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Study of the ionosphere of Mars: application and limitations of the Chapman-layer model

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Abstract

The study of data from Viking, Mars Global Surveyor and Mars Express missions is enabling a rapid progress in the knowledge of ionosphere of Mars. Although the Earth's ionosphere is a reference is necessary to note that Mars doesnt have a global magnetic field to form a magnetosphere and the composition of his atmosphere is very different from the case of the Earth. Therefore, the effect of solar wind on the atmosphere, chemical reactions and ionization processes are very different in the two planets. For this reason there may be doubts about the applicability of terrestrial ionospheric models to the ionosphere of Mars. In a first step in this line of study we have applied the Chapman layer model to a significant number of radio-occultation data obtained by the Mars Global Surveyor mission to check the validity range for the fit of the electron density profiles. We also analyze the status of the ionosphere under different conditions of latitude, longitude, time of observation, Martian seasons and solar activity to compare these results with the characteristics and variations in the Earth's ionosphere.

1 Introduction

The ionosphere of Mars has been an important subject of research over the last 40 years within the framework of our current knowledge of the physics and chemistry of planetary atmospheres and ionospheres. Unfortunately, however, until the arrival of Mars Express in 2003, none of the missions destined for Mars carried the necessary instruments for on-site measurements of this ionosphere [2]. Thus, for many years the only information available was the data collected from radio occultation profiles. This technique is very commonly used in the case of the Earth's ionosphere [4], and there was thus a tendency to compare the ionospheres of both planets. However it is important to bear in mind that Mars lacks a global magnetic field which permits the appearance of a magnetosphere, and that the composition of its atmosphere is very different to that of the Earth. Moreover there are regions on the planet's crust which are intensely magnetized, particularly in the range between latitude 30°S–85°S and longitude 120°W–210°W, where the fields may have values of up to $\sim$ 1600 nT measured at an altitude of $\sim$100 km, which may affect this atmospheric layer [1]. All this raises doubts as to the applicability of Earth ionospheric models in the case of the ionosphere of Mars.

The first step in this line of study was to apply the Chapman-layer model to a significant sample of radio-occultation data obtained by the Mars Global Surveyor mission, MGS and verify the degree of validity in order to adjust the electron density profiles.The situation of the ionosphere was analyzed under different conditions of latitude, longitude, time of observation, season of the Martian year and solar activity, and these were compared with the characteristics and variations in the Earth's ionosphere.

2 Chapman model

The ionized area of the upper atmosphere of our planet is characterized by a dynamic balance in which the net concentration of free electrons, *the electron density*, depends on the relative speed of the production and loss processes, which in turn vary according to the type of ions existing in the plasma and on their corresponding interactions with the neutral gas [3]. In general terms, the rate of electron density exchange n is expressed by its continuity equation:

$$\frac{dn}{dt} = q - L - \nabla(nv), \tag{1}$$

where q is the rate of ion production per unit of volume, L is the rate of ion loss due to recombination, and $\nabla(nv)$ is the electron loss due to the effects of transport, fundamentally vertical, where v is their average speed.

The aim of this study is to analyze the degree of validity of the Chapman model developed for the Earth's ionosphere when applied to the ionosphere of Mars. The analysis is based on the premises introduced in the model; that is to say, a situation in which the atmosphere is in hydrostatic balance, the incoming radiation is monochromatic, each photon produces a single electron, the atmospheric layers are horizontal, electrically neutral, comprising homogeneous gas formed by a single component, and in equilibrium. If this situation is combined with Eq. 1, the ion production rate per unit of volume is given by the expression:

$$q(x,\chi) = q_{m,0}\exp(1 - z - e^{-z}\sec(\chi)), \tag{2}$$

where $z = \frac{h - h_{m,0}}{H}$ is the reduced height, $q_{m,0}$ is the maximum ion production in the case of vertical incidence, and χ is the solar zenith angle. In addition, and bearing in mind that there are several different processes for ion loss through recombination, two different expressions are obtained for the term L: the first under conditions of recombination through radiation ($e + X^+ \rightarrow X + h\nu$) and by dissociation ($e + XY^+ \rightarrow X + Y$), where positive ions are lost when they recombine with electrons:

$$L = \alpha n^2, \tag{3}$$

where α is the recombination coefficient and n the electron density. The other expression is obtained under conditions of recombination through attachment ($\mathrm{e} + \mathrm{Z} \rightarrow \mathrm{Z}^-$) involving the loss of neutral atoms which bond with electrons:

$$L = \beta n, \tag{4}$$

where β is the recombination coefficient for this situation and n the electron density. The combination of Eqs. 2 with 3 and 4 gives two different expressions for electron density based on reduced height and solar zenith angle. The first is entitled α-Chapman layers and the second β-Chapman layers:

$$n(x, \chi) = n_{m,0} \exp\left(\frac{1}{2}(1 - z - e^{-z} \sec(\chi))\right), \tag{5}$$

$$n(x, \chi) = n_{m,0} \exp(1 - z - e^{-z} \sec(\chi)). \tag{6}$$

3 Data and methodology

The study had access to 5600 files from radio-occultation experiments carried out by the MGS craft between 24-12-1998 and 9-6-2005, of which 559 profiles were selected. This sample offers a representative number of profiles in different conditions of latitude, longitude, time of observation, season of the Martian year and solar activity. The data set was used to analyze the degree of validity of the Chapman-layer model described above, and hence to study the photochemical behaviour of the Martian ionosphere. Both hemispheres were studied separately.

