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

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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

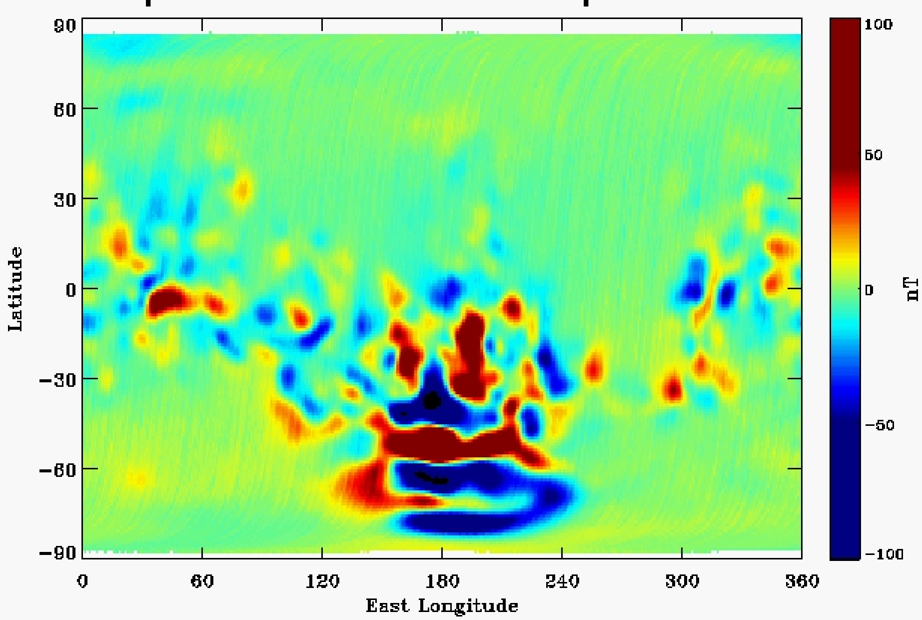
Summary

- 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
  → horizontal currents, electric fields, Joule heating

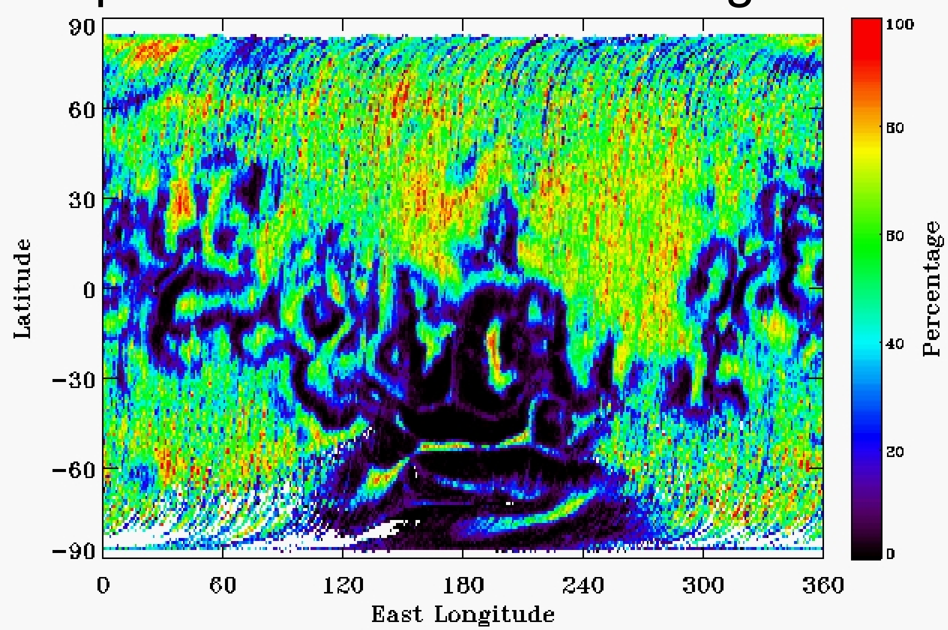
Martian Magnetic Field and Cusps

- 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”

