The Response of an Ionosphere to changes in the solar $F_{10.7}$ flux: Comparison of Venus, Earth and Mars

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Abstract

There are many similarities between the terrestrial E region and the ionospheres of Venus and Mars. All are dominated by photochemical, not transport, processes. The dissociative recombination of molecular oxygen ions is an important loss mechanism for all three regions. Various workers have studied how ionospheric properties, such as the peak electron density, in these regions respond to changes in solar flux, especially as represented by the F10.7 index. Timescales of interest include the solar cycle, the solar rotation period, and shorter periods, such as one day. We shall discuss the many parameterizations of such responses that have been published and examine their consistencies with known photochemical processes.
Neutral Atmosphere
Venus
Bougher et al. (2002)
Neutral Atmosphere
Mars
Bougher et al. (2002)
## Planetary Properties at Ionospheric Peak

<table>
<thead>
<tr>
<th></th>
<th>Venus</th>
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<tbody>
<tr>
<td><strong>g (m s(^{-2}))</strong></td>
<td>8.9 (p263, purple)</td>
<td>9.8 (p263, purple)</td>
<td>3.7 (p263, purple)</td>
</tr>
<tr>
<td><strong>Solar distance (AU)</strong></td>
<td>0.7 (p263, purple)</td>
<td>1.0 (p263, purple)</td>
<td>1.4 – 1.7 (p263, purple)</td>
</tr>
<tr>
<td><strong>z(_{\text{peak}}) (km)</strong></td>
<td>140 (p781 and 830, V1)</td>
<td>110 (p 228, C+H)</td>
<td>120 (p540, Hantsch)</td>
</tr>
<tr>
<td><strong>Neutrals</strong></td>
<td>CO(_2) (p263, purple)</td>
<td>N(_2), O(_2) (p263, purple)</td>
<td>CO(_2) (p263, purple)</td>
</tr>
<tr>
<td><strong>Ions</strong></td>
<td>O(_2^+) (p780, V1)</td>
<td>O(_2^+), NO(^+) (p232, C+H)</td>
<td>O(_2^+) (p1070, Mars)</td>
</tr>
<tr>
<td><strong>Production process</strong></td>
<td>CO(_2)+hv -&gt; CO(_2^+)+ e</td>
<td>N(_2^+)+hv -&gt; N(_2^+)+ e</td>
<td>CO(_2^+)+hv -&gt; CO(_2^+)+ e</td>
</tr>
<tr>
<td></td>
<td>CO(_2^+)+O -&gt; CO + O(_2^+) (p855, V1)</td>
<td>N(_2^+)+ O -&gt; N + NO(^+)</td>
<td>CO(_2^+)+O -&gt; CO + O(_2^+) (p1069, Mars)</td>
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<tr>
<td><strong>Loss process</strong></td>
<td>Dissociative Recombination (p855, V1)</td>
<td>DR (p232, C+H)</td>
<td>DR (p263, C+H)</td>
</tr>
<tr>
<td><strong>N(_n) (cm(^{-3}))</strong></td>
<td>1 E 11 (p265, purple)</td>
<td>1 E 13 (p265, purple)</td>
<td>1 E 11 (p204, Fox)</td>
</tr>
<tr>
<td><strong>N(_e) (cm(^{-3}))</strong></td>
<td>7 E 5 (p856, V1)</td>
<td>1 E 4 (p229, C+H)</td>
<td>2 E 5 (p541, Hantsch)</td>
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<tr>
<td><strong>T(_n) (K)</strong></td>
<td>200 (p264, purple)</td>
<td>300 (p264, purple)</td>
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<tr>
<td><strong>T(_e) (K)</strong></td>
<td>1000 K (p791, V1)</td>
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Ionospheric composition of Venus
PVO data (symbols) and Nagy model (lines)
Chamberlain and Hunten (1987)
Ionospheric structure
Venus
PVO radio occultations
Kliore (1992)
Ionospheric composition
Earth
Chamberlain and Hunten (1987)

$14^+ = N^+$, $16^+ = O^+$, $18^+ = H_2O^+$

$28^+ = N_2^+$, $30^+ = NO^+$, $32^+ = O_2^+$

Solar zenith angle = 60°
White Sands
15 Feb. 1963
0934 MST
NRL
Ionospheric composition
Mars
Viking Lander 1 RPA data
and Hanson model
Chamberlain and Hunten (1987)
Ionospheric structure
Mars – Mariner 9
radio occultations
Kliore (1992)
Chapman Theory for a Simple Ionospheric Layer

\[ \alpha(T_e) \times N^2(z) = \left( \frac{F_{1AU}}{(D/1AU)^2} \right) \frac{1}{\text{Ch}(\chi)} \frac{1}{He} \times f(z) \]

\[ f(z) = \exp\left(1 - \frac{z - z_m}{H}\right) - \exp\left(-\frac{z - z_m}{H}\right) \]

\[ z_m = z_0 + H \ln \text{Ch} \]

