Overview of the Plasma Environment of Mars as seen by the Radar Sounder on Mars Express Spacecraft

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Abstract

The Mars Express Spacecraft carries a radar sounder that is in its 6^{th} year of operation in orbit around Mars. The sounder provides both local and remote measurements of electron densities and in some cases the magnitude of the magnetic field in the Martian ionosphere. Here, we give an overview of the plasma environment of Mars as seen by the radar. Both local and remote electron density profiles are reported, including density fluctuations and gradients, magnetically controlled structures, interaction between the ionosphere and the solar wind, and holes and other structures in the nightside ionosphere.

1. Introduction

The Mars Express spacecraft, which was placed in an elliptical orbit around Mars on 25 December 2003, carries a low-frequency radar called MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) [1]. MARSIS is designed to perform both subsurface and ionospheric soundings [2]. Initially, Mars Express had a periapsis altitude of about 275 km, an apoapsis altitude of about 10,100 km, with a period of 6.75 hours. A typical MARSIS ionospheric sounding starts at about 1300 km on the inbound leg, passes through periapsis, and ends at about 1300 km on the outbound leg and lasts about 40 min. Here, we provide an overview of the ionospheric sounding results after more than 5 years of operation.

2. Ionospheric Sounding

Radar sounding is performed by transmitting a short pulse of radio waves at a fixed frequency, f, and then by measuring the time delay, Δt, of the returning echo. For normal incidence on a horizontally stratified ionosphere, reflection occurs when the wave frequency is equal to the electron plasma frequency, f_p. The electron plasma frequency, f_p is given by

$$f_p = 8980\sqrt{n_e} \quad (1)$$

where f_p is in Hz and n_e is the electron density in cm^{-3}. To obtain a vertical profile of the electron density, the frequency of the MARSIS transmitter is sequentially stepped through 160 quasi-logarithmically spaced frequencies from 0.1 to 5.4 MHz, and the time delay of the received pulses is recorded in 80 time bins from 0 to 7.54 s [3].

In addition to remote soundings, with MARSIS local electron densities are obtained by measuring the frequency of local electron plasma oscillations excited by the radar transmitter [4]. As the transmitter steps in frequency, strong local electrostatic plasma oscillations, called Langmuir waves, are excited when the transmitter frequency is equal to the local electron plasma frequency. From the local electron plasma frequency, local electron density can be calculated by using equation 1. This technique provides local electron density measurements at much higher altitudes than can be determined from remote sounding.

A plot of the echo intensity as a function of time delay and frequency, called an ionogram, is often used to display MARSIS data. An example is shown in Figure 1. In this figure, the ionospheric echo is seen at low frequencies, at about 4 ms of time delay. At higher frequencies and higher time delays the surface reflection, from the ground of Mars is seen. A cusp, centered on $f_p(max)$, is formed between the ionospheric echo and surface reflection. Harmonics of the electron plasma oscillation (caused by distortion in the receiver) are seen as equally spaced, vertical lines at the upper left corner. The oblique ionospheric echo at higher time delays is due to an oblique reflection from a small scale feature in the ionosphere. In some of the ionograms, it is also possible to see equally spaced, horizontal lines at low frequencies that are at multiples of the electron cyclotron period. These echoes are due to electrons accelerated by the transmitter pulse that are orbiting in the local magnetic field. When detected, the magnitude of the magnetic field can be computed from the period of these echoes, which are called electron cyclotron echoes.

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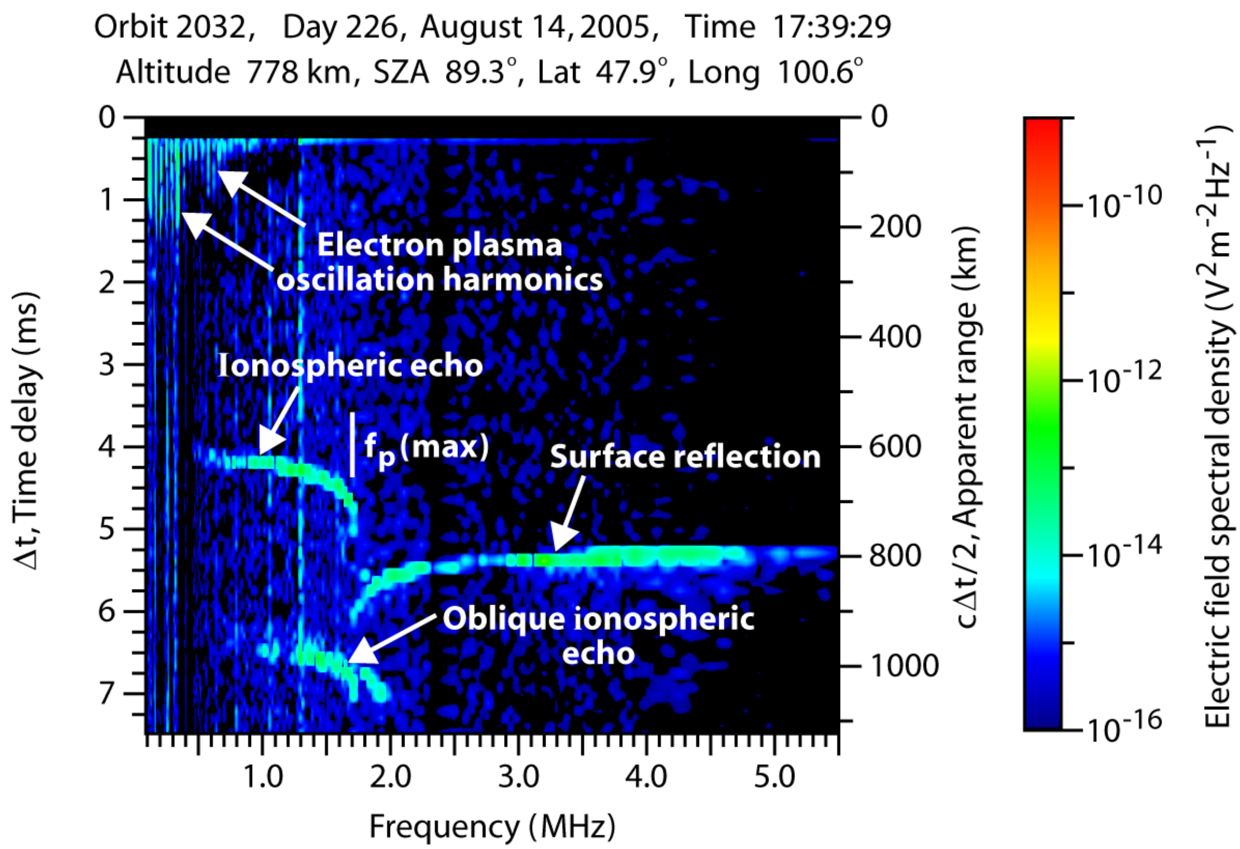

