Ionization Patches on the Night Side of Mars and Their Seasonal and Solar Cycle Variations

M. O. Fillingim\textsuperscript{1}, L. M. Peticolas\textsuperscript{1}, R. J. Lillis\textsuperscript{1}, D. A. Brain\textsuperscript{1}, J. S. Halekas\textsuperscript{1}, D. Lummerzheim\textsuperscript{2}, and S. W. Bougher\textsuperscript{3}

\textsuperscript{1}Space Sciences Laboratory, University of California, Berkeley
\textsuperscript{2}Geophysical Institute, University of Alaska, Fairbanks
\textsuperscript{3}Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor

7\textsuperscript{th} International Conference on Mars July 11, 2007 Pasadena, CA
Summary

• The complex magnetic topology at Mars allows solar wind (and accelerated) electrons to ionize the night side atmosphere in limited regions (cusps) → patchy distribution of ionization

• The resulting maximum electron density ($n_e^{\text{max}}$) and total electron content (TEC) vary considerably with season and solar cycle as the scale height of the atmosphere changes

• Both $n_e^{\text{max}}$ and TEC impact subsurface science that can be done from orbit:
  higher $n_e^{\text{max}}$ → lower penetration depths
Martian Magnetic Field and Cusps

- Mars has no global magnetic field, but it does have strong crustal fields.
- “Cusps” form where radial crustal fields connect to the IMF.
  - Solar wind has access to the night side atmosphere → ionization.
- Accelerated electrons, ionospheric structure, and aurora seen near cusps.
- Non-uniform global distribution of cusps (i.e., ionization) → “patchy.”
Accelerated (Auroral) Electrons
(from Brain et al. [2006])

- MGS at 400 km at SZA ~ 125°
- Downward energy flux for accelerated spectrum 10 X greater than that for typical tail spectrum

MGS orbit
Plasma void
Trapped electrons
Cusp
Accelerated electrons

7th International Conference on Mars July 11, 2007 Pasadena, CA
Global distribution of peaked spectra ($dj/dE > 0$) found in MGS dataset
- Clustered around perimeter of closed field regions (contours) → cusps
- Wide range of energy fluxes – up to 40 X higher than previous example
- Accelerated electrons also seen by Mars Express [Lundin et al., 2006]
**Observations of Night Side Ionosphere**

<table>
<thead>
<tr>
<th>$n_e^{\text{max}}$ (cm$^{-3}$)</th>
<th>Altitude of $n_e^{\text{max}}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7 x 10$^3$</td>
<td>110</td>
</tr>
<tr>
<td>5 x 10$^3$</td>
<td>150</td>
</tr>
</tbody>
</table>

- Radio occultation (RO) profiles
  - Mars 4 [Savich et al., 1976] 4.7 x 10$^3$ 110
  - Viking 1 & 2 [Zhang et al., 1990] 5 x 10$^3$ 150
  (in all cases, solar zenith angle (SZA) ≤ ~ 125°)

- Mars Express MARSIS Active Ionospheric Sounder (AIS) [Kirchner et al., 2006, 2007]
  - Non-magnetic regions (typical) 8 x 10$^3$ 175
  - Magnetic regions (typical) 5 x 10$^4$ 127

- Both MARSIS AIS observations [Gurnett et al., 2005; Duru et al., 2006] and near-terminator (SZA ~ 90°) MGS RO profiles [Withers et al., 2005] show evidence of small-scale ionospheric structure associated with cusps → Patchy distribution of ionization consistent with particle measurements
# Models of Night Side Ionosphere

