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To cite this version:

HAL Id: insu-01427750
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Submitted on 19 Jul 2020

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Schumann resonances at Mars: Effects of the day-night asymmetry and the dust-loaded ionosphere

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Abstract Schumann resonances are standing waves that oscillate in the electromagnetic cavity formed between the conducting lower ionosphere and the surface of the planet. They have been measured in situ only on Earth and Titan, although they are believed to exist on other planets like Mars. We report numerical simulations of the Martian electromagnetic cavity, accounting for the day-night asymmetry and different dust scenarios. It has been found that the resonances are more energetic on the nightside, the first resonance is expected to be 9–14 Hz depending on the dust activity and to have low quality factors \((Q \approx 2)\). This work serves as an input for the upcoming ExoMars surface platform (launch 2020), who will attempt to measure them for the first time.

1. Introduction

Schumann resonances (SR) are standing waves oscillating in the electromagnetic cavity formed by the conducting planetary surface and the lower ionosphere. The first SR mode wavelength is of the size of the planetary circumference. SR are transverse modes to the radial direction \((\mathbf{T})\), with \(\mathbf{E}\) in the radial direction \((\mathbf{E})\) and \(\mathbf{B}\) tangential to ground [Toledo-Redondo et al., 2010, Figure 1]. They were predicted by Schumann [1952] and first measured on Earth by Balser and Wagner [1960]. The main source of energy exciting SR on Earth is lightning and hence their direct link with global climate processes [e.g., Williams, 1992; Price and Rind, 1994; Füllekrug and Fraser-Smith, 1997; Heckman et al., 1998; Nickolaenko et al., 1999; Williams, 2005; Yang and Pasko, 2007]. Measuring SR on different planets provides valuable information about electromagnetic properties of the cavity, i.e., the composition of its surface, atmosphere, and ionosphere [Simões et al., 2008]. The Huygens descent probe on board the Cassini mission [Lebreton et al., 2005] measured them on Titan [Béghin et al., 2007; Morente et al., 2008; Béghin et al., 2009]. These measurements suggested the existence of a buried ocean in Titan [Béghin et al., 2012]. The main source of excitation of the Titan cavity is believed to be the interaction with Saturn’s magnetosphere, which induces large-scale currents on the Titan’s ionosphere [Béghin, 2014].

Dust storms and dust devils are common on Mars [e.g., Newman et al., 2002; Ringrose et al., 2003], and they have been proposed as a possible source of electric activity [Farrell and Desch, 2001; Kurgansky et al., 2007], although no lightning-like signature has been detected so far [Gurnett et al., 2010]. Remote observations using the Deep Space Network found signals that may correspond to SR [Ruf et al., 2009; Renno and Ruf, 2012; Martinez et al., 2012]. The ExoMars mission [Vago et al., 2015] included a descent module, expected to land in October 2016, which carried the microAtmospheric Relaxation and Electric field Sensor (μARES) instrument [Déprez et al., 2015], capable of measuring \(E\), from DC up to 3.2 kHz. After the unsuccessful soft landing of the first ExoMars lander, the second part of the ExoMars mission (to be launched in 2020) will carry another version of an electric field sensor and will constitute the first attempt to characterize the electrical properties of the Martian atmosphere and its global electric circuit, including in situ detection of SR.

Since there are no in situ measurements of plasma properties at altitudes below 80 km on Mars, photochemical models are the best available tool to infer the electromagnetic properties [Whitten et al., 1971; Molina-Cuberos et al., 2001, 2002]. Dust has been found to play a major role in the atmospheric conductivity of Mars by reducing it and enhancing the day-night asymmetry of the Martian cavity, where the conductivity...
can differ by 2 orders of magnitude [Michael et al., 2007, 2008; Aplin, 2013; Cardnell et al., 2016]. In addition, a layer created by meteoric ablation at 80–90 km of altitude is known to be present [Molina-Cuberos et al., 2003; Withers et al., 2008]. Several works have studied the properties of the SR on Mars [Sukhorukov, 1991; Pechony and Price, 2004; Molina-Cuberos et al., 2006; Yang et al., 2006; Soriano et al., 2007; Rozakiewicz et al., 2015]. However, the effects of the changing day-night conditions and dust were not considered by these previous studies.

In this work, we model the Martian atmosphere-ionosphere cavity using the Transmission Line Matrix (TLM) method, taking into account the effects of dust and the large day-night asymmetry of the electromagnetic cavity. The effects of the meteoric layer are also investigated. These results serve as a reference for the ExoMars mission in its attempt to measure SR on Mars for the first time.