Map of the radial component of B

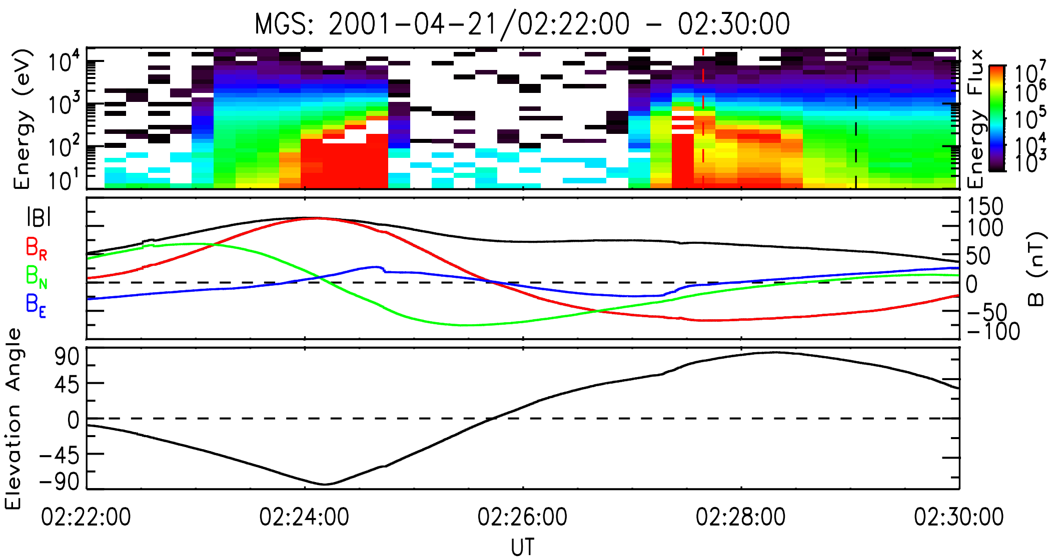


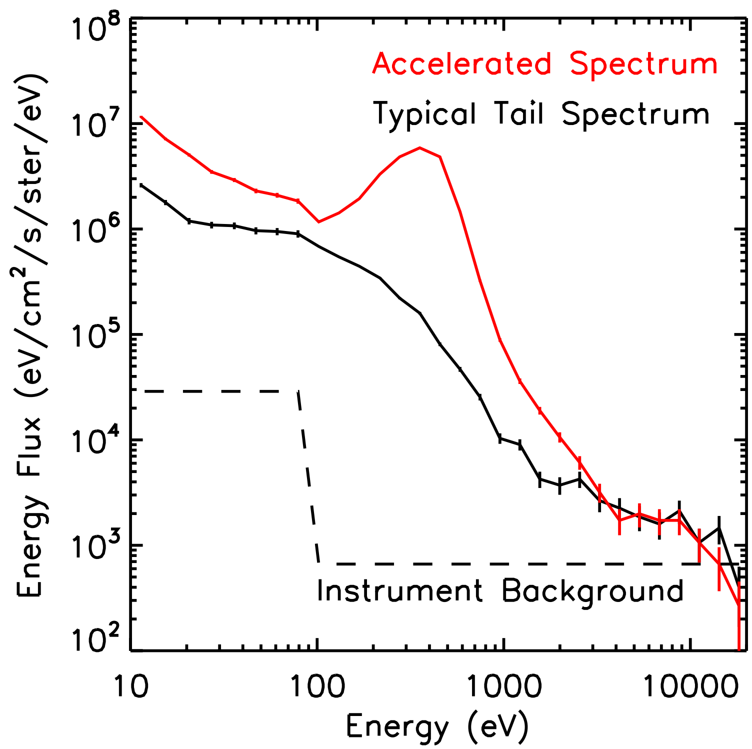
Map of the probability of observing upward loss cones on the nightside