\( \alpha \) = Dissociative recombination coefficient
\( T_e \) = Electron temperature
\( N \) = Number density of electrons
\( F_{1AU} \) = Ionizing flux at 1 AU
\( D \) = Distance from Sun
\( \text{Ch}(\chi) \) = Geometrical correction function, secant(\( \chi \)) for small \( \chi \)
\( \chi \) = Solar zenith angle
\( He \) = Scale height of neutral atmosphere
\( e \) = \( \exp(1) \)
\( z \) = Altitude
\( z_m \) = Altitude at which \( N(z) \) is maximum
\( z_0 \) = Altitude at which \( N(z) \) is maximum for \( \chi = 0 \)
Chapman Theory for a Simple Ionospheric Peak

\[ N_m^2 \times (D / 1AU)^2 H = \frac{1}{Ch(\chi)} \frac{F_{1AU}}{\alpha(T_e)e} \]

\[ \alpha_{NO^+} = 4.0E-7 \text{ cm}^3 \text{ s}^{-1} (300K/Te)^{0.5} \]
\[ \alpha_{O_2^+} = 1.95E-7 \text{ cm}^3 \text{ s}^{-1} (300K/Te)^{0.5} \text{ for } Te < 1200 \text{ K} \]
\[ \alpha_{O_2^+} = 7.38E-8 \text{ cm}^3 \text{ s}^{-1} (1200K/Te)^{0.56} \text{ for } Te > 1200 \text{ K} \]

If \( H \) and \( T_e \) are independent of \( F_{1AU} \), then:

\[ \frac{\partial \ln N_m}{\partial \ln F_{1AU}} = 0.5 \]
But H and Te are not independent of $F_{1\text{AU}}$ ... 

- So $d\ln(Nm) / d\ln(F)$ will not equal 0.5
- Response of H and Te to changes in $F_{1\text{AU}}$ may vary with (a) planet (thermal structure, composition, etc) and (b) timescale (diurnal, solar rotational, solar cycle)
- Plus, H and Te may vary with $\chi$ as well
- Does $d\ln(Nm) / d\ln(F) = m$ accurately represent the response of all three planets and all timescales for any single value of $m$?
## Published studies of $\frac{d \ln (N_m)}{d \ln (F)} = m$

<table>
<thead>
<tr>
<th>Reference</th>
<th>Planet</th>
<th>Equation for $m$</th>
<th>Result for $m$</th>
<th>Timescale</th>
<th>Correction for changing solar phase and distance?</th>
<th>Spacecraft</th>
<th>Solar Flux Proxy, $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elphic et al. (1984)</td>
<td>Venus</td>
<td>$\frac{\partial \ln (N_m \sqrt{\sec \chi})}{\partial \ln F}$</td>
<td>$m=0.33$</td>
<td>Few months?</td>
<td>Yes</td>
<td>PVO</td>
<td>PVO/LP derived proxy</td>
</tr>
<tr>
<td>Kliore and Mullen (1989)</td>
<td>Venus</td>
<td>$\frac{\partial \ln (N_m (\sec \chi)^{0.511})}{\partial \ln F}$</td>
<td>$m=0.376+/-0.011$</td>
<td>7 years</td>
<td>Yes</td>
<td>PVO</td>
<td>AE-E/F10.7 derived proxy</td>
</tr>
<tr>
<td>Rishbeth and Garriott (1969)</td>
<td>Earth</td>
<td>$\frac{\partial \ln (N_m \sqrt{\sec \chi})}{\partial \ln F}$</td>
<td>$m=0.35-0.50$</td>
<td>Years</td>
<td>N/A</td>
<td>“Ground-based”</td>
<td>F10.7</td>
</tr>
<tr>
<td>Titheridge (1997)</td>
<td>Earth</td>
<td>$\frac{\partial \ln N_0}{\partial \ln F}$</td>
<td>$m=0.32-0.40$</td>
<td>Years</td>
<td>N/A</td>
<td>“IRI-90”</td>
<td>F10.7</td>
</tr>
<tr>
<td>Stewart and Hanson (1982)</td>
<td>Mars</td>
<td>$\frac{\partial \ln (N_m D \sqrt{\sec \chi})}{\partial \ln F}$</td>
<td>$m=0.5$</td>
<td>1 year</td>
<td>Yes</td>
<td>Mariner 9</td>
<td>F10.7</td>
</tr>
<tr>
<td>Hantsch and Bauer (1990)</td>
<td>Mars</td>
<td>$\frac{\partial \ln (N_m \sqrt{\sec \chi})}{\partial \ln F}$</td>
<td>$m=0.36$</td>
<td>$&gt;10$ years</td>
<td>No</td>
<td>Mars 2,4,6, Mariner 4,6,7,9 VO1,2, VL1,2</td>
<td>F10.7</td>
</tr>
<tr>
<td>Breus et al. (2004)</td>
<td>Mars</td>
<td>$\frac{\partial \ln (N_m \sqrt{H \sec \chi})}{\partial \ln F}$</td>
<td>$m=0.37+/-0.06$</td>
<td>3 months?</td>
<td>Yes</td>
<td>MGS</td>
<td>E10.7</td>
</tr>
<tr>
<td>Withers et al. (2005)</td>
<td>Mars</td>
<td>$\frac{\partial \ln (N_m D \sqrt{HCh})}{\partial \ln F}$</td>
<td>$m=0.243+/-0.031$</td>
<td>3 weeks</td>
<td>Yes</td>
<td>MGS</td>
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</tr>
</tbody>
</table>
Comments on Published Studies – Venus and Earth

