Horizontal Gradients in the Nighttime Ionosphere of Mars and Their Electromagnetic Consequences

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

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# Outline

## Introduction
- Magnetic environment of nighttime ionosphere
- Previous observations: *In-situ* (precipitating electrons)
  - Radio occultation/Radar
- Previous modeling
- Goals and methodology

## Results!
- Nighttime ionospheric electron density
- Ratios of gyro to collision frequencies
- Horizontal plasma pressure gradients

## Consequences
- Currents, electric fields, Joule heating
Summary

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

• This patchy distribution of ionization leads to large horizontal gradients in plasma pressure, $\nabla(nkT)$, which can drive plasma motion

• At altitudes where ions are collisionally coupled to the neutral atmosphere while electrons are not, plasma pressure gradients (and neutral winds) can drive an ionospheric dynamo

  $\rightarrow$ horizontal currents, electric fields, Joule heating
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**
• Global distribution of peaked spectra (d\(j/dE > 0\)) 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^{max} (cm^{-3})</th>
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<tbody>
<tr>
<td>Radio occultation (RO) profiles</td>
<td></td>
</tr>
<tr>
<td>Mars 4 [Savich et al., 1976]</td>
<td>4.7 x 10^3</td>
</tr>
<tr>
<td>Viking 1 &amp; 2 [Zhang et al., 1990]</td>
<td>5 x 10^3</td>
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<td>(in all cases, solar zenith angle (SZA) ≤ ~ 125°)</td>
<td></td>
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<tr>
<td>Mars Express MARSIS Active Ionospheric Sounder (AIS) [Kirchner et al., 2006, 2007]</td>
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<tr>
<td>Non-magnetic regions (typical)</td>
<td>8 x 10^3</td>
</tr>
<tr>
<td>Magnetic regions (typical)</td>
<td>5 x 10^4</td>
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<td>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</td>
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# Models of Night Side Ionosphere

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

- ne\(_{\text{max}}\) 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

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- $n_e^{\text{max}}$ due to accelerated spectrum is $\sim 3 \times$ typical tail spectrum value
- Latitudinal width of enhanced ionization $\sim 200$ km
  $\Rightarrow$ Consistent with observed small-scale ionospheric structure
Goal & Methodology

• Large horizontal plasma pressure gradients are expected in the nighttime ionosphere due to the close proximity of magnetic cusps and plasma voids
  ➔ *What are the magnitudes of these gradients? and*
  ➔ *How do these gradients affect the ionospheric electrodynamics?*

• Calculate ionospheric electron density as a function of altitude and latitude using, as input, MGS observations coupled to an electron transport model – Mars Discrete Ordinante Transport (MDOT) Code
  • modification of multi-stream code of *Lummerzheim & Lilensten* [1994]
  • uses discrete-ordinante method to solve electron transport problem

• The electron density is determined from
  \[ n_e(z) = \sqrt{P(z)/\alpha_{\text{eff}}(z)} \text{ cm}^{-3}, \]
  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,
  \[ \alpha_{\text{eff}}(z) = O_2^+ \text{ recombination rate} = 1.95 \times 10^{-7} \left(300/T_e(z)\right)^{0.7} \text{ cm}^3 \text{ s}^{-1}, \]
  where \( T_e \) is the electron temperature

**Assume:** *all ions are \( O_2^+ \) and electron temperature = neutral temperature*
Neutral Atmosphere Profile (MTGCM)

[Bougher et al., 1999, 2000]

- Includes CO$_2$, CO, O$_2$, O, & N$_2$ (and Ar – but not included in transport model)
- Profile from 2.5° N at 3 AM LT under solar medium conditions at equinox
- Extrapolate above 250 km: assume diffusive equilibrium & isothermal profile
Electron Density

Electron energy flux spectrogram observed by MGS at 400 km altitude at 2 AM local time moving north to south.

Use electron data as input at upper boundary…
Electron Density

Electron energy flux spectrogram observed by MGS at 400 km altitude at 2 AM local time moving north to south.

Use electron data as input at upper boundary...

Modeled electron density as a function of altitude and latitude.

Peak $n_e^{\text{max}} = 3.1 \times 10^4 \text{ cm}^{-3}$

Peak TEC = $1.4 \times 10^{15} \text{ m}^{-2}$ = 0.14 TECU

> 10% of dayside values
Ionospheric Electrodynamics

Ratio of gyrofrequency to collision frequency, $f = \frac{\Omega}{\nu}$

For electrons,

$$f_e = \frac{\Omega_e}{\nu_{en}} \sim \frac{|B|}{n_n T_e^\alpha},$$

where $\alpha \approx 0.5 - 3$ depending upon neutral species

For ions ($O_2^+$ in this case),

$$f_i = \frac{\Omega_i}{\nu_{in}} \sim \frac{|B|}{n_n}$$

$f < 1$: collisions dominate

$f > 1$: magnetic field effects dominate

$f_e = 1$ at about 110 km

$f_i = 1$ at about 160 km
The altitude range where ions are collisionally coupled to the atmosphere but electrons are not coincides with the peak in ionospheric density:

\[ j = ne(v_i - v_e) \]

