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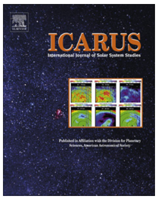

Topside of the martian ionosphere near the terminator: Variations with season and solar zenith angle and implications for the origin of the transient layers

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ABSTRACT

In this paper, the morphological variations of the M2 layer of the martian ionosphere with the martian seasons and solar zenith angle (SZA) at the terminator are investigated. The data used are the MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) measurements (approximately 5000 ionograms) that were acquired from 2005 to 2012, which have a SZA $\geqslant 85^\circ$ and detect the topside transient layers. A simple, effective data inversion method is developed for the situation in which the upper portion of the height profile is non-monotonic and the observed data are insufficient for adequate reduction. The inverted parameters are subsequently explored using a statistical approach. The results reveal that the main body of the M2 layer (approximately 10 km below the first topside layer) can be well-characterized as a Chapman layer near the terminator (SZA = 85–98°), notwithstanding the high SZA and the presence of the topside layers. The height of the first topside layer tends to be concentrated approximately 60 km (with a standard deviation of $\sim$20 km) above the main density peak. The peak density and height of the first topside layer are positively correlated to the density and height of the main peak, respectively. The density and height of the first topside layer appear to be independent of the SZA, but possess seasonal variations that are similar to those of the main layer. The height of the topside layer is greater (by $\sim$10 km on average) in the southern spring and summer than in the southern autumn and winter, coinciding with the observation that, in the southern spring and summer, the underlying atmosphere is warmer due to dust heating (e.g., Smith, M.D. [2004]. Icarus 167, 148–165). The statistical regularities of the parameters suggest a possibility that the formation of the topside layers are closely related to the processes of photoionization and diffusion that occur on the topside of the M2 layer. We propose that development of beam-plasma instabilities in the transitional region (between the lower Chapman region and the upper transport-dominating region) is possibly a mechanism that is responsible for the occurrences of the topside layers.

1. Introduction

Characterization of the martian ionosphere has been greatly promoted since 2005 when measurements by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) on board the ESA mission Mars Express (MEX) (Picardi et al., 2004), became available. Based on MARSIS data, extensive investigations have been conducted by many researchers to characterize the daytime (e.g., Gurnett et al., 2005, 2008; Morgan et al., 2008; Kopf et al., 2008; Nielsen et al., 2007a, 2007b; Akalin et al., 2010; Němec et al., 2011) and nighttime (Safaeinili et al., 2007; Gurnett et al., 2008; Němec et al., 2010) ionosphere of Mars. Current knowledge of the main ionospheric layer of Mars (called M2) that have been achieved by using observations from various instruments, including MARSIS, can be found in a review by Withers (2009).

Previous studies indicate that the daytime M2 layer is well approximated by the Chapman model, which represents a photoionization and dissociative recombination quasi-equilibrium mechanism that is controlled mainly by the solar zenith angle (SZA) (e.g., Gurnett et al., 2005, 2008; Morgan et al., 2008; Němec et al., 2011). Beside the SZA, many factors affect the martian ionosphere to various degrees. For example, seasonal atmospheric

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Notation

c	speed of light in vacuum (=2.998e+8 m s^{-1})
f	wave frequency (Hz)
f_c	electron cyclotron frequency (Hz)
f_j	wave frequency in the jth extracted data point (Hz)
f_p	plasma frequency (Hz)
$f_{p,1}$	plasma frequency at the height z_1 (Hz)
$f_{p,m}$	peak plasma frequency of the main ionospheric layer (Hz)
k	wave number (m^{-1})
k_c	critical wave number above which a beam-plasma instability may occur (m^{-1})
k_B	the Boltzmann's constant (=1.381e−23 J K^{-1})
L_S	solar longitude (°)
m	data point number
m_e	electron mass (=9.109e−31 kg)
n	refractive index (dimensionless)
v_b	drift velocity of an electron beam or stream (km s^{-1})
v_{th}	electron thermal velocity (km s^{-1})
z	height (m, km)
z_1	height corresponding to the data point (f_1, τ_1) (m, km)
z_1	height of the bottom of the supposed uniform plasma slab (m, km)
z_m	height of the density peak of the main ionospheric layer (m, km)
z_{SC}	spacecraft height (m, km)
z_t	height of the density peak of the first topside layer (m, km)
B	magnetic field strength (nT)
D	deviation quadratic sum of F_j ($(km\ ms)^2$)
$D(z)$	diffusion coefficient as a function of height z ($m^2\ s^{-1}$))
F_j	difference between the estimated and observed quantity of $c\tau_j/2f_j$ (km ms)
H	the neutral scale height (km)
H_t	height thickness of the first topside layer (km)
N	plasma density (m^{-3})
N_1	plasma density at the height z_1 (m^{-3})
N_m	peak plasma density of the main ionospheric layer (m^{-3})
N_t	peak plasma density of the first topside layer (m^{-3})
N_{top}	density of the supposed uniform plasma slab (m^{-3})
Q	total fit (a quantity which controls the optimization of inversion) $(km\ ms)^2$
R	composite correlation coefficient (dimensionless)
T_e	electron temperature (K)
$V(x)$	variance of x
Δf	frequency step of the transmitted waves of MARSIS (Hz)
Δz_1	height difference ($=z_t - z_1$) (km)
Δz_m	acceptable error of z_m during optimization (<0.2 km)
γ_{max}	the maximum growth rate of a beam-plasma instability (rad s^{-1})
λ	wavelength (m)
ω_p	angular plasma frequency (rad s^{-1})
ω_{pb}	angular electron oscillation frequency of an electron beam or stream (rad s^{-1})
τ	roundtrip time delay (s, μs)
τ_j	roundtrip time delay in the jth extracted data point (s, μs)
ζ	a height between z_1 and z_m at which the plasma density equals N_{top} (km)
(f_j, τ_j)	the jth extracted data point, $j = 1, 2, \ldots, m$
$\langle x \rangle$	mean value of x