• Kliore and Mullen’s (1989) work on Venus used a large dataset with an extensive range of solar zenith angles and solar fluxes. Their quantitative analysis included the effects of errors. Elphic et al.’s (1984) work is less suitable for our purposes.

• There are surprisingly few relationships between $N_m$ and $F$ for the Earth, probably because terrestrial workers are rarely interested in such simple analyses. We adapted the two relationships that we could find in order to determine $\frac{d\ln(N_m)}{d\ln(F)}$. However, the relationships that do exist benefit from large datasets, so they should be reliable.
Comments on Published Studies - Mars

- Stewart and Hanson (1982) assumed that $\frac{d\ln(Nm)}{d\ln(F)} = 0.5$ and then fitted other model parameters to data.
- Hantsch and Bauer (1990) did not consider the effects of solar rotation, nor of changes in the Mars-Sun distance. They appear to have treated results from individual flybys on equal terms with averages from many measurements by Mariner 9. They did not correct $\sec(\chi)$ at high solar zenith angles and did not consider the effects of errors.
- Breus et al. (2004) did not correct $\sec(\chi)$ at high solar zenith angles despite half their data being at $\chi > 80^\circ$. It is unclear whether they have corrected for solar rotation and, if so, how.
- Withers et al. (2005) included an explicit H dependence and used Tobiska’s $E_{10.7}$ proxy for solar flux, which changes with each new release of Solar2000, but their result only changes from $0.243 +/- 0.031$ to $0.241 +/- 0.012$ if $F_{10.7}$ and a constant scale height are used instead. Their timescale of a few weeks is much shorter than those of the Venus and Earth studies, but has values of $E_{10.7}$ that range from 126 to 291.
N\textsubscript{0} vs Flux for Venus
Logarithmic axes
Kliore and Mullen (1989)
$N_0$ vs $F_{10.7}$ for Mars
Logarithmic axes
Hantsch and Bauer (1990)
$\ln (N_m H^{0.5} \sec(\chi)^{0.5})$ vs $\ln E_{10.7}$

Brueus et al. (2004)
\[
\ln\left(\frac{N_m}{10^4 \text{ cm}^{-3}}\sqrt{CnH/10\text{km}(D/\text{AU})}\right) = (0.243 \pm 0.031)\ln\left(E_{10.7}^{\text{Mars,1AU}}\right) + (2.181 \pm 0.165)
\]

Withers et al. (2005)
Results for Venus, Earth, and Mars

- $\frac{\mathrm{dln}(Nm)}{\mathrm{dln}(F)} = 0.35-0.40$ is a reasonable approximation for Earth and Venus on timescales of years.

- It is not clear if it is valid at Mars. There are problems with published work studying long timescales. Withers et al. (2005), studying timescales of a few weeks, found that $\frac{\mathrm{dln}(Nm)}{\mathrm{dln}(F)} = 0.24 \pm 0.03$. 
Electron Temperatures and Scale Heights

\[ N_m^2 = \frac{1}{H \times \alpha(T_e)} \frac{F_{1AU}}{(D/1AU)^2 Ch(\chi)e} \]

- \( H \times \alpha(T_e) \) responds similarly to changes in \( F \) on Venus and Earth, but seems to respond differently on Mars.
- If true, this could be due to the relatively low \( T_e \) on Mars (~200 K) compared to Venus and Earth (~1000 K)
Conclusions

• Despite similarities between their photochemistry, peak electron density in the terrestrial planet ionospheres does not respond in the same way to changes in ionizing solar flux.

  dln(Nm) / dln(F) = 0.35-0.40 for Venus and Earth on timescales of years, but 0.24 for Mars on timescales of weeks.

• dln(Nm) / dln(F) differs from 0.5 on Venus, Earth, and Mars due to the dependence of H and Te on solar flux. The response of H and Te to changes in F might be different from planet to planet.

  Is this response function different when solar flux changes on very short timescales, e.g. due to flares, when ion production rates increase instantly but H and Te have a longer response time?

• Properly calibrated, this response function can be used to determine the ionizing solar flux at Venus or Mars from routine ionospheric measurements.
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• Hantsch and Bauer (1990) PSS, 38(4), 539-542
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• Kliore and Mullen (1989) JGR-A, 94, 13339-13351
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