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MARS IONOSPHERE VARIABILITY

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Abstract. The ionosphere of Mars is an integral part of the atmosphere that links the lower atmosphere with the solar wind. Understanding the ionospheric response to internal and external forcing is essential to determining the whole atmosphere variability, as the ionospheric and atmospheric systems are strongly coupled. This proceeding focus on two main aspects of this variability, one from inside the planet and another one from outside. Starting from internal sources, it focuses on how lower atmosphere cycles, such as the seasonal carbon dioxide cycle, have a seasonal influence on the upper atmosphere, especially notable at Northern hemisphere spring when the Northern polar cap sublimates. Then, moving to external sources, it focuses on the effect of electron precipitation from a large space weather event in the Martian atmosphere. This event is important because it created lower-ionosphere absorption layers at ∼60-80 km on both the day and night-sides that strongly affect instrument performances for several days. This work is based on observations from Mars Express, Mars Reconnaissance Orbiter, and Mars Atmosphere and Volatile EvolutioN (MAVEN) missions, as well as on numerical ionospheric modelling.

Keywords: Mars, ionosphere, variability, space weather, atmospheric cycles

1 Introduction

The ionosphere of Mars is an integral part of the atmosphere that links the lower atmosphere with the solar wind. The different regions of the Martian atmosphere are fundamentally interconnected, behaving as a unique and coherent system (e.g. Sánchez-Cano et al. 2019b, and references there). This means that the whole atmospheric structure reacts together to external and internal sources of variability, and therefore, plays an important role in the volatile escape processes that have dehydrated Mars over the Solar System's history, holding clues to the evolution of Mars' climate. Understanding the ionospheric response to internal and external forcing is essential to determining the whole atmospheric variability.

The dayside ionosphere of Mars consists of two layers, formed mainly by solar photoionization, and located on average at ∼135 km and ∼110 km altitude, respectively, with typical electron densities of $10^{11}m^{-3}$ and $10^{10}m^{-3}$, respectively. Sometimes other layers above and below the two main ones occur. The phenomena that produce these extra layers are diverse, such as for example, topside extra layers can be associated with local current sheets in the upper Martian ionosphere (related in turn to Kelvin-Helmholtz instabilities) (e.g. Kopf et al. 2017), and bottomside extra layers can be associated with particle precipitation such as meteor or solar energetic particles showers (e.g. Sánchez-Cano et al. 2019a). Since the Sun is the main source of ionization, any variations in the solar radiation produce large variability in the electron density, both in time and in space. In this sense, the solar cycle is the factor that plays the most important long-term role and dominates the ionospheric variability at Mars (e.g. Sánchez-Cano et al. 2015, 2016). However, additional ionospheric variability can be caused by many other factors. External factors such as solar flares, coronal mass ejections (CMEs) or corotating interaction regions (CIR), among others contribute significantly to that. In addition, internal factors such as seasons, gravity waves, atmospheric tides, dust storms, or crustal magnetic fields are also major driving sources that modulate the behaviour of the ionosphere.

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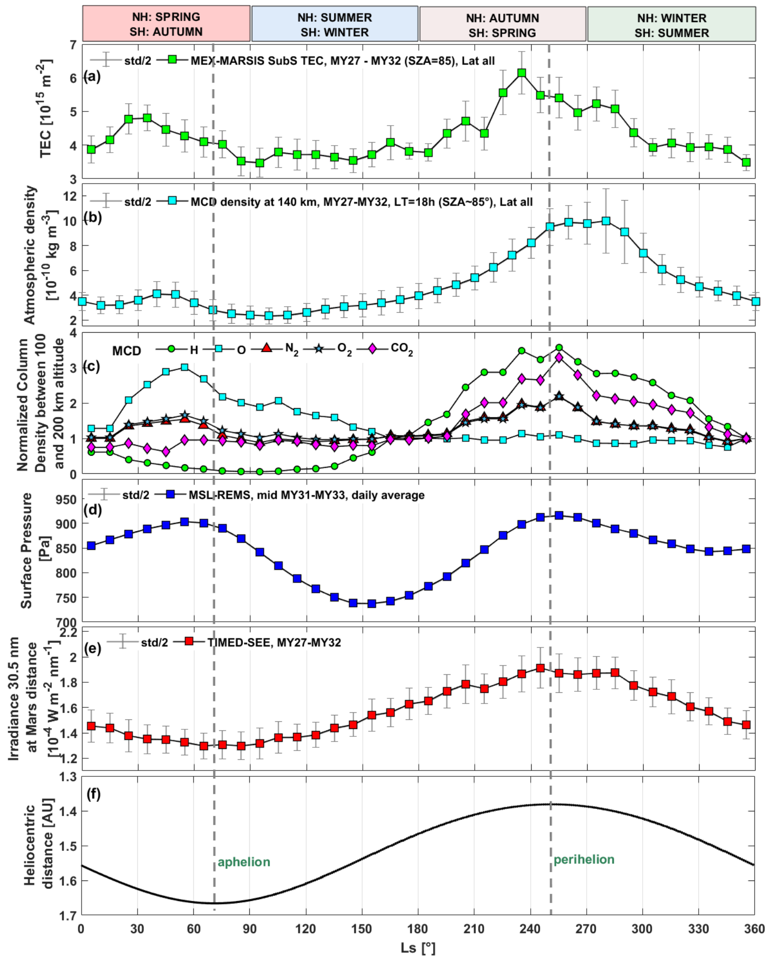

