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An overview of radar soundings of the martian ionosphere from the Mars Express spacecraft

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Abstract

The Mars Express spacecraft carries a low-frequency radar called MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) that is designed to study the subsurface and ionosphere of Mars. In this paper, we give an overview of the ionospheric sounding results after approximately one year of operation in orbit around Mars. Several types of ionospheric echoes are commonly observed. These include vertical echoes caused by specular reflection from the horizontally stratified ionosphere; echoes from a second layer in the topside ionosphere, possibly associated with O^+ ions; oblique echoes from upward bulges in the ionosphere; and a variety of other echoes that are poorly understood. The vertical echoes provide electron density profiles that are in reasonable agreement with the Chapman photo-equilibrium model of planetary ionospheres. On the dayside of Mars the maximum electron density is approximately $2 \times 10^5\ \mathrm{cm}^{-3}$. On the nightside the echoes are often very diffuse and highly irregular, with maximum electron densities less than $10^4\ \mathrm{cm}^{-3}$. Surface reflections are sometimes observed in the same frequency range as the diffuse echoes, suggesting that small isolated holes exist in the nightside ionosphere, possibly similar to those that occur on the nightside of Venus. The oblique echoes arise from upward bulges in the ionosphere in regions where the crustal magnetic field of Mars is strong and nearly vertical. The bulges tend to be elongated in the horizontal direction and located in regions between oppositely directed arch-like structures in the crustal magnetic field. The nearly vertical magnetic field lines in the region between the arches are thought to connect into the solar wind, thereby allowing solar wind electrons to heat the lower levels of the ionosphere, with an attendant increase in the scale height and electron density.

Keywords: Mars ionosphere; Ionosphere radar sounding; Mars

1. Introduction

The Mars Express spacecraft, which was placed in an eccentric orbit around Mars on December 25, 2003, includes a low-frequency radar called MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) that is designed to perform subsurface and ionosphere soundings. This paper gives an overview of the ionospheric sounding results after the first year of operation in orbit. The nominal orbit of Mars Express has a periapsis altitude of about 275 km, an apoapsis altitude of about 10,100 km, and an inclination of 86°. A typical MARSIS ionospheric sounding pass lasts about 40 min and starts at an altitude of 1200 km on the inbound leg, continues through periapsis, and ends at an altitude of 1200 km on the outbound

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leg. Because of difficulties with the MARSIS antenna deployment, the instrument did not start operating until July 4, 2005. For a detailed description of the MARSIS instrument and its operation, see Picardi et al. (2004); and for a more detailed description of the Mars express spacecraft, see Chicarro et al. (2004).

Prior to the Mars Express mission, most of our knowledge of the Martian ionosphere came from radio occultation studies. This technique involves making accurate measurements of the phase shift produced as the telemetry signal from a spacecraft passes through the ionosphere. The phase shift provides a measurement of the average electron density along the line of sight. The first radio occultation measurements of the ionosphere of Mars were obtained from the Mariner 4 spacecraft, which flew by Mars in 1964 (Fjeldbo et al., 1966). Since then, extensive radio occultation measurements have been obtained from a variety of spacecraft in orbit around Mars, such as Viking 1 and 2, Mars Global Surveyor, and most recently by Mars Express. For radio occultation results from these and other spacecraft, see Zhang et al. (1990a,b), Luhmann and Brace (1991), Kliore (1992), Mendillo et al. (2004), and Pätzold et al. (2005). Because of geometric considerations involving the orbits of Earth and Mars, occultations can only be obtained at solar zenith angles from about 44° to 136°. As we will show the MARSIS ionospheric soundings nicely complement these radio occultation measurements by providing improved horizontal spatial resolution and the ability to make observations at solar zenith angles where radio occultations cannot be obtained.

