New observations of the topside ionosphere of Mars

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A “step”, or change in gradient, in electron density at ~160 km can be seen in MEX RS, MGS RS, and MEX MARSIS data.

- What is it?
- Why is it not apparent in Mariner 9, Viking Orbiter, or Viking Lander data?
- Why is it not predicted by models?
This “step” is visible in many MGS profiles.
MARSIS is a topside ionospheric sounder on Mars Express. It also sees a "step" in the topside.

MARSIS data
Nielsen et al. (2006)
Space Sci. Rev.

Figure 6. The solid and dash-dot curve is the estimated profile of the topside electron densities derived using the lamination technique. The solid curve covers the densities for which echoes were observed, and the dash-dot curve the assumed exponential decrease. Note, the dash-dot curve starts at the derived electron density (star) at the height of the spacecraft. The dashed curve is a Chapman layer fitted to the observations. In the plot is noted the associated maximum electron density (148279 el/cm$^3$) and altitude of the maximum (~124 km) in the sub solar region, together with the neutral scale height (10.0 km), a top-side scale height (~28 km), and solar zenith angle (~28 degrees).
Typical Ionospheric Profiles for Earth and Mars

Earth (Hargreaves, 1992)
F layer due to EUV photons
E layer due to soft X-rays
D layer due to hard X-rays
Soft ~ 10 nm, hard ~ 1 nm

Mars (MGS RS data)
Transport important above ~180 km
Main peak at 140 km due to EUV photons
Lower peak at 110 km due to X-rays. Lower peak is very variable and often absent
Mars ionospheric chemistry

- \( \text{CO}_2 + \text{hv} \rightarrow \text{CO}_2^+ + e \) (production)
- \( \text{CO}_2^+ + \text{O} \rightarrow \text{O}_2^+ + \text{CO} \) (chemistry)
- \( \text{O}_2^+ + e \rightarrow \text{O} + \text{O} \) (loss)

- The presence of neutral O affects ionospheric chemistry and electron densities

Bougher et al., 2002

- Few observations of neutral atmosphere composition exist
- \( \text{O}/\text{CO}_2 \) ratio is predicted to vary with altitude, season, time of day, etc
- This is a challenge for ionospheric modelling and data analysis
Data and model for Mars atmospheric composition from Viking 1. Hanson et al. (1977) and Nier and McElroy (1977)
# Planetary Properties at Ionospheric Peak

<table>
<thead>
<tr>
<th></th>
<th>Venus</th>
<th>Earth E-region</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>g (m s(^{-2}))</td>
<td>8.9</td>
<td>9.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Solar distance (AU)</td>
<td>0.7</td>
<td>1.0</td>
<td>1.4 – 1.7</td>
</tr>
<tr>
<td>(z_{\text{peak}}) (km)</td>
<td>140</td>
<td>110</td>
<td>120</td>
</tr>
<tr>
<td>Neutrals</td>
<td>(\text{CO}_2)</td>
<td>(\text{N}_2, \text{O}_2)</td>
<td>(\text{CO}_2)</td>
</tr>
<tr>
<td>Ions</td>
<td>(\text{O}_2^+)</td>
<td>(\text{O}_2^+), (\text{NO}^+)</td>
<td>(\text{O}_2^+)</td>
</tr>
<tr>
<td>Production process</td>
<td>(\text{CO}_2^{+}+\text{hv} \rightarrow \text{CO}_2^{+}+\text{e})</td>
<td>(\text{N}_2^{+}+\text{hv} \rightarrow \text{N}_2^{+}+\text{e})</td>
<td>(\text{CO}_2^{+}+\text{hv} \rightarrow \text{CO}_2^{+}+\text{e})</td>
</tr>
<tr>
<td></td>
<td>(\text{CO}_2^{+}+\text{O} \rightarrow \text{CO}+\text{O}_2^{+})</td>
<td>(\text{N}_2^{+}+\text{O} \rightarrow \text{N}+\text{NO}^{+})</td>
<td>(\text{CO}_2^{+}+\text{O} \rightarrow \text{CO}+\text{O}_2^{+})</td>
</tr>
<tr>
<td>Loss process</td>
<td>Dissociative Recombination</td>
<td>DR</td>
<td>DR</td>
</tr>
<tr>
<td>(N_n) (cm(^{-3}))</td>
<td>1 E 11</td>
<td>1 E 13</td>
<td>1 E 11</td>
</tr>
<tr>
<td>(N_e) (cm(^{-3}))</td>
<td>7 E 5</td>
<td>1 E 4</td>
<td>2 E 5</td>
</tr>
<tr>
<td>(T_n) (K)</td>
<td>200</td>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>(T_e) (K)</td>
<td>1000</td>
<td>300 – but ~1000 at 150 km</td>
<td>200</td>
</tr>
</tbody>
</table>
The only observations of Mars ionospheric composition (Hanson et al., 1977)
No “step” or similar feature is visible on the topside
Mariner 9 and Viking Orbiter radio occultation electron density profiles (Kiore 1992). No obvious “steps” are visible.