Figure 1: A typical ionogram.

3. Electron Density Profiles

The ionospheric echo trace can be converted to an electron density profile [5]. This is done by scaling the time delay as a function of frequency from the ionogram and then computing the dispersion-corrected altitude of the ionospheric reflection. The electron density profiles computed this way are compared with the Chapman (1931) photo-equilibrium theory of planetary ionospheres [6]. We find that computed density profiles are in reasonable agreement at lower altitudes near the density peak. However, there are often significant deviations from the model at altitudes above about 200 km. Also, the maximum plasma frequency in the ionosphere as a function of solar zenith angle (SZA) is in very good agreement with the predictions of the Chapman model.

The study of local electron density profiles over an altitude range between 275 to 1300 km, showed that the electron density decreases almost exponentially with increasing altitude. On the dayside, the electron densities are found to be almost independent of the SZA [4].

3.1 Large Density Fluctuations

Density measurements in the Martian ionosphere show a persistent level of large fluctuations, which can be as much as a factor of three or more [7]. Large magnetic field magnitude fluctuations are also observed. The power spectrums of both the electron density and magnetic field showed that fluctuations are consistent with the Kolmogorov spectrum for isotropic fluid turbulence. Factors like solar wind pressure perturbations, an instability in the magnetosheath plasma, or Kelvin-Helmholtz instability are thought to cause these large fluctuations.

4. Ionopause

The study of local electron density profiles revealed that very sharp gradients in the electron density are sometimes observed which are similar to the ionopause boundary commonly observed at Venus [8]. The fact that these nearly discontinuous density changes are seen only in 18% of the total sample studied suggests that Mars has a transient ionopause. In one third of the cases, remote sounding data have also confirmed identical locations of ionopause-like density discontinuities. It is shown that, although the individual cases occur over a wide range of altitudes, the average altitude is almost constant around 450 km, up to 65°. Also, it has been confirmed that the presence of strong crustal magnetic fields has the effect of raising the ionopause boundary, sometimes by more than 100 km from its average position.

5. Magnetically Controlled Structures

MARSIS remote sounding data show that the dayside ionosphere has considerable structure over regions of strong crustal magnetic fields. These structures are typically seen as hyperbola-shaped features in a display of echo intensity versus apparent altitude and time, at a fixed frequency [9]. The hyperbola shaped features are consistent with oblique reflections from regions of enhanced electron density that are fixed with respect to Mars. The apex of the hyperbola often coincides with a region of strong vertical crustal magnetic field. It is believed that the bulges are formed due to ionospheric heating caused by solar wind electrons reaching the base of the ionosphere through nearly vertical open magnetic field lines.

6. Overlapping Ionospheric and Surface Echoes near Terminator

From time to time, radar soundings from MARSIS show ionospheric and surface echoes that overlap in frequency, which is not possible for specular reflection from a horizontally stratified ionosphere, since the ionospheric echo and surface reflection occur at frequencies below and above the maximum ionospheric frequency, respectively [10]. It is seen that overlap cases are observed only around the terminator region. It is possible to explain overlapping echoes as a result of a nadir-directed reflection from the surface of Mars and an oblique reflection due to the ionosphere which has slowly increasing density around the terminator.

7. Holes in the Nightside Ionosphere

The study of the nightside ionosphere of Mars through local electron densities [11] showed that nightside ionosphere is highly variable. An inverse relationship is observed between the electron density and altitude. At altitudes between 200 and 400 km, the median electron density decreases with increasing SZA, whereas, at high altitudes no dependence on SZA is seen. Nightside density holes, which are seen as deep troughs in the local electron density profiles, are commonly encountered structures on the nightside. These are large structures with an average width of 950 km. Although the exact reasons for their existence is not known, they could be plasma flow regions associated with open magnetic fields.

8. Conclusion

Important information has been obtained about the Martian plasma environment by the ionospheric soundings obtained from MARSIS from five years of operation. MARSIS, in addition to remote soundings of the ionosphere, provided electron densities and magnetic field magnitude at the location of spacecraft. It is shown that at low altitudes the ionosphere of Mars is in good agreement with Chapman's theory. At altitudes higher than 300 km, the electron density decreases exponentially with altitude and the median electron densities are almost constant on the dayside. Both dayside and nightside ionopsheres of Mars have highly fluctuating electron density and local magnetic field profiles. An ionopause-like boundary has been observed on the dayside. Also, several types of oblique echoes have been studied. On the nightside, density holes are commonly seen structures.

9. Acknowledgments

Research at the University of Iowa was founded by contract 1224107 with the Jet Propulsion Laboratory.

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