<table>
<thead>
<tr>
<th>$n_e^{\text{max}}$ (cm$^{-3}$)</th>
<th>Altitude of $n_e^{\text{max}}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High altitude (~ 10,000 km) Phobos 2 HARP spectra</strong></td>
<td></td>
</tr>
<tr>
<td>Magnetotail lobe [Verigin et al., 1991]</td>
<td>$7 \times 10^3$</td>
</tr>
<tr>
<td>Magnetotail lobe [Haider et al., 1992]</td>
<td>$1.2 \times 10^4$</td>
</tr>
<tr>
<td>Plasma sheet [Haider et al., 1992]</td>
<td>$1.7 \times 10^4$</td>
</tr>
<tr>
<td>20 eV Maxwellian [Fox et al., 1993]</td>
<td>$1.4 \times 10^4$</td>
</tr>
<tr>
<td>180 eV Gaussian [Fox et al., 1993]</td>
<td>$1.9 \times 10^4$</td>
</tr>
<tr>
<td><strong>Low altitude (~400 km) MGS MAG/ER spectra</strong></td>
<td></td>
</tr>
<tr>
<td>Solar wind (&lt; 1 keV) [Haider et al., 2002]</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Typical tail [Fillingim et al., 2007]</td>
<td>$1.7 \times 10^3$</td>
</tr>
<tr>
<td>Accelerated [Fillingim et al., 2007]</td>
<td>$5.7 \times 10^3$</td>
</tr>
</tbody>
</table>

- $n_e^{\text{max}}$ due to accelerated spectrum is ~ 3 X typical tail spectrum value
- Latitudinal width of enhanced ionization ~ 200 km
  - Consistent with observed small-scale ionospheric structure
Models of Night Side Ionosphere

\[
\begin{array}{lll}
\text{n}_e^{\text{max}} \text{ (cm}^{-3}\text{)} & \text{Altitude of } \text{n}_e^{\text{max}} \text{(km)} \\
\end{array}
\]

- High altitude (~10,000 km) Phobos 2 HARP spectra
  - Magnetotail lobe [Verigin et al., 1991] \(7 \times 10^3\) 165
  - Magnetotail lobe [Haider et al., 1992] \(1.2 \times 10^4\) 158
  - Plasma sheet [Haider et al., 1992] \(1.7 \times 10^4\) 144
  - 20 eV Maxwellian [Fox et al., 1993] \(1.4 \times 10^4\) 172
  - 180 eV Gaussian [Fox et al., 1993] \(1.9 \times 10^4\) 159

- Low altitude (~400 km) MGS MAG/ER spectra
  - Solar wind (<1 keV) [Haider et al., 2002] \(5 \times 10^3\) 140
  - Typical tail [Fillingim et al., 2007] \(1.7 \times 10^3\) 166
  - Accelerated [Fillingim et al., 2007] \(5.7 \times 10^3\) 156

- \(n_e^{\text{max}}\) due to accelerated spectrum is ~ 3 X typical tail spectrum value
- Latitudinal width of enhanced ionization ~ 200 km
  \(\rightarrow\) Consistent with observed small-scale ionospheric structure

7th International Conference on Mars July 11, 2007 Pasadena, CA
Purpose & Methodology

• The upper atmosphere changes significantly with season and solar cycle
  ➔ How do these changes affect the precipitation induced ionosphere?

• Model the changes in electron density ($n_e$) and total electron content (TEC) due to atmospheric variations for both typical tail and accelerated spectra

• Examine four cases:
  • Solar moderate, perihelion, northern winter solstice ($L_S = 270°$)
  • Solar minimum, perihelion, northern winter solstice ($L_S = 270°$)
  • Solar moderate, aphelion, northern summer solstice ($L_S = 90°$)
  • Solar minimum, aphelion, northern summer solstice ($L_S = 90°$)

• For each case, the electron density is determined from
  \[ n_e(z) = \sqrt{\frac{P(z)}{\alpha_{\text{eff}}(z)}} \text{ cm}^{-3}, \]
  where $P(z)$ is the ion production rate and $\alpha_{\text{eff}}(z)$ is the recombination rate

• Since $O_2^+$ is the dominant ionospheric ion due to rapid chemical reactions,
  \[ \alpha_{\text{eff}}(z) = O_2^+ \text{ recombination rate} = 1.95 \times 10^{-7} \left(\frac{300}{T_e(z)}\right)^{0.7} \text{ cm}^3 \text{ s}^{-1}, \]
  where $T_e$ is the electron temperature (assume $T_e = \text{neutral temperature}$)
Model contains $\text{CO}_2$, $\text{CO}$, $\text{O}_2$, $\text{O}$, & $\text{N}_2$; all profiles from 2.5° N & 2 AM LT

