EPSC Abstracts
Vol. 12, EPSC2018-137, 2018
European Planetary Science Congress 2018

MARSIS observations of field-aligned irregularities and ducted radio propagation in the Martian ionosphere

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Abstract

Knowledge of Mars's ionosphere has been significantly advanced in recent years by observations from Mars Express (MEX) and lately MAVEN. A topic of particular interest are the interactions between the planet's ionospheric plasma and its highly structured crustal magnetic fields, and how these lead to the redistribution of plasma and affect the propagation of radio waves in the system. In this paper, we elucidate a possible relationship between two anomalous radar signatures previously reported in observations from the MARSIS instrument on MEX. Relatively uncommon observations of localized, extreme increases in the ionospheric peak density in regions of radial (cusp-like) magnetic fields and spread-echo radar signatures are shown to be coincident with ducting of the same radar pulses at higher altitudes on the same field lines. We suggest that these two observations are both caused by a high electric field (perpendicular to $\mathbf{B}$) having distinctly different effects in two altitude regimes. At lower altitudes, where ions are demagnetized and electrons magnetized, and recombination dominantes, a high electric field causes irregularities, plasma turbulence, electron heating, slower recombination and ultimately enhanced plasma densities. However, at higher altitudes, where both ions and electrons are magnetized and atomic oxygen ions cannot recombine directly, the high electric field instead causes frictional heating, a faster production of molecular ions by charge exchange, and so a density decrease. The latter enables ducting of radar pulses on closed field lines, in an analogous fashion to inter-hemispheric ducting in the Earth's ionosphere.

1. Observations

In Figure 1 we show four MARSIS ionograms obtained on orbit 2359, close to periapsis at similar altitudes and longitudes, though with significant variation in both latitude and solar zenith angle. The format of each is identical, with reflected intensity shown color-coded versus the sounding frequency f and delay time. All four were taken on the dayside, and each shows a clear ionospheric reflection at a delay of ∼1-1.5 ms.

Figure 1a shows a fairly typical ionospheric reflection trace. The ionogram shown in Figure 1b was obtained at slightly lower altitudes and marginally closer to the sub-solar point than that shown in Figure 1a. The ionospheric reflection is markedly different than that observed in Figure 1a, just northward of the location of the spacecraft in Figure 1b. Firstly, the maximum frequency of the ionospheric trace has significantly increased to ∼4.5 MHz ($n_e \approx 2.4 \times 10^5$ cm^{-3}). This indicates a peak plasma density in the ionosphere well above the ∼$1.3{\times}10^5$cm^{-3} expected at this solar zenith angle according to models of the 'nominal' ionosphere. Here, the ionospheric trace is everywhere more spread out in delay than the sharp nadir reflection shown in Figure 1a, indicating a very non-planar ionosphere. Nielsen et al. [2007], in an analysis of the iongram shown in Figure 1b and other similar features observed on the same orbit, suggested that these greatly enhanced peak densities could be caused by a two-stream (Farley-Buneman) instability acting in the ionosphere.

Figure 1c was obtained shortly after a second such peak density enhancement and delay spreading event. An additional trace is also discernible below the principal nadir reflection, extending still to high frequencies. We suggest that this additional trace is associated with the peak density enhancement, having effectively "detached" from the original feature and moved to higher delays in the intervening soundings, appearing now in this ionogram at delays of ∼1.9-2.4 ms.

The final ionogram shown in Figure 1d depicts one of the so-called 'epsilon' signatures, reported first in the Martian ionosphere by [*Zhang et al.*(2016)]. In addition to a more-typical ionospheric reflection similar to that seen in Figure 1a, three connected traces are are also visible over much larger delays of ∼3-4.4 ms. [*Zhang et al.*(2016)] suggest that this particular signature is the result of ducted propagation of the MARSIS sounding pulse in a plasma cavity, by analogy to similar signatures noted in Earth-orbiting topside ionospheric sounders.

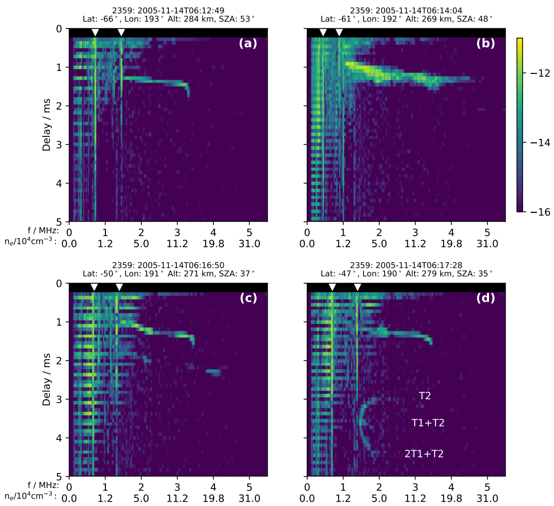

Figure 1: Four MARSIS ionograms obtained on orbit 2359.

2 Interpretation

The two uncommon features noted here – greatly enhanced peak densities and ducted propagation in plasma cavities – are shown to be related to one another. Ionospheric irregularities lying on the same field line are shown to be able to produce both effects, including the delay-spread signatures (Figure 2). Unusually high perpendicular electric fields are shown to be a likely cause of both effects, as the modification of the ionospheric plasma density these will cause will be different at different altitudes. Taken together with other recent observations, this study points towards processes in the Martian ionosphere that share both similarities and significant departures from related processes widely studied in the Earth's ionosphere.

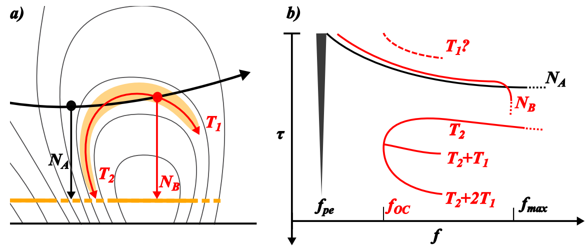

Figure 2: a) MEX's trajectory and MARSIS radar echoes obtained at two locations during a passage through a crustal field arcade, including both nadir and ducted reflections. b) Illustrative features of the two ionograms corresponding to the locations in a), versus time delay τ and sounding frequency f.

Acknowledgements

Work at IRF was supported by grants from the Swedish National Space Agency (DNR 162/14) and the Swedish Research Council (DNR 621-2014-5526). Work at Iowa was supported by NASA through contract 1224107 from the Jet Propulsion Laboratory. Work at Boston University was supported by NASA award NNX15AM59G. All data used in this paper are available in the ESA planetary science archive, https://archives.esac.esa.int/psa.

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