Fig. 1. Annual Martian ionospheric observations. Figure from Sánchez-Cano et al. (2018). (a) MEX MARSIS-TEC of MY 27-32 averaged over all latitudes and for SZA = 85°. (b) Averaged atmospheric density obtained at 140 km for MY27-32 and all latitudes. (c) Temporal variability of the averaged column density between 100 and 200 km and latitude for the major neutral species and normalized to their relevant value at Ls = 355°. (d) MSL-REMS surface pressure average of mid MY 31-33. (e) TIMED-SEE solar irradiance for the 30.5-nm wavelength extrapolated to Mars' distance from MY 27 to 32. (f) Mars' heliocentric distance.

This proceeding focuses on two main aspects of this Martian ionospheric variability that have been recently discovered. First, we focus on the annual role of lower atmosphere cycles, such as the seasonal carbon dioxide cycle, on the upper atmosphere. Then, we focus on the strong and sudden effects of electron precipitation from a large space weather event in the Martian atmosphere. The objective is to give a coherent view of the reaction of the Martian upper atmosphere under two major drivers of variability.

2 Internal Sources of Variability

Mars lower atmospheric variability is known to affect the upper atmosphere through different aspects, such as planetary and tidal waves that move from the low atmosphere to the thermosphere, gravity waves, northern polar warming of the lower thermosphere near the perihelion/winter solstice, seasonal thermal expansion/contraction of the Mars lower atmosphere or the expansion of the entire atmosphere during dust storms (e.g. Sánchez-Cano et al. 2018, and references there). There are other processes that occur in the lower-middle atmosphere, such as atmospheric cycles of different species, which can propagate upward to the upper atmosphere, e.g. the carbon dioxide, water vapour and ozone cycles. These cycles are a direct consequence of the carbon dioxide condensation that every winter occurs at high latitudes and the subsequent sublimation during the spring and summer seasons. The carbon dioxide cycle induces a large semiannual variation in the daily averaged surface pressure all over the planet (e.g. Forget et al. 2007).

The European Mars Express mission, in orbit about Mars since December 2004, has the capability of routinely measure the total electron content (TEC) of the Martian atmosphere with its Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS). The TEC is an important parameter for monitoring the state of the ionosphere, and it is defined as the number of free electrons that are contained in an atmospheric column. Sánchez-Cano et al. (2018) recently showed that, in fact, the TEC is not only a good tracer of the state of the thermosphere but seems to be a reliable indicator of the state of the lower-upper atmospheric coupling.

Figure 1 shows different ionospheric-atmospheric observations from several Martian Years (MY) that have been averaged together and plotted with respect to the solar longitude (Ls), which can be used as a proxy for the MY. For more details of the data processing analysis, please refer to Sánchez-Cano et al. (2018).The entire TEC data set from MEX and for a narrow solar zenith angle interval (SZA=85°) and local time 18h is shown in panel a). In addition, other atmospheric parameters are including, such as the averaged atmospheric density at 140 km obtained from the Mars Climate Database (MCD, version 5.3) in panel b), and the global averaged thermospheric column density profile between 100 and 200 km altitude for each of the major species in Mars' thermosphere in panel c). To complete the figure, the daily averaged surface pressure (as a proxy for the atmospheric mass column variation) measured by the Mars Science Laboratory (MSL) mission for MY mid-31 to -33 is included in panel d), the solar irradiance measured in Earth's orbit and extrapolated to Mars in panel e), and the Mars' heliocentric distance in panel f). In general, the TEC observations follow pretty well the irradiance profile, which in turn is directly proportional to the heliocentric distance. This is somehow expected because the solar flux is the dominant ionization source in Mars' atmosphere. Therefore, both the TEC and the irradiance are maxima near Mars' perihelion and minima near aphelion. However, the TEC profile shows a secondary maximum between Ls = 25° and 75°, which is not related to the annual irradiance variation. This secondary peak occurs during the northern spring season and before aphelion, and nearly coincides with an increasing trend in both the thermospheric density and the surface pressure. This indicates that the neutral atmosphere is the dominant force for this TEC rise. The main TEC peak (Ls = 220°-290°) is also formed while there is an increase in the thermospheric density and surface pressure (during spring in the southern hemisphere), which is related to a larger abundance of CO_2, H, O_2, and N_2 with respect to their annual trends. However, it is difficult to evaluate whether there is an effect of the neutral atmosphere because the irradiance flux is clearly the dominant ionization factor and masks any other secondary ionospheric variability sources.