2. Model

TLM is a time domain numerical method based on discretizing time and space and solves the involved differential equations by approximating the derivatives to differences. Details of the algorithm used can be found in Toledo-Redondo et al. [2013, 2016]. The algorithm has been adapted to the size of Mars (radius of 3390 km).

We model the spherical cavity formed between the Martian surface and the lower ionosphere, up to 130 km in height, where the conductivity reaches $10^{-3}$ S/m, and no wave transmission is expected.

First, we validated our model for Mars by computing the resonances for the lossless Martian atmosphere-ionosphere cavity, which has an analytical solution. The first three analytical eigenfrequencies for the ideal Martian cavity are 19.6, 33.9, and 48.5 Hz [Molina-Cuberos et al., 2006]. The estimated eigenfrequencies from our model differ from the analytical solution by less than 3% using a 10 km sampling resolution for each direction and less than 1.5% using a 5 km resolution. We consider the 10 km resolution sufficient for the purpose of this work and for the rest of the study we use this accuracy, with the aim of reducing the computational costs.

The electrical properties of the Martian atmosphere-ionosphere system are obtained from a photochemical model [Cardnell et al., 2016] which uses the Mars Climate Database (MCD) [Forget et al., 1999; Millour et al., 2015] as an input for the properties of the neutral atmosphere. The conductivity profiles used in this work are detailed in Figure S1 in the supporting information and correspond to the conditions expected during the ExoMars landing (October 2016). The major findings that affect SR are the changing conductivity depending on the dust conditions of the atmosphere and the large day-night asymmetry present on Mars. Therefore, we have considered the three dust scenarios defined in Cardnell et al. [2016]: low, standard, and high. The standard dust scenario corresponds to a dust distribution reconstructed from seven Martian years (years 24 to 31) of observations, where global dust storms data have been removed. It is referred to as the climatology scenario in the MCD. The low dust scenario (cold scenario in the MCD) corresponds to an extremely clear atmosphere, i.e., 50% of the dust observed on the clearest day of the seven Martian years monitored. Finally, the high dust scenario (dust storm scenario in the MCD) corresponds to the darkest atmosphere to be expected at Mars [Ockert-Bell et al., 1997].

Different methods can be applied to approach the Schumann resonance cavity problem, like, for instance, finite differences in time domain [Yang et al., 2006], 2-D telegraph equations [Pechony and Price, 2004], full wave solution [Galuk et al., 2015], or the knee model [Nickolaenko and Hayakawa, 2015]. We make use of the 3-D TLM method [Toledo-Redondo et al., 2013, 2016], which can be easily adapted to model the large day-night asymmetry of the Martian cavity. This work considers two kinds of simulations: neglecting the day-night differences (symmetric cavity) and accounting for them (asymmetric cavity). In the former, either day or night conditions are assumed for the whole cavity. This symmetric approach has been widely used in SR studies at Mars [e.g., Pechony and Price, 2004; Molina-Cuberos et al., 2006; Yang et al., 2006; Soriano et al., 2007]. We show results from the two approaches for comparison, to illustrate the importance of accounting for the changing day-night conditions in the case of Mars. When the asymmetry is introduced, we assume a sharp (within one step of the grid, 10 km) transition from day to night conditions. Different spatial configurations between the energy source (SR trigger), observation points, and terminator are possible, and we have considered three different cases. Symmetric case with the source at the equator, asymmetric case with the source at the equatorial noon (day-night 1, DN1) and asymmetric case with the source at equatorial midnight (day-night 2, DN2).

The three cases are detailed in Figures 1–3 (top). The expected fields correspond to $B_y$ and $E_y$, the latter being measurable by $\mu$ARES. The real nature, location, duration, or strength of the electrical sources in the
Martian atmosphere are unknown, although dust storms and dust devils have been proposed as a plausible mechanism. For this study, we used a Gaussian current in the $r$ direction, with its energy comprised in the band 0 kHz–1 kHz. The spectrum of this Gaussian current is approximately flat in the SR band. More details on the source used can be found in Toledo-Redondo et al. [2016]. We use the same source for all the simulations, i.e., we inject the same amount of energy, and so the SR amplitudes can be compared among simulations. The fields are surveyed along the equator, corresponding to the expected latitude of the landing site of the ExoMars mission (Meridiani Planum, 0.2°N).

