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On the formation of ionization bulges at multiple altitudes in magnetic cusp regions of the Martian ionosphere

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Abstract

The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument aboard the Mars Express spacecraft regularly detects the ionization bulges in magnetic cusp regions of the Martian ionosphere. These ionization bulges are generally observed near the main peak. For the first time, we report the observation of the ionization bulges at altitudes much above and below the main peak. We found that the ionization bulges do form in the topside of the Martian ionosphere between 180-240 km and the location of these bulges coincides with the magnetic cusp regions. However, unlike the main layer, the recurrent occurrence of the bulges in the topside layer at the same location is not common. We also observe the signatures of the ionization bulges at the meteor layer altitudes (80-120 km) during the close passage of comet Siding Spring at Mars. We observed the presence oblique echoes, representing the ionization bulges, in regions of vertical magnetic fields. Thus, the formation of ionization bulges may not be a phenomenon of the main peak, but can occur at any altitudes wherever layering structures are there. The results of the present suggest that the vertical transport of plasma through open magnetic field lines contributes to the formation of ionization bulges in these regions. Electron Precipitation might be adding to the formation of ionization bulges in the topside ionosphere.

1. Introduction

The presence/absence of magnetic fields on a planet plays an important role in the spatial distribution of its ionospheric plasma, interaction with solar wind and interplanetary magnetic fields. From this viewpoint, the three major terrestrial planets act as three distinct laboratories with Venus having no intrinsic magnetic field, Mars with weak crustal magnetic fields, and Earth is having a strong global intrinsic magnetic field [1]. The strong magnetic fields on Earth significantly control its ionosphere, while the lack of intrinsic magnetic fields on Venus left its ionosphere to be dominated by non-magnetic plasma processes and that of interplanetary magnetic fields. On the other hand, the weak and spatially non-uniform crustal magnetic fields on Mars have considerable effect on its through plasma confinement in regions of closed magnetic fields and vertical transport and solar wind electron precipitation in regions of open magnetic fields.

The ionosphere of Mars consists of a main layer at ~135 km, a secondary layer at ~ 110 km and a meteor ion layer at ~ 80-100 km. In addition, there is a layer at topside of the main ionospheric layer which is less in density, but highly transient. Among the effects of crustal magnetic fields on the Martian ionosphere, the formation of ionization bulges near the main ionospheric peak in regions of vertical magnetic fields is a very distinct phenomenon [2]. The characteristics of ionization bulges have been studied in detail by several authors in the last decade. These ionization bulges are generally observed near the main peak [3]. For the first time, we found that these ionization bulges can occur in the topside ionosphere and in meteoric ion layers as well.

2. Instrument and data analysis

MARSIS is a space based radar sounder that looks in nadir direction to probe the subsurface and ionospheric features of Mars [2]. It consists of a 40 m tip-to-tip dipole antenna that is used to transmit the frequencies between 0.1 MHz and 5.5 MHz and to receive reflected rays. In active ionospheric sounding (AIS) mode of operation, it sweeps 160 frequencies that are distributed quasi-logarithmically. When it transmits a frequency, the reflections from ionized targets occur from those altitudes where the sounding frequency matches to the electron density which is given by the relation, $f_p = 8980\sqrt{n_e}$, where f_p is the transmitted frequency in Hz and n_e is the electron density in cm^{-3}.The reflections occur when the iso-density surfaces of the electron density are perpendicular to the transmitted rays. Accordingly, lower frequencies reflect from higher altitudes and vice-versa. At higher sounding frequencies greater than the main peak, the reflections come from the surface of Mars. The received echoes are generally colour coded and are shown as a function of frequency and delay time, known as an ionogram. The 'delay time' is often converted to an 'apparent altitude' with an assumption that the rays travel at the speed of light. In the present paper, we use the MARSIS measurements to show that the ionization bulges can occur at multiple altitudes.