Focusing on the chemistry of the first peak (Ls = 25°-75°), oxygen and nitrogen (O, O_2 and N_2) species have their largest abundances in the annual profile at this time of the year, indicating that these three components may have a more prominent role during this period. The increase of these neutral species results in more N_2^+, O_2^+, O^+, and NO^+ ions during this time of the year, and therefore, in a significant TEC increase. This thermospheric variability is likely linked to atmospheric variability produced by cycles at lower atmospheric levels. Our results seem to be supported by the MEX-SPICAM observations of the lower atmosphere as thermospheric O_2 column densities have similar increases both in latitude and Ls with respect to O_2 column density observations of the low-middle atmosphere (Montmessin et al. 2017), being maximum in the early northern and southern springs in both hemispheres. As a consequence, the double peak in the TEC as a function of a MY seems consistent with a larger increase in the column density of oxygen species, caused by the semiannual atmospheric cycles produced by the sublimation of the polar caps.

3 External Sources of Variability

In addition to internal sources, external drivers like space weather are other important sources of very intense and short variability that affect the entire Martian system. Its study is very important because they enhance atmospheric escape, currently a major topic in the research at Mars. In counterpoint with Earth, the solar wind directly interacts with the Martian upper atmosphere because of the absence of a global inner magnetic field, creating many different effects on the structure of the ionosphere (e.g. Ramírez-Nicolás et al. 2016; Andrews et al. 2016; Sánchez-Cano et al. 2017). This interaction is also dependent on the solar cycle as the ionosphere becomes more magnetized during periods of low solar activity because less ionization is produced (Sánchez-Cano et al. 2017).

Despite the numerous effects that space weather events produce on Mars' ionosphere, very little is known about the ionization processes that occur at low altitude from solar energetic particles (SEP) that precipitate into the atmosphere during these events. The recent study of Sánchez-Cano et al. (2019a) has shown that in fact particle precipitation greatly enhances the low ionosphere (at ∼90 km, below the main peak) at all local times, and locations over the planet (and not only over crustal magnetic fields). In turn, these low ionospheric layers are able to absorb radar signals because they are formed in regions where the atmosphere is denser and collisions between electrons and neutral species (mainly CO_2 at Mars) are not negligible. As consequence, instruments that operate in high frequency (HF) do not work for many days (as long as particle precipitation persists), which has fatal consequences for both science and exploration purposes. However, we do not know the exact nature and formation of these layers as no mission has been able to measure them.

Thanks to the co-joined study of radar measurements from Mars Express (MARSIS radar) and Mars Reconnaissance Orbiter (SHARAD radar), together with analysis of the high energetic particles recorded by the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, Sánchez-Cano et al. (2019a) has shown for the first time that high energetic electrons are mainly the responsible for these blackouts, contrary to the proton events that occur at Earth. Figure 2 shows this proof based on a large space weather event that hit Mars in September 2017, where X-rays (0.1-7 nm) and differential flux spectra from solar energetic particles (electrons and ions) from MAVEN are plotted in the three first panels, together with the timing when both MARSIS and SHARAD radars were blackout (i.e., the radars were transmitting but not receiving signals). For this event,