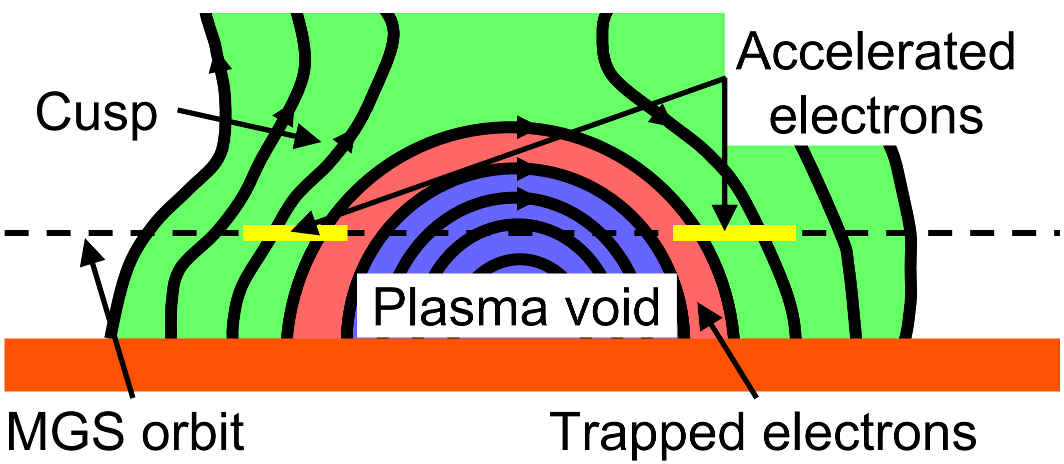


Accelerated (Auroral) Electrons

(from *Brain et al.* [2006])