The analysis centred on the northern hemisphere, and involved a comparison of Martian electron density profiles for the same latitude on two different dates of solar activity. Two sets of data from two periods of different solar activity were selected (March 2001 and February 2005) in order to study the effect of the Sun's radiation on the area of the ionosphere of Mars in which there is no presence of magnetic anomalies. In both cases, the latitudes of the profiles were $\varphi = 79° - 85°$ and the solar longitude, from which we can deduce the season of the year, was $L_{\mathrm{s}} = 12° - 163°$, therefore summer.

Using an algorithm created in MATLAB to represent these profiles both individually and collectively, and to adjust them to Chapman α and β layers (Fig. 1), it can be seen that the maximum electron density in high solar activity is 18% greater for layer M1 and 26% greater for layer M2 than the figures obtained for low solar activity. Additionally, and as indicated by Chapman's theory, the height of these density maximums is 2% lower for M1 and 7% lower for M2 during high solar activity when compared to low activity. Another parameter obtained from these adjustments is scale height. A comparison of this parameter with the composition and temperature in this region of the Martian atmosphere demonstrates that the predominant loss processes are radiation and dissociation; that is to say, the α as opposed to β layers.

The study of the profiles for the southern hemisphere was centered on analyzing a possible relationship between the magnetic anomalies on the surface of Mars and its ionosphere.

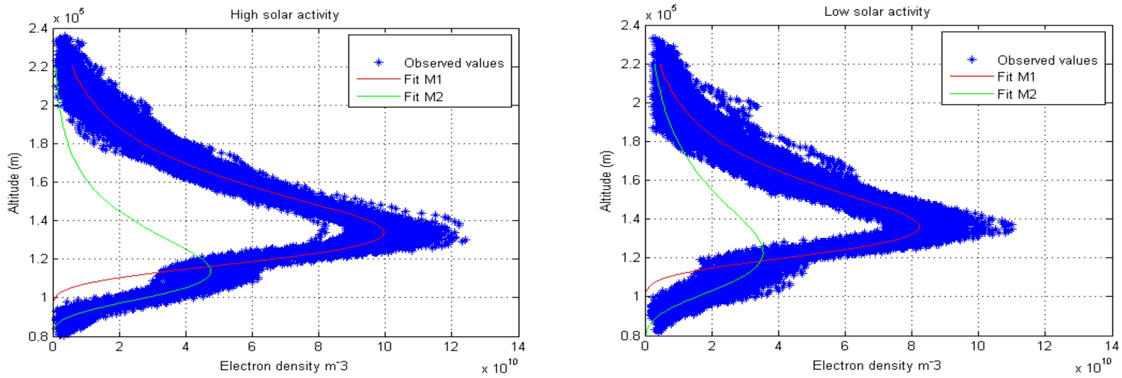

Figure 1: Representation of the observational data obtained by the MGS through radio occultation in the period between March 2001 (left) and February 2005 (right). The red and green lines are the adjustments to the Chapman layers in MATLAB.

Table 1: Results I.

Solar activity	Layers	N_mM1 (m^{-3})	h_mM1 (km)	N_mM2 (m^{-3})	h_mM2 (km)
High	α	$(9.9 \pm 0.4) \times 10^{10}$	134 ± 2	$(4.8 \pm 0.3) \times 10^{10}$	114 ± 2
	β	$(9.7 \pm 0.4) \times 10^{10}$	135 ± 2	$(4.7 \pm 0.3) \times 10^{10}$	113 ± 2
Low	α	$(8.2 \pm 0.4) \times 10^{10}$	137 ± 2	$(3.5 \pm 0.3) \times 10^{10}$	122 ± 2
	β	$(8.1 \pm 0.4) \times 10^{10}$	138 ± 2	$(3.4 \pm 0.3) \times 10^{10}$	120 ± 2

Results I obtained for the maximum electron density peak through nonlinear adjustments to Chapman α and β layers.

The study used the only available data on electron density profiles in the Southern Hemisphere obtained by the Mars Global Surveyor (May 1999). This is the hemisphere where most of the crustal magnetic anomalies on the Martian surface are found, and the procedure therefore involves a preliminary study of the variation that these anomalies cause in the Martian ionosphere.