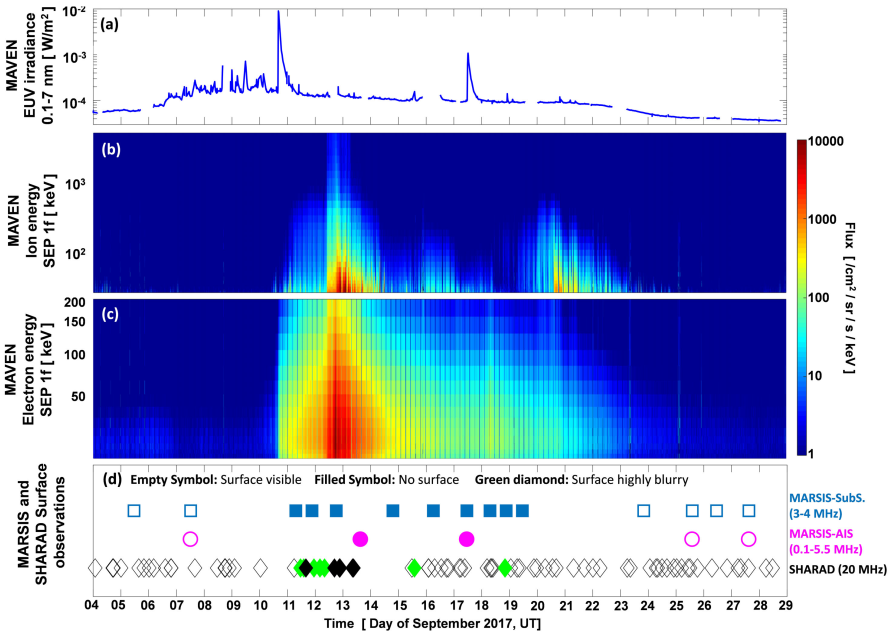

Fig. 2. Mars radio blackouts caused by a large space weather event. Figure from Sánchez-Cano et al. (2019a) a) MAVEN-EUV irradiance observations of wavelength 0.1-7 nm. (b) MAVEN-SEP ion differential flux spectra.(c) MAVEN-SEP electron differential flux spectra. (d) Radio blackouts. Each symbol denotes when MARSIS and SHARAD were in operation. Empty symbols designate the cases when the surface was observed, and filled symbols when was not observed. The exceptions are green diamonds that indicate the times when SHARAD observed a highly blurry surface.

the Active Region (AR) 12673 at the western limb of the solar disk emitted a X8.2-class flare on 10 September 2017 and also released a powerful coronal mass ejection (CME). The SEP electrons (20-200 keV) started to arrive at Mars ∼3 hr later, and the ions (20 keV-6 MeV) ∼6 hr later. Both SEP electrons and ions show a sharp flux increase on 12 September 2017 (reddish colors) when the CME shock passed over Mars. After that, SEP electrons gradually decreased over 13 days until 23 September, but with a small enhancement on 18 September caused by another solar flare. In contrast, SEP ions sharply decreased on 14 September when the CME completed its passage past Mars. After that, the ion flux was very low until 20 September.

As can be seen in Figure 2, the blackout lasted at least ∼10 days for the MARSIS radar, but the blackout lasted only ∼3 days for SHARAD because radio absorption processes are frequency-dependent and SHARAD carrier frequency is much larger than the MARSIS one (20 and 1.8-5 MHz, respectively). Since MARSIS blackouts occurred also while the ion SEP flux was very low but the electron SEP flux was still enhanced, we can conclude that precipitating electrons, rather than ions, were responsible for the creation of a lower ionospheric layer all over the planet that absorbed the radar signals.

Based on Figure 2, Sánchez-Cano et al. (2019a) performed a numerical simulation with the Mars version of the numerical/physical Institut de Recherche en Astrophysique et Planétologie (IRAP) plasmasphere-ionosphere model (IPIM) (Marchaudon & Blelly 2015). The simulation was performed for the conditions of the MARSIS observations and with a flux of downward precipitating electrons at 500 km as input. Results from the Sánchez-Cano et al. (2019a) simulation shows that indeed a layer of density of $\sim 10^{10}$ m^{-3} peaking at 90 km was formed, mainly composed of O_2^+ with a lesser contribution of NO^+. Such a layer had its peak absorption at 70 km and was the responsible for the blackout observed in September 2017 at Mars.

4 Conclusions

The Martian space environment is a complex system with simultaneous downward and upward couplings, which still need much work to be understood. The ionosphere is in the end the mediating layer between the lower and middle atmosphere and the solar wind, where most of the atmospheric coupling processes occur. Therefore, driven variability from outside and inside the planet need to be totally understood in order to have a broader control of the system dynamics as a whole. This proceeding has focused on two of these drivers, that have been recently discovered and have important roles in the Martian plasma and atmospheric systems, such as the seasonal effect of lower-middle atmospheric cycle on the upper atmosphere, and the effect of electron precipitation from space weather events on the lower atmosphere of Mars. In both cases, a good characterization of the ionosphere is clearly necessary.

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