Fig. 6. Vertical electron density profiles in the Mars ionosphere as observed with Viking 1 and Viking 2 at high solar zenith angles, which are shown above each profile.
Mariner 9 and Viking Orbiter radio occultation electron density profiles (Kiore 1992). No obvious "steps" are visible.
New observations of the topside ionosphere at Mars

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The daytime Martian ionosphere consists of a main layer M2 at typically 135 km altitude and a secondary layer M1 at 110 km altitude, both formed by solar radiation at EUV and X-ray, respectively. The peak altitudes and peak densities vary according to the diurnal changes in solar zenith angle as expected when under solar control. These layers are controlled by photochemical processes and can be represented as Chapman layers. However, the topside ionosphere is more complex and difficult to model. It is affected by plasma transport due to dynamical processes and changing ion chemistry (increasing amounts of O+ ions, as observed by the Viking Landers). New Mars Express Radio Science experiment MaRS observations show the transition from the region around the photochemically-controlled EUV peak, which is effectively an O2+ Chapman layer, to the topside in great detail. We discuss how these observations can be used to better understand the complex topside ionosphere, relating them to Mars Global Surveyor observations and predictions from numerical models. Vertical profiles of excess topside electron density have shapes that resemble a Chapman function. We shall investigate whether these shapes are caused by photochemical processes or the transition to a transport-dominated region.
Viking-era models do not show any topside "step".

1-D models include photochemistry and vertical transport by diffusion. "Transport processes begin to control the ion density distribution at altitudes above 200 km." (Chen et al., 1978)
Recent MHD models do not show a topside “step” (Ma et al., 2004).

Figure 8. The calculated solar cycle minimum density profiles for case 4 along radial lines for different latitudes in the X-Z plane compared with Viking observation.
Recent 1-D photochemistry/diffusion models do not show a “step”, although this figure does hint at interesting behaviour at 180 km. SZA=60 degrees. Krasnopolsky (2002)
Another recent 1-D photochemistry/diffusion model shows something happening at 180 km, but does not show the topside “step”.

Top left: High solar activity
Bottom left: Low solar activity

SZA = 60 degrees
Fox et al. (1996)
MGS RS data
3012G12A.EDS
2003-01-12
Lat = 76N
LST = 04.4 hrs
SZA = 75 deg

Open black circles = Observed Ne(z)
Red curves = Two Chapman fits
First fit to X-ray peak in observed Ne(z)
Second fit to residual after first fit subtracted from observed Ne(z)
Green curve = Sum of two Chapman fits
Blue curve = Residual after both fits subtracted from observed Ne(z)

After fits to the X-ray and EUV ionospheric layers are removed, excess electron density in the topside is visible around 175 km.
Peak altitude, peak electron density, and neutral scale height for three fitted Chapman layers:

112 km, 47 m$^{-3}$, 9 km
137 km, 86 m$^{-3}$, 9 km
173 km, 22 m$^{-3}$, 10 km

The sum of three Chapman layers (green curve) is a good match to the observed Ne(z) (open black circles). The residuals (blue curve) are consistent with the uncertainties in the observed Ne(z) (vertical black lines).
MGS RS data
3081P28A.EDS
2003-03-22
Lat = 81N
LST = 12.4 hrs
SZA = 71 deg

Open black circles = Observed Ne(z)

Red curves = Two Chapman fits
First fit to X-ray peak in observed Ne(z)
Second fit to residual after first fit subtracted from observed Ne(z)

Green curve = Sum of two Chapman fits

Blue curve = Residual after both fits subtracted from observed Ne(z)

After fits to the X-ray and EUV ionospheric layers are removed, excess electron density in the topside is visible around 180 km.
Peak altitude, peak electron density, and neutral scale height for three fitted Chapman layers:

- 115 km, 42 m$^{-3}$, 12 km
- 140 km, 75 m$^{-3}$, 9 km
- 174 km, 7.8 m$^{-3}$, 11 km

The sum of three Chapman layers (green curve) is a good match to the observed Ne(z) (open black circles). The residuals (blue curve) are consistent with the uncertainties in the observed Ne(z) (vertical black lines).
MEX RS data
2005-12-31    Orbit 2528
Lat = 61.0N    Lon = 211E
LST = 13:24 hrs Ls = 349.2 deg
SZA = 67.7 deg

In this example production functions are added together
Ne proportional to square root(PF)
MEX RS data
2006-01-01 Orbit 2531
Lat = 60.7N Lon = 277E
LST = 13:26 hrs Ls = 349.7 deg
SZA = 67.3 deg

In this example production functions are added together
Ne proportional to square root(PF)
Why fit a Chapman Layer to the topside ionosphere?

- Shape described by only three parameters (N, z, H)
- Electron density decreases rapidly below peak altitude, decreases slowly above peak altitude. Any fit to the topside “step” must not affect electron densities around the ionospheric peak significantly.
- This mathematical function has been used previously to describe ionospheric regions controlled by photochemistry and regions controlled by diffusion
- This choice of fitting function does not imply that the topside “step” is a classical monochromatic, isothermal, photochemical Chapman layer.
Hypotheses

• Change in O/CO$_2$ ratio with altitude makes O$^+$, not O$_2^+$, the dominant ionospheric species. Subsequent change in recombination rate and/or diffusion coefficient affects electron density profile.

• Change in temperature with altitude affects scale height, which affects the change in optical depth with altitude and diffusion. Both of these can affect the electron density profile.

• Transition from photochemistry-dominated regime to diffusion-dominated regime.
Lack of Previous Observations and Theoretical Predictions

• Vertical resolution of Viking RPA measurements was ~5 km, so this “step” would be difficult to distinguish from the general trends in the topside.

• Mariner 9 and Viking Orbiter RS profiles are no longer available in digital format. Their noise level was $10^3$ cm$^{-3}$, comparable with that of MEX and smaller than the MGS value of $3 \times 10^3$ cm$^{-3}$. This lack of detection is a puzzle.

• The scarcity of observations of the composition and temperatures of the Mars neutral upper atmosphere and ionosphere means that many model inputs are poorly constrained. In this situation, models are often tuned to reproduce existing observations, rather than fully explore the allowed regions of parameter space.
Conclusions

• A step, ledge, layer, or feature in the topside Mars ionosphere has been observed by MEX RS, MGS RS, and MARSIS.

• This is not visible in prior observations nor is it predicted by existing models.

• Hypotheses for the origin of this feature include vertical variations in chemistry, temperature, or the importance of photochemistry relative to transport.
Predicted O/CO₂ ratio varies greatly

Bougher et al. (1999, above) and (2000, right).

Figure 4. Mars Thermosphere General Circulation Model (MTGCM) equatorial fields and their variations over the solar cycle. (a) Mid-afternoon (LT = 1500, solid), and early morning (LT = 0400, dashed) temperature profiles over 100 to 220 km for SMIN, SMED, and SMAX cases; (b) midafternoon (LT = 1500) and early morning (LT = 0400) O/CO₂ profiles over 100 to 220 km for the same 3-EUV flux cases. At the F1-ionospheric peak (~130 km) at LT=1500, the O mixing ratio varies from ~2-4% over the solar cycle. Mixing ratio curves are delineated as follows: LT=1500 (solid) and LT=0400 (dashed) for SMIN, SMED, and SMAX cases.

Figure 4: MTGCM subsolar latitude variations over the solar cycle for solstices. (a) Northern summer solstice (NSL): midafternoon (LT = 1500, solid lines), and midnight (LT = 0000, dashed lines) O/ profiles over 120 to 220 km for min, mod, and max cases. (b) Southern summer solstice (SSL): midafternoon (LT = 1500, solid lines), and midnight (LT = 0000, dashed lines) O/ profiles over 120 to 220 km for min, mod, and max cases.
The $\text{O}_2^+$/CO$_2^+$ ratio is affected by the O/CO$_2$ ratio
Hanson et al. (1977)
Introduction

Background

Previous Observations
Models

Topside Fits

Interpretation