actions (e.g., Zou et al. 2005; Morgan et al. 2008), the crustal magnetic field (e.g., Krymskii et al., 2003; Lillis et al., 2008; Withers et al., 2005), the martian longitude (related to tides in the atmosphere that influence the ionosphere) (e.g., Bougher et al., 2004; Breus et al., 2004), the martian ground surface topography (related to wind patterns on Mars Wang and Nielsen, 2004), Mars rotation (Shinagawa, 2000), solar rotation (related to periods of relatively high and low solar fluxes) (Withers and Mendillo, 2005), distance from Mars to the Sun (related to the strength of solar radiation e.g., Breus et al., 2004; Morgan et al., 2008; Němec et al. 2011), and the solar wind (induces magnetic fields and interacts with the topside of the ionosphere) (e.g., Wang and Nielsen, 2003a; Kopf et al., 2008; Dubinin et al., 2008). Near the terminator, the ionosphere has a sparser plasma density, higher altitude and stronger variability in the profile shape than the ionosphere far from the terminator in the daytime (e.g., Gurnett et al., 2005, 2008; Morgan et al., 2008; Withers, 2009; Němec et al., 2011). The nighttime martian ionosphere is characterized as patchy and more variable in density; it is formed mainly by plasma transport from the daytime, as well as by energetic electron precipitation where open magnetic field lines of crustal magnetic anomalies exist (Fox and Bzannon, 1993; Withers et al., 2005; Safaeinili et al., 2007; Lillis et al., 2009; Fillingim et al., 2010; Němec et al., 2010). The nighttime ionosphere is much less frequently detected by MARSIS as compared to its daytime counterpart (the occurrence rate of ionospheric reflections in the nighttime MARSIS data records is <20% at SZA = 100° and <5% at SZA = 125°) (Němec et al. 2010).

A second layer above the main density peak is often detected by MARSIS throughout the daytime, as was reported by several groups (Gurnett et al. 2008; Kopf et al., 2008; Wang et al., 2009). The second layer is characterized as transient, variable in density (2.0e+10–7.0e+10 m^{-3}) and altitude (180–220 km), and has a decreasing occurrence rate with increasing SZA (from approximately 60% near the sub-solar point to less than 5% near the terminator) (Kopf et al., 2008). A third layer can also be observed in the MARSIS data, but it is rare (~1%) (Kopf et al., 2008). No clear relationships are found between the layers and surface features, the crustal magnetic fields, variations in the solar EUV radiation and solar energetic particle events (Kopf et al., 2008). The origin of the transient layers is not well understood. Gurnett et al. (2005) and Kopf et al. (2008) suggest that the layers might result from the velocity shear between the solar wind and the main layer ionosphere, which may generate non-linear structures, such as curl-over or detached plasma clouds, due to Kelvin–Helmholtz instability. However, the reason that the occurrence rate of the layers decreases toward the terminator (where the velocity shear is expected to be stronger) remains unclear (Kopf et al., 2008).

In this paper, we investigate the upper portion of the M2 layer near the terminator using the MARSIS Active Ionosphere Sounding mode (AIS) measurements. "Upper portion" refers to the altitude where the topside transient layers are detected. Hereafter, we call a topside transient layer a "top layer". Our goal is to examine how plasma density changes in this region with martian seasons and SZA and if and how these changes are related to the variations of the main density peak. This may provide more constraints on the origin of the transient layers in the near-terminator region, and it may also provide information on the daytime ionosphere transition into the nighttime ionosphere. A simple, effective method for data inversion is developed to retrieve the relevant ionospheric parameters. The inverted parameters are investigated by a