3. Results

The composition of metallic ion layers in the Martian upper atmosphere has not been directly measured until recently. On 19 October 2014, comet Siding Spring (C/2013 A1, CSS) passed near to Mars at 18:29 UT with a closest approach distance of ~134,000 km and a relative velocity of 56 km s^{-1}. During this close encounter several instruments on various spacecraft detected the effects of CSS on the Martian upper atmosphere. Several metal ions such as Na^+ ,Mg^+, Al^+, K^+, Ti^+, Cr^+, Mn^+, Fe^+, Co^+, Ni^+, Cu^+ and Zn^+ has been detected during the CSS event. The MARSIS instrument measured the ionization due to this on three successive passes which show that a transient ionization layer is produced in the Martian ionosphere and upper atmosphere. From these passes, we found that the transient ionization layer due to CSS was sustained at least for 19 h on the nightside and 12 h on the dayside.

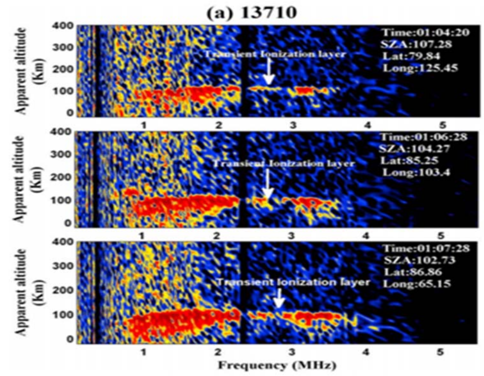

Figure 1. Sample ionograms illustrating the presence of the transient ionization layers on orbit 13710.

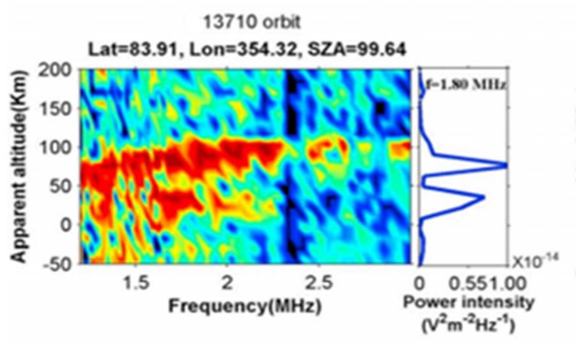

Figure 2. An ionogram from orbit 13710 that illustrates the presence of a double layer at the altitude of meteor ion layer. The line plot on the right-hand side represents the power intensity at a given frequency and is shown to clearly bring out the double-layer structure.

Figure 1 illustrates the presence of a transient ionization layer on the nightside using three ionograms from orbit 13710, which were obtained 5 h after the peak dust deposition by CSS. In the topside ionogram of Figure 1, the transient ionization layer is clearly visible with a peak density of ~1.6 × 10^5 cm^{-3} and at an average apparent altitude of ~100 km. interestingly, the transient ionization layer in some ionograms displayed a double-layer structure, i.e., appearance of the transient ionization layer at two apparent altitudes separated by several kilometers. This is illustrated through an ionogram and a line plot in Figure 2. This double layered structure is also observed in several ionograms in subsequent orbits up to 19 h after peak dust deposition. The difference in apparent altitudes between the two layers is ~60 km.

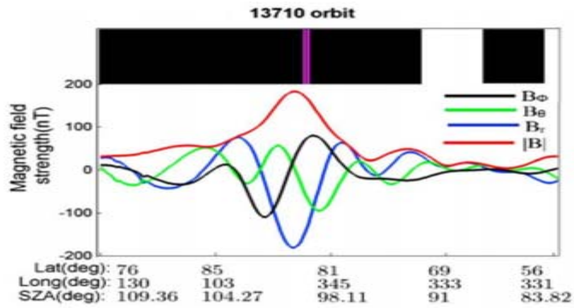

Figure 3. The three magnetic field components computed from a magnetic field model at an altitude of 100 km along the trajectory of the orbit 13710. The black shaded region and magenta lines at the top represent the presence of transient ionization layer and double layers, respectively, along the satellite tracks. The white space at the top (between black shaded regions and magenta lines) indicates the absence of transient ionization layers.

In order to identify the mechanism for the formation of the ionization bulges, in Figure 3 we compare the regions of double layers with those of crustal magnetic anomalies. From Figure 3, it is clear that the double layers occur in regions where the magnetic field is nearly vertical as seen from the radial component B_r. This is the case everywhere in all the three orbits. Thus, the results of the present study clearly show that the bulges of ionization can occur at meteor ion layer altitudes when the densities at these altitudes are larger.