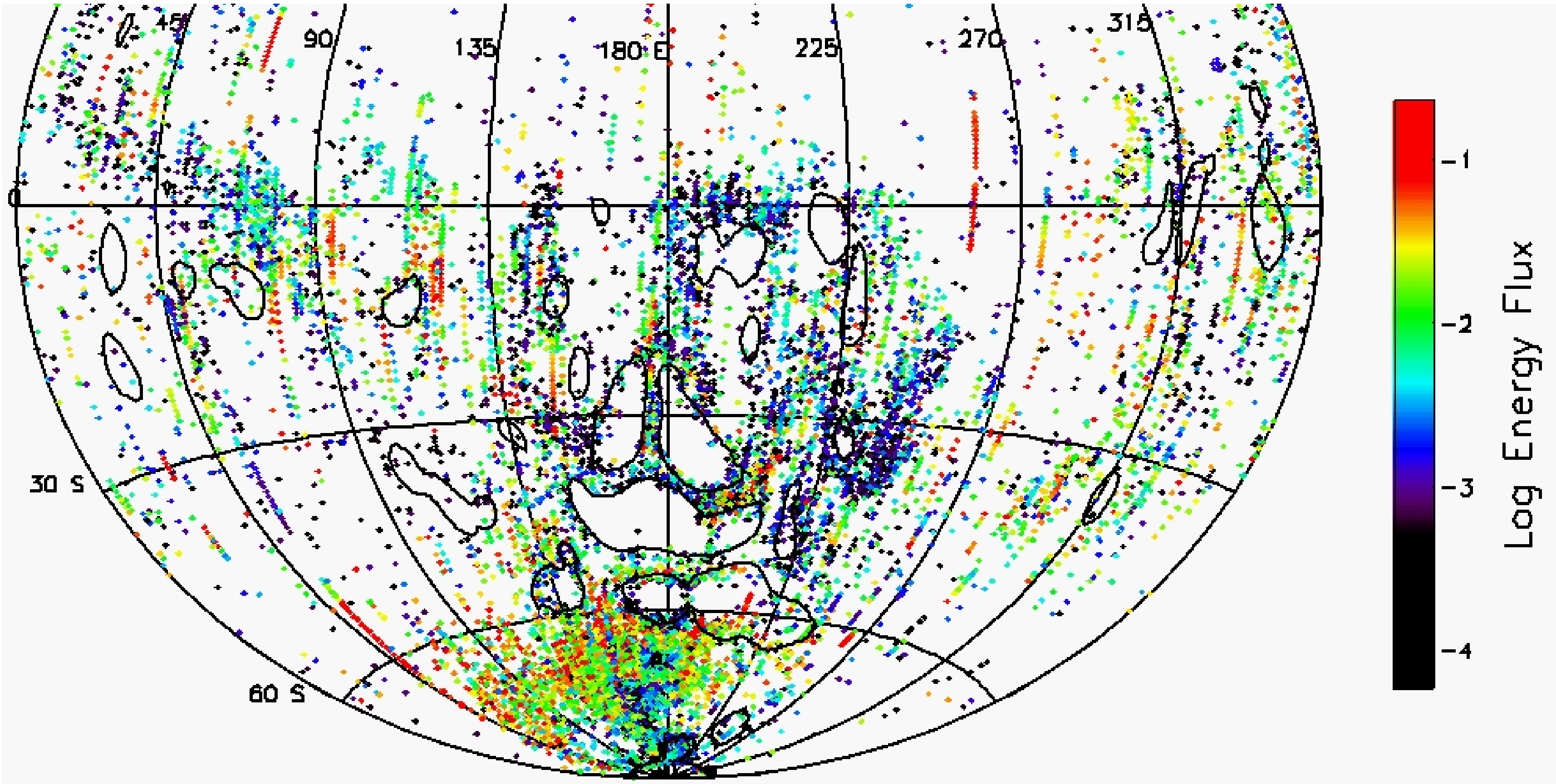






- MGS at 400 km at SZA ~ 125°
- Downward energy flux for **accelerated spectrum** 10 X greater than that for **typical tail spectrum**

Distribution of Accelerated Electrons



- 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

	n_e^{max} (cm^{-3})	Altitude of n_e^{max} (km)
• Radio occultation (RO) profiles		
• Mars 4 [*Savich et al.*, 1976]	4.7×10^3	110
• Viking 1 & 2 [*Zhang et al.*, 1990]	5×10^3	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)	8×10^3	175
• Magnetic regions (typical)	5×10^4	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

	n_e^{max} (cm^{-3})	Altitude of n_e^{max} (km)
• High altitude (~ 10,000 km) Phobos 2 HARP spectra		
• Magnetotail lobe [*Verigin et al.*, 1991]	7×10^3	165
• Magnetotail lobe [*Haider et al.*, 1992]	1.2×10^4	158
• Plasma sheet [*Haider et al.*, 1992]	1.7×10^4	144
• 20 eV Maxwellian [*Fox et al.*, 1993]	1.4×10^4	172
• 180 eV Gaussian [*Fox et al.*, 1993]	1.9×10^4	159
• Low altitude (~400 km) MGS MAG/ER spectra		
• Solar wind (< 1 keV) [*Haider et al.*, 2002]	5×10^3	140
• Typical tail [*Fillingim et al.*, 2007]	1.7×10^3	166
• Accelerated [*Fillingim et al.*, 2007]	5.7×10^3	156

- n_e^{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

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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

$$\mathbf{n_e(z) = \sqrt{(P(z)/\alpha_{eff}(z))}\ cm^{-3}},$$

  where **P(z)** is the ion production rate and $\boldsymbol{\alpha_{eff}}$**(z)** is the recombination rate

