group velocity of a radio signal and the plasma frequency of the ionosphere is as follows:

$$v_g = c\sqrt{\frac{1}{1 - \frac{(f_p(z))^2}{f^2}}} \tag{8}$$

where v_g is the group velocity of the wave in the plasma, c is the speed of light in vacuum, $f_p(\mathrm{kHz}) = 8.98\sqrt{n_e(\mathrm{cm}^{-3})}$ and f are the plasma frequency and the frequency of the radio wave, respectively. From this relation it is obvious that a radio wave cannot propagate in a plasma if its frequency is lower than plasma frequency. As the radio signal propagates, if local plasma frequency increases and finally exceeds the signal frequency, the signal will be reflected at the place where two frequencies meet. The reflected signal can then be detected, and the time delay from the transmission of the initial signal can be measured. The time delay is usually multiplied by the speed of light in vacuum, giving an apparent range of the reflection point. This working cycle is performed on a series of discrete frequencies, so we can get the apparent range of reflection point as a function of electron density. The apparent range of a certain frequency can be written as

$$z' = ct_d = c\int_{z_0}^{z_r} \frac{dz}{v_g} \tag{9}$$

where z_0 and z_r are the *real* altitudes of the spacecraft and the reflection point. The shape of this function is determined by the electron density profile. If the sounding frequency is higher than the critical frequency of the ionosphere determined by the peak electron density, the signal will penetrate the ionosphere and get reflected by the surface of Mars. So we can measure the peak electron density within the accuracy of neighboring frequency step.

The AIS mode is turned on when the spacecraft is lower than 1200 km, in order to avoid too much attenuation due to large distance and to maintain the time delay in the time range of measurement. A total sounding cycle consists of 160 soundings