3. Results

First, we run our simulation using the symmetric cavity model, i.e., when the day-night asymmetry is not taken into account (Figure 1, top). We use either day or night conditions for the whole cavity and consider different dust scenarios (low, standard, and high). The conductivity profiles for each situation are detailed in the supporting information (Figure S1).
Figure 2. (top) Schematics of the DN1 simulation. (a, c, and e) Magnetic and (b, d, and f) electric field power spectra as a function of frequency and distance to the source ($\phi$), for the different dust scenarios. The white (black) horizontal dash-dot lines correspond to cuts at $\phi = 25^\circ$ ($\phi = 155^\circ$), used in Figure 4.

Figures 1a and 1b correspond to $B_\theta(E_r)$ energy spectrums in the frequency-distance ($\phi$) plane for standard dust dayside conditions. The vertical axis (longitude) corresponds to the field surveyed at different distances to the energy source. It can be observed that no SR develop, owing to the large conductivity (losses) of the atmosphere. The wave power is severely damped within one loop around the planet [Toledo-Redondo et al., 2016]. Similar results are obtained when considering low or high dust (not shown). On the other hand, for nighttime conditions, the losses are much lower, and SR are generated (Figures 1c–1h). The lowest atmospheric conductivity occurs for high dust conditions, and therefore, even high modes can be easily identified (Figures 1c and 1d). White dots mark the location of the local maximum for modes 1 to 3, indicating the central frequency of the resonances. The average central frequencies of the modes 1 to 3 are summarized in Table 1, together with their standard deviation (the central frequency changes with the relative distance to the source in a lossy cavity) [Toledo-Redondo et al., 2016]. The first SR is at 11–12 Hz for low and standard dust conditions, but the frequency is shifted up to $\sim$15.5 Hz when high dust conditions prevail. The shift is also observed for $f_2$ and $f_3$. High dust conditions decrease the conductivity of the atmosphere, reducing the losses in the cavity, and therefore, the SR are closer to the eigenfrequencies of the lossless cavity.

The results from Cardnell et al. [2016] indicate that the Martian atmospheric conductivity varies roughly 2 orders of magnitude at ground level depending on solar illumination. Results from Figure 1 tell us that dayside conditions cannot accommodate SR, while nightside conditions can. The next simulations consider the day and night conductivity profiles on each half of the cavity.

Figure 2 shows the $E_r$ and $B_\theta$ components in the frequency-distance plane for the three dust scenarios for the DN1 case. The results show that only the first mode of the SR develops and is better observed at the nightside, while on the dayside it is difficult to identify the SR, owing to the large damping of the standing
Figure 3. (top) Schematics of the DN2 simulation. (a, c, and e) Magnetic and (b, d, and f) electric field power spectra as a function of frequency and distance to the source ($\phi$), considering the day-night asymmetry of the Martian atmosphere-ionosphere electrical cavity. The white (black) horizontal dash-dotted lines correspond to cuts at $\phi = 25^\circ$ ($\phi = 155^\circ$), used in Figure 4.

Table 1. SR Central Frequencies and Standard Deviation Owing to the Source Distance for the Different Simulations: Symmetric, DN1, and DN2

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Profile</th>
<th>Dust</th>
<th>$f_1$ (Hz)</th>
<th>$f_2$ (Hz)</th>
<th>$f_3$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$E_r$</td>
<td>$B_\theta$</td>
<td>$E_r$</td>
</tr>
<tr>
<td>Symmetric</td>
<td>Low</td>
<td></td>
<td>11.2 ± 0.4</td>
<td>11.1 ± 0.5</td>
<td>20.4 ± 1.0</td>
</tr>
<tr>
<td>Night</td>
<td>Standard</td>
<td></td>
<td>12.2 ± 0.3</td>
<td>12.1 ± 0.4</td>
<td>22.0 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
<td>15.6 ± 0.2</td>
<td>15.5 ± 0.3</td>
<td>27.9 ± 0.6</td>
</tr>
<tr>
<td>DN2 Low</td>
<td></td>
<td></td>
<td>9.4 ± 0.4</td>
<td>8.2 ± 0.6</td>
<td>26.9 ± 2.2</td>
</tr>
<tr>
<td>Nightside</td>
<td>Standard</td>
<td></td>
<td>10.3 ± 0.4</td>
<td>9.2 ± 0.5</td>
<td>29.3 ± 1.8</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
<td>13.4 ± 0.4</td>
<td>12.1 ± 0.6</td>
<td>37.8 ± 1.5</td>
</tr>
<tr>
<td>DN2 Low</td>
<td></td>
<td></td>
<td>9.4 ± 0.4</td>
<td>9.2 ± 0.2</td>
<td>25.4 ± 1.1</td>
</tr>
<tr>
<td>Dayside</td>
<td>Standard</td>
<td></td>
<td>10.2 ± 0.3</td>
<td>10.0 ± 0.1</td>
<td>27.8 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
<td>13.4 ± 0.4</td>
<td>13.0 ± 0.2</td>
<td>36.7 ± 0.8</td>
</tr>
<tr>
<td>DN1 Low</td>
<td></td>
<td></td>
<td>8.2 ± 0.9</td>
<td>9.8 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>Nightside</td>
<td>Standard</td>
<td></td>
<td>9.1 ± 0.9</td>
<td>10.5 ± 0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
<td>11.3 ± 1.2</td>
<td>13.0 ± 0.3</td>
<td></td>
</tr>
</tbody>
</table>
Er field energy spectrums at (left column) $\phi = 25^\circ$ and (right column) $\phi = 155^\circ$ for three models of the cavity (symmetric nighttime, DN1, DN2). Different dust conditions have been considered and are color coded (black, blue, and red). The SR have been fitted by Lorentzian curves, and their parameters are detailed in Table 2.