- Since O_2^+ is the dominant ionospheric ion due to rapid chemical reactions,

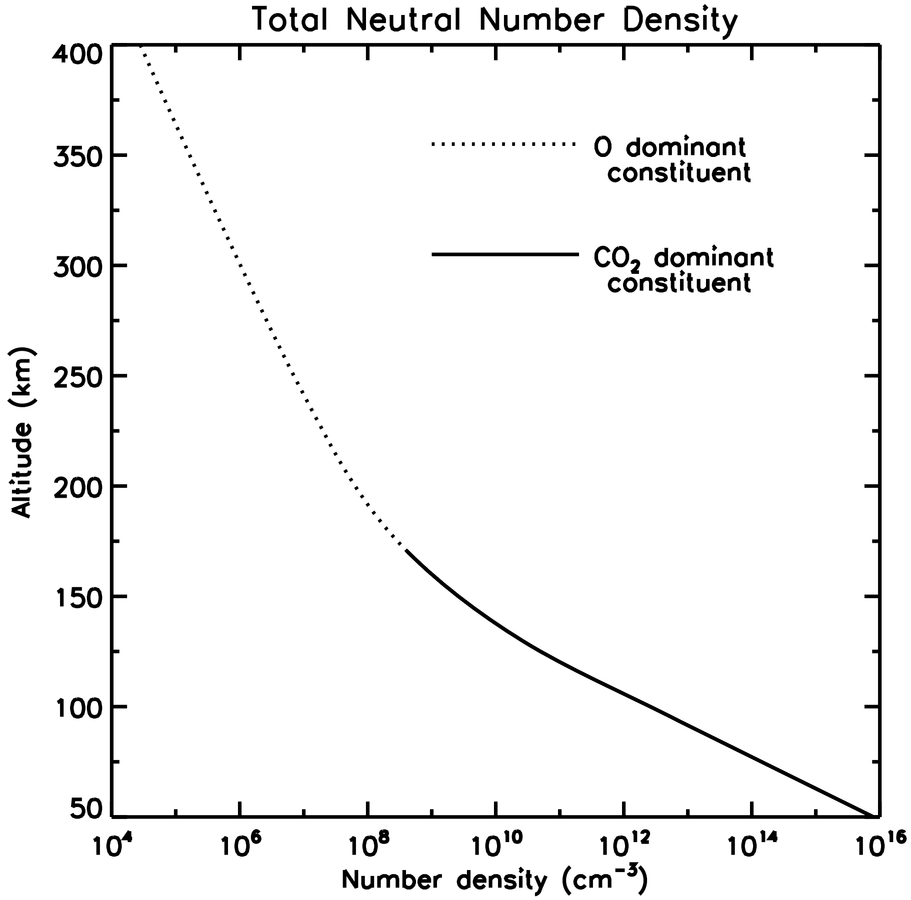
$$\boldsymbol{\alpha_{eff}(z)} = O_2^+ \text{ recombination rate} = \mathbf{1.95 \times 10^{-7}\ (300/T_e(z))^{0.7}\ cm^3\ s^{-1}},$$