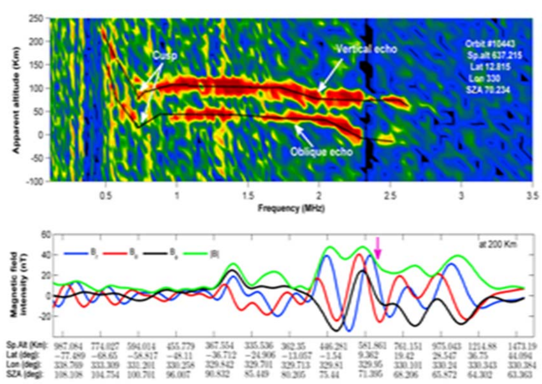

Figure 4. (top) An ionogram taken on orbit 10,443 to illustrate the topside layer with oblique echoes. (bottom) The magnitude values computed from a magnetic field model along the sub-satellite point for 200 km altitude. The downward magenta arrow indicates the location of the ionogram shown in the top panel.

Apart from the main layer, some MARSIS ionograms show another layer at the top of the main ionospheric layer [4], called the topside layer which is generally identified through a cusp in the ionospheric trace at lower frequency side as shown in Figure 4. There are two echo traces in the ionogram of Figure 4, each associated with the main ionospheric layer (between 0.73 MHz and 2.54 MHz) and a topside layer (between 0.50 MHz and 0.73 MHz) with cusps at 0.73 MHz. Following the principle of MARSIS, the upper trace is due to vertical reflections and the lower trace is due to reflections from oblique directions. The vertical and oblique echo traces from the main layer of the ionosphere are known features, while the oblique echo trace from the topside layer is a new result. As can be seen from bottom panel of Figure 4, the ionogram with oblique echoes from the topside layer is located in a region close to the magnetic field anomalies (marked with downward magenta arrow). One interesting observation with oblique echoes is that in all the cases that we examined, the oblique echoes from the topside layer are always associated with those from the main layer. In other words, there are no ionograms that show the oblique echoes from the topside layer without those from the main layer of the ionosphere.

Such oblique echo traces from the topside layer are not rare, though they are limited in number. In fact, there are several individual ionograms in different orbits which show the oblique echo traces from the topside layer. The latitude-longitude distribution of the oblique echoes also confirms that the oblique echoes associated with the topside layer occur in regions of strong crustal magnetic fields. Previous studies have shown that the topside layer is a transient layer [4]. In addition, the presence of local plasma frequency lines contaminates the appearance of the topside layer as the layer is generally observed at the low-frequency end of an ionogram (for both the vertical and oblique echoes). Moreover, as the oblique echoes are generally observed in regions of strong crustal magnetic fields the presence of ion cyclotron lines also obscures the observation of a topside layer. Therefore, it is difficult to observe the topside layer in regions of strong crustal magnetic fields. As a result, a number of ionograms that show the oblique echoes from topside layer are limited. From the orbits we analyzed, we found one orbit in which there are at least 10 consecutive ionograms which show the presence of topside layer with oblique echoes. From these echoes, we constructed a echogram which shows a hyperbola shaped structure which is clear indication of the ionization bulge. However, the ionization bulges in the topside layer, unlike those of the main layer are not showing repeatability over the same location [5].

4. Discussion and conclusions

The ablation of meteor dust from comet Siding Spring resulted in the formation of a dense transient ionization layer in the Martian upper atmosphere at altitudes between 80 and 120 km. This also gave us an opportunity to examine the presence of ionization bulges at these altitudes, which otherwise is not possible considering the less density at these altitudes and the limitations of the MARSIS instrument observing capability. We found that the transient ionization layer can persist for at least 19 h on the nightside and for 12 h on the dayside after the time of peak dust deposition. The altitude of occurrence and the depletion rates of the layer are agreeing with those of model simulations.

To explain the occurrence of double layered structure in MARSIS ionograms, two mechanisms have been proposed. Horizontal bifurcation of the original layer and specular reflections from both the regions is one possibility. However, the presence of these oblique echoes in regions of strong vertical magnetic fields suggests that they are ionization bulges. However, due to the less number of ionograms with oblique echoes, the typical downward hyperbola shaped structure of oblique echoes that is normally observed in the ionospheric radargrams could not be examined for the metallic ion layer. Further studies are required to examine whether solar wind electrons can reach to the altitudes of ~100 km and form a bulge at these altitudes that can give rise to the oblique reflections.