The central frequencies are significantly different for $E_r$ and $B_\theta$ fields and depend on the dust conditions (see Table 1). For the $E_r$ component, the central frequency of the first SR mode changes from 8.2 Hz (low dust) to 11.3 (high dust).

Figure 3 shows the results of the DN2 case, i.e., day-night asymmetric cavity with the energy source located at midnight. When compared to DN1, it can be observed that not only the first SR is well defined but also higher modes can be identified, both at the dayside and nightside. The central frequencies of modes 1 and 2, obtained from maximum detection (white dots in Figures 3a–3f), are summarized in Table 1 (DN2 dayside and nightside). The uncertainties correspond to one standard deviation. The $E_r$ component of the first mode varies between 9.4 Hz (low dust) and 13.4 Hz (high dust) both at the dayside and nightside hemispheres. The $B_\theta$ component of the first mode is higher at the dayside than at the nightside. The second mode of the SR is at frequencies significantly larger than for the symmetric case. For instance, for the standard dust scenario, the symmetric-night model predicted 22.0 Hz, while the asymmetric DN2 model predicts 27.8 Hz and 29.3 Hz at the dayside and nightside hemispheres.

In the previous plots we characterized SR based on the central frequencies of each mode, which were found by detecting maximums of the electric and magnetic energy frequency spectrums. Typically, the nth SR mode is characterized not only by its central frequency ($f_n$) but also by its maximum amplitude ($A_n$) and quality factor ($Q_n$). These parameters are obtained by fitting a Lorentzian curve for each resonance in the energy
Table 2. SR Lorentzian Fit Parameters of $E_z$: Magnitude ($A_n$), Central Frequency ($f_n$), and Quality Factor ($Q_n$) at $\phi = 25^\circ$ and $\phi = 155^\circ$

<table>
<thead>
<tr>
<th></th>
<th>First Resonance</th>
<th>Second Resonance</th>
<th>Third Resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_1$ $f_1$ $Q_1$</td>
<td>$A_2$ $f_2$ $Q_2$</td>
<td>$A_3$ $f_3$ $Q_3$</td>
</tr>
<tr>
<td>Night</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0.87 11.1 4.9</td>
<td>0.38 21.0 5.2</td>
<td>0.24 31.4 3.3</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.66 11.3 3.8</td>
<td>0.20 19.9 2.7</td>
<td>0.032 28.7 6.0</td>
</tr>
<tr>
<td>Standard</td>
<td>1.03 12.2 6.5</td>
<td>0.48 22.5 6.8</td>
<td>0.28 33.3 5.0</td>
</tr>
<tr>
<td>High</td>
<td>0.87 12.3 5.4</td>
<td>0.31 21.8 4.0</td>
<td>0.082 31.2 4.6</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.51 15.5 8.6</td>
<td>0.28 28.1 9.6</td>
<td>0.16 41.3 8.9</td>
</tr>
<tr>
<td>DN2 Low</td>
<td>0.45 9.3 1.9</td>
<td>0.27 28.9 2.0</td>
<td>--</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.02 9.3 1.4</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Standard</td>
<td>0.37 10.2 2.2</td>
<td>0.28 30.8 2.9</td>
<td>--</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.01 10.1 1.6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>High</td>
<td>0.12 13.3 2.3</td>
<td>0.13 39.3 3.5</td>
<td>--</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.01 13.1 1.8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>DN1 Low</td>
<td>0.06 10.4 2.8</td>
<td>0.12 18.6 1.7</td>
<td>0.13 29.2 1.8</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.08 8.9 1.5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Standard</td>
<td>0.04 10.8 2.6</td>
<td>0.08 19.2 1.6</td>
<td>0.09 30.0 1.8</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.05 9.6 1.4</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>High</td>
<td>0.07 12.1 2.3</td>
<td>0.07 19.8 1.9</td>
<td>0.06 28.3 1.9</td>
</tr>
<tr>
<td>155$^\circ$</td>
<td>0.04 11.7 1.4</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