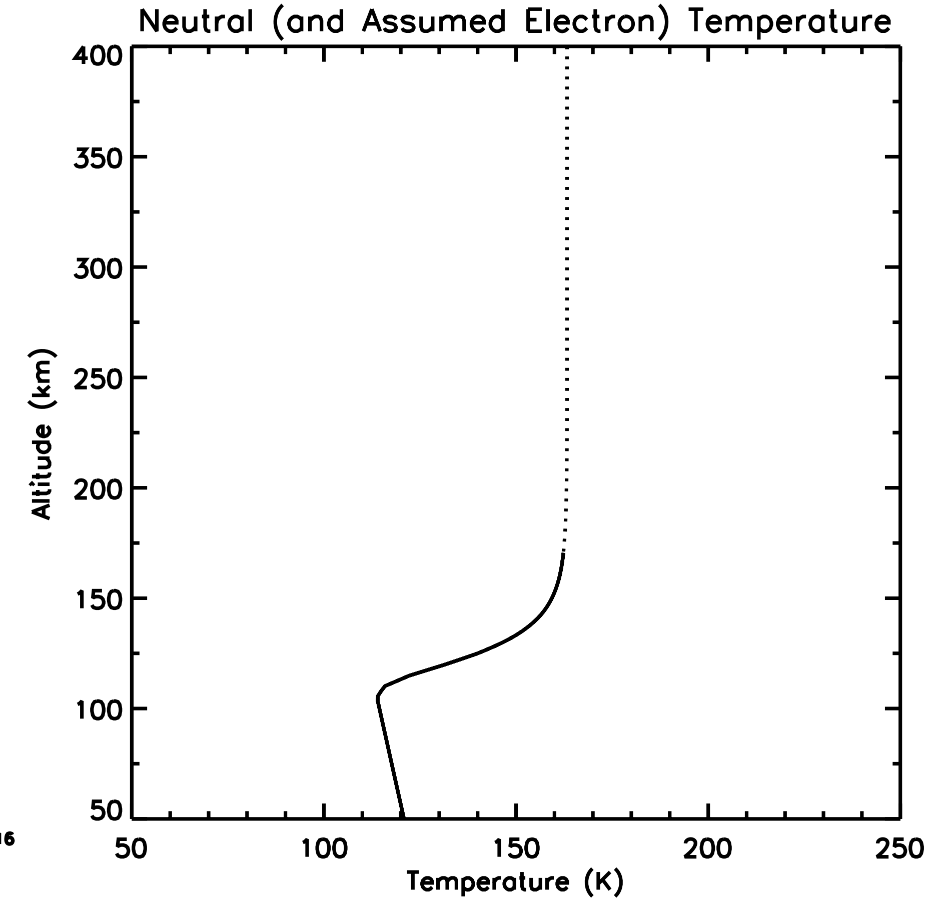
  where $\mathbf{T_e}$ is the electron temperature

Assume: ***all ions are*** O_2^+ and ***electron temperature = neutral temperature***

Neutral Atmosphere Profile (MTGCM)

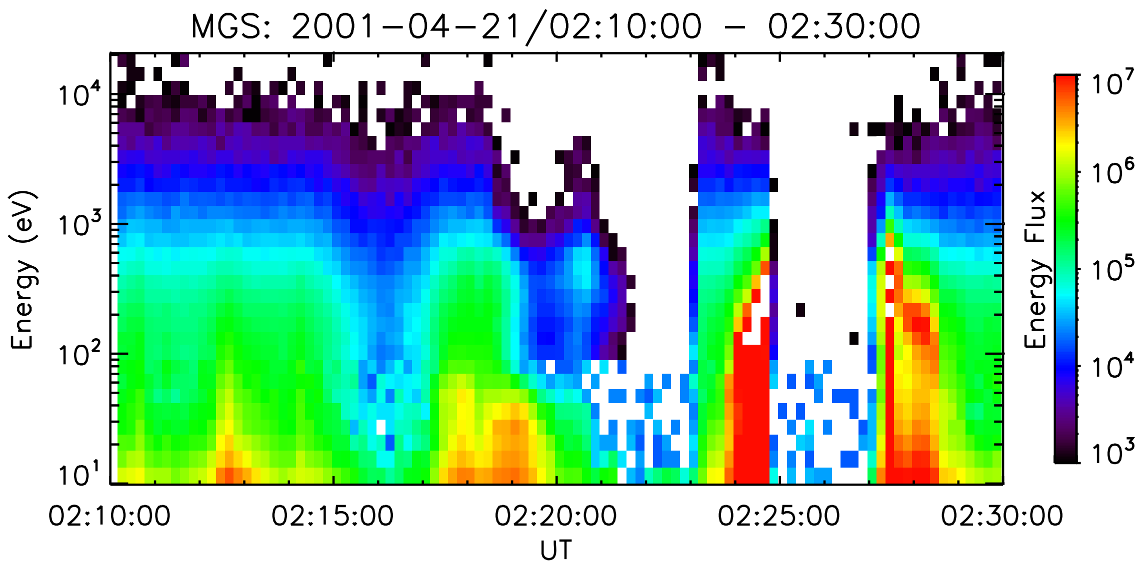
[*Bougher et al.*, 1999, 2000]