As far as the oblique echoes from the topside layer are concerned, their occurrence is limited. Out of 2514 orbits that we analyzed, only 39 orbits (1.5%) showed the oblique echoes from the topside layer. On a few occasions the topside layers with oblique echoes are observed in continuous ionograms allowing us to construct a echogram to identify the hyperbola shape and the relation of the shape to the crustal magnetic field anomalies. Furthermore, the oblique echoes from the topside layer are always associated with those from the main layer.

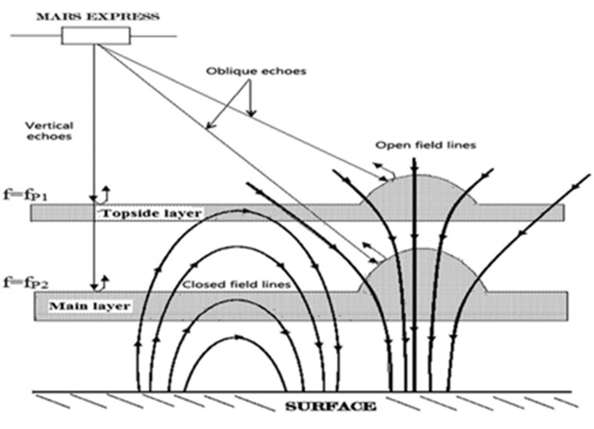

Figure 5. A sketch of the ionization bulges that are thought to be responsible for simultaneous observation of oblique echoes from the topside and main ionospheric layers. As the spacecraft approaches the ionization bulges, vertical echoes are received from the normal ionosphere and oblique echoes from the ionization bulges. A similar schematic also explains the ionization bulges at the meteor ion layer.

Going by the same concept of ionization bulge, the simultaneous observations of oblique echoes from the topside and main ionospheric layers are explained through a schematic shown in Figure 5. Here we assume two ionization bulges, one each at altitudes of the topside and main layers of the Martian ionosphere. Both these ionization bulges are assumed to be in regions of vertical magnetic fields. Then, the lower frequency radio waves get reflected from the topside layer and from its ionization bulge ($f=fp_1$ surface), forming vertical and oblique echo traces in an ionogram, respectively. This will form a double layer structure of the topside layer at the low-frequency end of an ionogram. Similarly, higher frequency radio waves get reflected from the main ionospheric layer and its bulge ($f=fp_2$ surface), resulting in vertical and oblique echo traces, respectively. Thus, the concept of ionization bulges at altitudes of the topside and main layers of ionosphere can explain the simultaneous observation of oblique echoes from these layers.

Based on the results of the present study and the current understanding of the two layers, the following appears the most plausible explanation for the formation of ionization bulges at the altitude of the two layers [5]. We assume that the main layer is a stable layer formed by the photo-ionization, where the topside layer is due to the beam plasma instability. We further assume that the local electrodynamics is important and heating by solar wind electron precipitation is not a prerequisite condition for the formation of ionization bulges. Particularly, the field-aligned transport of the plasma along vertical magnetic fields is probably the most important for the formation of ionization bulges at the altitudes of both the topside and main layers. Then the vertical diffusion of the plasma along the open magnetic fields leads to the formation of the ionization bulges at the main layer of the ionosphere. A similar vertical diffusion of the plasma at the topside layer will lead to enhanced beam plasma instability that pushes the plasma further upward, forming a local ascension in electron density that lies at higher altitudes in regions of vertical magnetic fields than in other regions. The processes that reduce the electron-ion recombination rate by increasing the Joule heating along open magnetic fields may add up to inflate the ionization bulge further. Thus, the combination of beam plasma instability and vertical diffusion leads to the formation of ionization bulges in the topside layer. Thus, the results of the present study suggest that the ionization bulges exist at altitudes other than originally thought of and can occur at altitudes well above and well below that of the main layer.

6. Acknowledgements

The MARSIS data are publicly archived at the Planetary Geosciences node of the Planetary Data System (http://pdsgeosciences.wustl.edu/missions/mars_express/marsis.htm). P. Mohanamanasa thanks the Department of Science and Technology, Government of India, for supporting the research presented here through a JRF fellowship.

7. References

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