Using the same algorithm as before, it can be seen that the maximum electron density in layer M2 is 20% greater in areas with magnetic anomalies than in those where there are no such anomalies, and in addition, that the height of this maximum in these areas is 7% greater (Fig. 2). Moreover, as these anomalies have bands of different polarity, the profiles found over positive anomalies have been processed separately from profiles over negative anomalies, with the result that the maximum density of layer M2 is 5.4% lower in areas of negative anomalies, while the height of the maximum in these same areas is 4% greater (Fig. 3).

4 Conclusions

After analyzing a significant sample of data collected by radio occultation from the Mars Global Surveyor mission, it can be said that the ionosphere of Mars responds adequately to

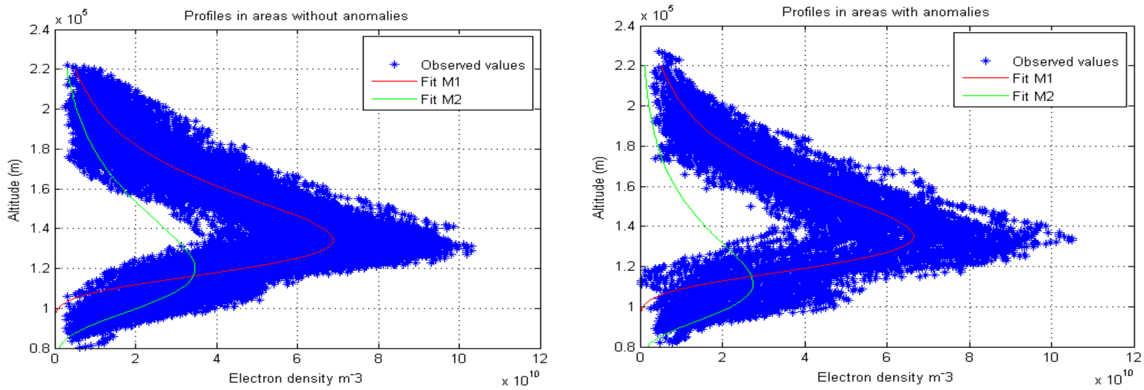

Figure 2: Representation of the observational data obtained by the MGS by radio occultation in May 1999. On the left are the profiles over areas without anomalies and on the right the profiles over areas with anomalies. The red and green lines are the adjustments to the Chapman α and β layers.

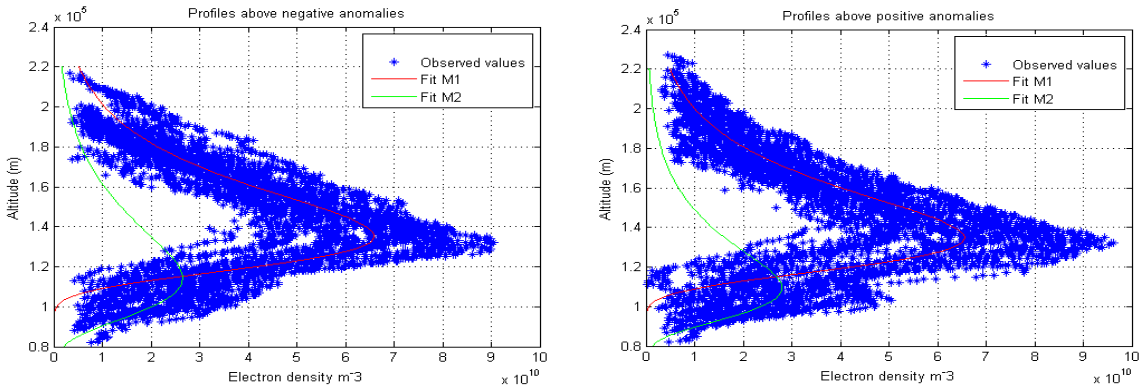

Figure 3: Representation of the observational data obtained by the MGS by radio occultation in May 1999. On the left are the profiles over areas with negative anomalies and on the right the profiles over areas with positive anomalies. The red and green lines are the adjustments to the Chapman α and β layers.

Table 2: Results II.

Solar activity	Layers	H M1 (km)	H M2 (km)
High	α	12.9 ± 0.6	11.7 ± 0.6
	β	20 ± 1	14.4 ± 0.7
Low	α	12.4 ± 0.4	16.2 ± 0.8
	β	18.8 ± 0.9	19 ± 1

Results II obtained for the maximum electron density peak through nonlinear adjustments to Chapman α and β layers.

the Chapman-layer model. Specifically, the α-Chapman layer model (loss processes through radiation and dissociation) appears to be the model that best describes the ionization process in the area.

The heights of the two maximum electron densities were found to be located on average between 135 km for the main density peak (M1) and 110 km for the secondary peak (M2), with the following electron densities: $\sim 1 \times 10^{11}$ m^{-3} (M1) and $\sim 4 \times 10^{10}$ m^{-3} (M2) respectively.

Finally, in the secondary M2 layer a significant difference was observed between the southern hemisphere profiles which cross areas with magnetic anomalies and those that do not. This is also the case for profiles which cross areas with a different polarity.

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