The only direct in situ measurements of the Martian ionosphere are from retarding potential analyzers on the Viking 1 and 2 landers, which descended through the ionosphere of Mars on July 20 and September 3, 1976 (Hanson et al., 1977). These measurements showed that the peak electron density is about $10^5\ \mathrm{cm}^{-3}$ at an altitude of about 125–135 km, and that the dominant ion is O_2^+. Smaller concentrations of CO_2^+ and O^+ were also observed. Scale heights inferred from the density profiles were about 20–30 km, and typical electron temperatures were found to be 2000–4000 K (Hanson and Mantas, 1988). The Viking data also showed that the solar wind provides an important energy source in the upper levels of the ionosphere, and that the plasma pressure in the ionosphere is less than the average solar wind dynamic pressure (Hanson and Mantas, 1988; Luhmann and Brace, 1991). It was estimated that a magnetic field of about 30–40 nT is required in the ionosphere to provide pressure balance on the dayside of Mars. Although Mars has no intrinsic large-scale magnetic field, later measurements from the Mars Global Surveyor (MGS) spacecraft showed that Mars has significant small-scale crustal magnetic fields, with peak field strengths at 100 km sometimes as high as 1600 nT (Acuña et al., 1998, 1999). As we will show, crustal magnetic fields play an important role in controlling small-scale structures in the Martian ionosphere.

2. Principles of ionospheric sounding

Spacecraft-borne ionospheric sounders were initially developed in the 1960s to study the topside of Earth's ionosphere (Calvert, 1966; Franklin and Maclean, 1969; Hagg et al., 1969). Ionospheric sounders operate by transmitting a short pulse at a fixed frequency, f, and then detecting any echoes that are reflected from the ionosphere. Reflection occurs because free-space electromagnetic radiation cannot propagate at frequencies below the electron plasma frequency, which is given by $f_p = 8980\sqrt{n_e}\,\mathrm{Hz}$, where n_e is the electron number density in cm^{-3} (Gurnett and Bhattacharjee, 2005). For normal incidence on a horizontally stratified ionosphere, reflection occurs at the altitude where the plasma frequency is equal to the wave frequency, i.e., $f_p = f$. By measuring the time delay, Δt, between the transmission of the pulse and the time that the echo is received, the range to the reflection point can be computed. The basic geometry is illustrated in the top panel of Fig. 1, which shows a representative plot of the plasma frequency as a function of altitude, $f_p(z)$, in the Martian ionosphere. By sequentially stepping the transmitter frequency after each transmit-receive cycle, the time delay, and hence the range to the reflection point, can be determined as a function of frequency. A plot of the time delay as a function of frequency, $\Delta t(f)$, can then be made, as illustrated in the

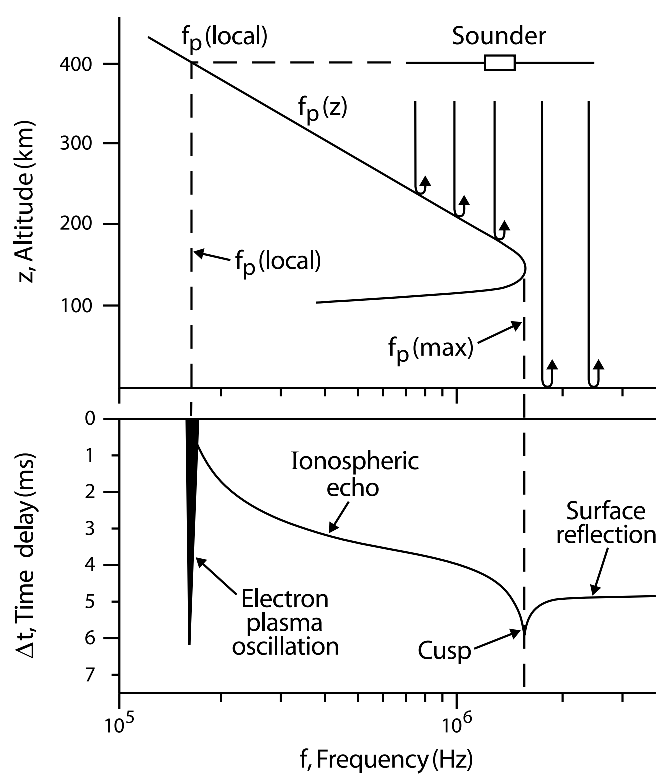

Fig. 1. The top panel shows a representative profile of the electron plasma frequency, f_p, in the Martian ionosphere, and the bottom panel shows the corresponding ionogram, which is a plot of the time delay, Δt, for a sounder pulse of frequency, f, to reflect from the ionosphere and return to the spacecraft.