- At low altitude, seasonal/orbital effects dominate
- At high altitude, solar cycle effects are important
Electron Density (Typical Tail Spectrum)

- $n_e^{\text{max}}$ larger at solar min \(\rightarrow\) solar cycle controls magnitude of peak
- Altitude of $n_e^{\text{max}}$ higher at perihelion \(\rightarrow\) season controls altitude of peak
- TEC larger at solar mod \(\rightarrow\) solar cycle controls thickness of ionosphere
Electron Density (Accelerated Spectrum)

- $n_e^{\text{max}}$ larger at solar min $\rightarrow$ **solar cycle** controls magnitude of peak
- **Altitude** of $n_e^{\text{max}}$ higher at perihelion $\rightarrow$ **season** controls altitude of peak
- **TEC** larger at solar mod $\rightarrow$ **solar cycle** controls thickness of ionosphere

<table>
<thead>
<tr>
<th></th>
<th>$n_e^{\text{max}}$ ($\text{cm}^{-3}$)</th>
<th>Altitude of $n_e^{\text{max}}$ (km)</th>
<th>TEC ($10^{14} \text{ m}^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar mod; perihelion</td>
<td>5700</td>
<td>156</td>
<td>3.47</td>
</tr>
<tr>
<td>Solar min; perihelion</td>
<td>5900</td>
<td>153</td>
<td>2.95</td>
</tr>
<tr>
<td>Solar mod; aphelion</td>
<td>5860</td>
<td>140</td>
<td>3.06</td>
</tr>
<tr>
<td>Solar min; aphelion</td>
<td>6020</td>
<td>138</td>
<td>2.72</td>
</tr>
</tbody>
</table>

7th International Conference on Mars    July 11, 2007    Pasadena, CA
Summary

• In all 4 cases, the accelerated spectrum increased $n_e^{\text{max}}$ by a factor of ~3 and TEC by ~2.5 over that produced by the typical tail spectrum.

• Since cusps are localized and have a patchy global distribution, regions of enhanced $n_e$ and TEC will be localized and patchy.

• Largest $n_e^{\text{max}}$ occur during solar minimum at aphelion. Upper atmosphere coolest (smallest scale height) $\rightarrow$ thinnest ionosphere $\rightarrow$ smallest TEC.

• Smallest $n_e^{\text{max}}$ occur during solar moderate at perihelion. Upper atmosphere warmest (largest scale height) $\rightarrow$ thickest ionosphere $\rightarrow$ largest TEC.

• Between these two extremes, $n_e^{\text{max}}$ changes by ~10% $\rightarrow$ observable TEC changes by ~25% $\rightarrow$ changes!

$\Rightarrow$ Variations in the upper atmospheric scale height (temperature) over different seasonal and solar cycle conditions can drive variations in the ionospheric density profiles.
Implications (Why Should You Care?)

- Both $n_e^{\text{max}}$ and TEC impact subsurface science that can be done from orbit.
- Penetration depth of radar soundings is inversely proportional to frequency
  \[ D_{\text{penetration}} \sim 1/f_{\text{radar}} \]
- To traverse the ionosphere, the signal frequency must be greater than the peak ionospheric electron plasma frequency which is determined by $n_e^{\text{max}}$
  \[ f_{\text{radar}} > f_p^{\text{max}} \sim \sqrt{n_e^{\text{max}}} \]
- Therefore, penetration depth is limited by the maximum electron density;
  \[ D_{\text{penetration}} \sim 1/\sqrt{n_e^{\text{max}}} \]
- Dispersion, attenuation, & Faraday rotation of radar signals related to TEC
  \[ \rightarrow \text{times of smallest } n_e^{\text{max}} = \text{times of largest TEC} \]

\[ \Rightarrow \text{It is important to know not only where (geographically) but also when (season and solar cycle) } n_e^{\text{max}} \text{ and TEC are optimal to enable deep subsurface soundings} \]