Since plasma density, \( n \), and \( (v_i - v_e) \) are large in this region, currents should also be large.
From the computed electron density \((n_i = n_e)\) and assumed temperature profile \((T_n = T_i = T_e)\), compute the horizontal plasma pressure gradient force, \(-1/n \nabla(nkT)\) (positive values point left)

Significant structure at low altitude (< 100 km); 
\(n_e\) is low – little electrodynamic impact

Largest gradients near cusp-void interfaces
Consequences: Ionospheric Currents

- To determine ionospheric currents, start with simplified momentum equation assuming steady state conditions and all forces in equilibrium:

Ions: \[-1/n_i \nabla (n_i kT_i) + m_i g + e(E + \mathbf{V}_i \times \mathbf{B}) - m_i \nu_{in}(\mathbf{v}_i - \mathbf{u}) = 0\]
Electrons: \[-1/n_e \nabla (n_e kT_e) + m_e g - e(E + \mathbf{V}_e \times \mathbf{B}) - m_e \nu_{en}(\mathbf{v}_e - \mathbf{u}) = 0\]

- First, consider only the pressure gradient term:
  let \( \nabla \rightarrow d/dx \); ignore \( E, u \); and assume \( B = B_Z \)

- Then,
  \[v_{ix} = -1/n_i \nabla (n_i kT_i) \nu_{in}/m_i(\Omega^2_i + \nu_{in}^2); \quad v_{iy} = -(\Omega_i/\nu_{in}) v_{ix}\]
  \[v_{ex} = -1/n_e \nabla (n_e kT_e) \nu_{en}/m_i(\Omega^2_e + \nu_{en}^2); \quad v_{ey} = (\Omega_i/\nu_{in}) v_{ex}\]

- By using
  \[j = ne(\mathbf{v}_i - \mathbf{v}_e)\]
  we can compute \( j_x \) and \( j_y \)...
Current Density due to $\nabla P$

X- (top) and Y- (bottom) components of ionospheric currents driven by latitudinal pressure gradients

Largest gradients occur at cusp-void interfaces; hence, largest currents found in these regions

Currents flow toward low density voids and outward from high density cusps

Longitudinal currents flow along cusp boundaries
Current Density due to Neutral Winds

X- (top) and Y- (bottom) components of currents driven by latitudinal neutral wind:
\[ u_x = 100 \text{ m/s northward} \]

In high density regions, ion drag leads to large northward currents (~ 100 times larger than \( \nabla P \) currents)

In these same regions, longitudinal (Hall-like) currents flow as electrons drift in the \(-F \times B\) direction where
\[ F = F_x = m v_{e,n} u_x \]
Current Density due to Neutral Winds

X- (top) and Y- (bottom) components of currents driven by longitudinal neutral wind:

\[ u_y = 100 \text{ m/s} \textbf{westward} \]

Again, ion drag leads to large westward currents, \( j_y \)

Now, latitudinal (Hall-like) currents flow outward away from void (or inward toward void depending upon orientation of \( \mathbf{B} \))
Summary

• Using MGS data as input to an electron transport model, we have calculated the nighttime ionospheric electron density as a function of altitude and latitude over strong field regions (cusps and voids)

• Horizontal plasma pressure gradients are a result of spatially inhomogeneous magnetic field structure and spatially inhomogeneous precipitating electron energy spectra

• In regions where ions are collisionally coupled to the atmosphere while the electrons are not, these gradients drive ionospheric currents

• Horizontal winds also generate (much larger) horizontal currents
  ➔ Small scale $\mathbf{B}$ structure $\rightarrow$ small scale ionization $\rightarrow$ small scale currents

• These currents will generate polarization electric fields; also external magnetospheric electric fields may be imposed (like at Earth)

• Where $\mathbf{J} \cdot \mathbf{E} > 0$, Joule heating can locally modify atmospheric dynamics and chemistry in the ionosphere/thermosphere/exosphere system
Things We Have Not Addressed

• Electron transport model does not include magnetic gradients; assumes magnetic field lines are straight with a constant dip angle and magnitude
  → Bad assumptions at Mars (plan to incorporate Monte-Carlo code that includes realistic magnetic field profiles)

• Calculations assume $T_n = T_i = T_e$
  → Not too unreasonable at low altitudes where collisions are common; unreasonable at high altitudes where typically $T_n < T_i < T_e$
  → Underestimate $n_e$, $\nabla P$, $v_{en}$, and $j$ at high altitude

• So far, we have neglected effects of polarization and external electric fields
• We have not considered parallel current (= divergence of horizontal current)
• Ionospheric currents can modify magnetic field [Withers et al., 2005]
• What is needed to more adequately address these problems?
  → More complete, self-consistent, 2.5- to 3-D model of the electrodynamics of the nighttime ionosphere of Mars (under development)