By comparing the $A_n$ SR parameters in Table 2, we can see that the most energetic resonances are produced for the nonrealistic symmetric case, where night conditions were assumed for the whole cavity. For the DN1 model (energy source at nightside), the SR energy ($A_n$) is 1 order of magnitude larger at the nightside ($\phi = 25^\circ$) than at the dayside ($\phi = 155^\circ$). On the other hand, for DN2, the SR energy at dayside and nightside is comparable and much lower than on DN1 nightside. Therefore, the most favorable scenario to detect SR is when both the detector and the energy source are located at night (DN1, $\phi = 25^\circ$). Regarding the $Q$ factors, they are smaller than on Earth (losses are higher on Mars). Our estimations for the asymmetric cases are $Q \approx 2$.

Finally, we run our simulation for the standard dust scenario adding the effect of a layer present at $\sim 85$ km, originated by meteoric ablation [Molina-Cuberos et al., 2003], see Figure S1a in the supporting information. We found almost no differences when accounting for that layer.

4. Discussion and Conclusions

The recent findings by Cardnell et al. [2016] highlighted the large conductivity differences in the Martian atmosphere depending on solar illumination. Our simulations show that dayside conditions do not allow SR to develop, while nightside conditions, presenting conductivities 2 orders of magnitude lower, do (Figure 1). In addition, the sharp conductivity gradient at the terminator is likely to reflect a portion of the energy of the propagating waves, producing new SR modes in the dayside and nightside coupled cavities. This is consistent with the energy distributions shown in Figure 3. When compared to a simulation without asymmetry and terminator boundary (e.g., Figure 1c compared to Figure 3a), the energy maximums and minimums are distributed in a different way. For instance, Figure 3a does not show a minimum for the second mode.
Another effect that is observed for the asymmetric model is that the central frequency of the SR modes is different for $B_0$ and $E$ components (Table 1, DN$_1$ and DN$_2$ at nightside). This may be related to the relative importance between the superimposed modes (mode $n = 2$ of the whole cavity has approximately the same frequency as mode $n = 1$ of the half cavity), and the fact that the $E$ field maximums for each mode are collocated with their respective $B_0$ minimums.

The largest unknown with respect SR at Mars is the generation mechanism. Lightning is believed to possibly occur in dust storms [Eden and Vonnegut, 1973; Melnik and Parrot, 1998; Farrell et al., 1999; Renno et al., 2003], and dust devils themselves are electrically active [Crozier, 1964; Farrell and Desch, 2001; Kurgansky et al., 2007]. The amount of energy that these or other mechanisms can generate in the ELF band inside the Martian atmosphere is not known, as well as their spatial distribution or time patterns (daily, seasonal, etc.). All these aspects constrain the chances to effectively measure SR at Mars.

To summarize, we report numerical simulations of the SR to be expected at Mars, based on the latest modeling efforts of the Martian atmosphere-ionosphere chemical interactions and properties. The day-night asymmetry was never addressed before in SR studies at Mars, and our study highlights its importance for assessing the main SR parameters. In addition, the changing global dust conditions of the Martian planet have the ability to modulate the atmospheric conductivity. Under global dust conditions, the central frequencies and quality factors of the SR significantly increase. Finally, the meteoric layer (~85 km) seems to not affect SR. The best chance to detect SR by ExoMars ($E$ measurements) is when the detector is at the nightside and then search for the first ($n = 1$) mode at frequencies varying between 9 and 14 Hz, depending on the global dust conditions of the planet. The $Q$ factor is expected to be low ($Q \approx 2$), making it easier to distinguish from artificial tones, which typically have large $Q$ factors.

References