- 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

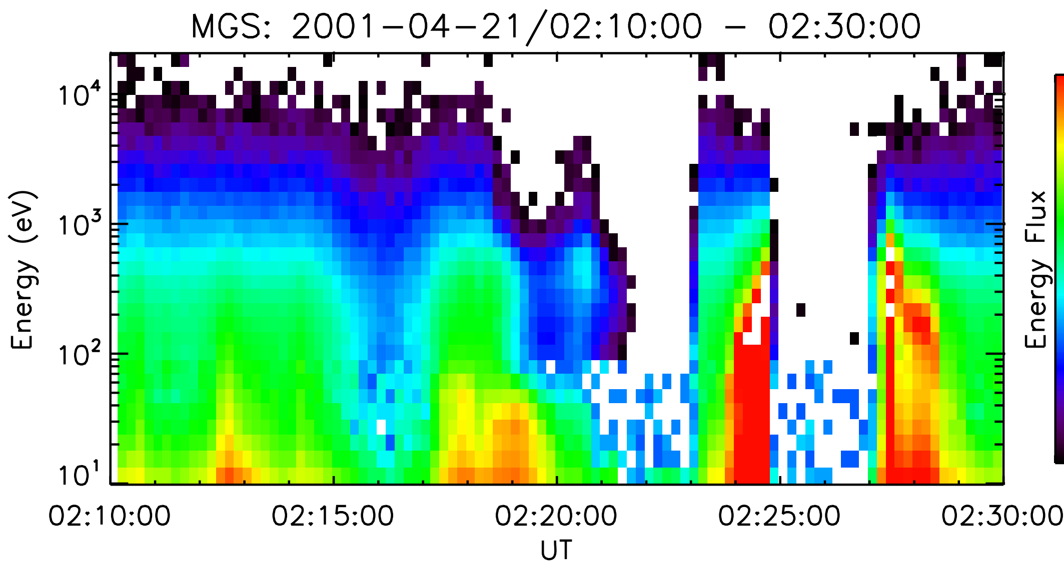
Electron Density



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



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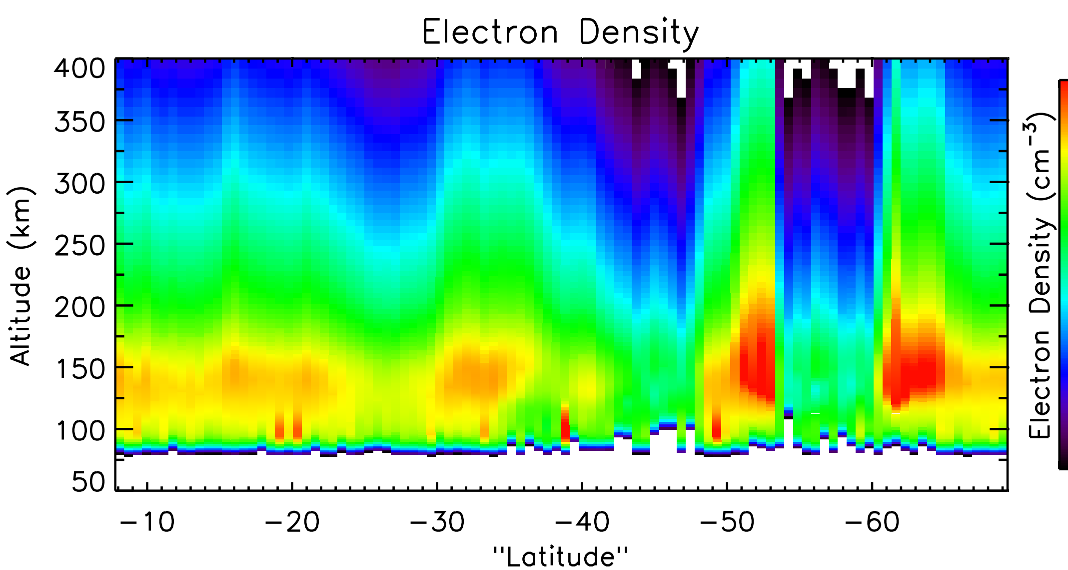


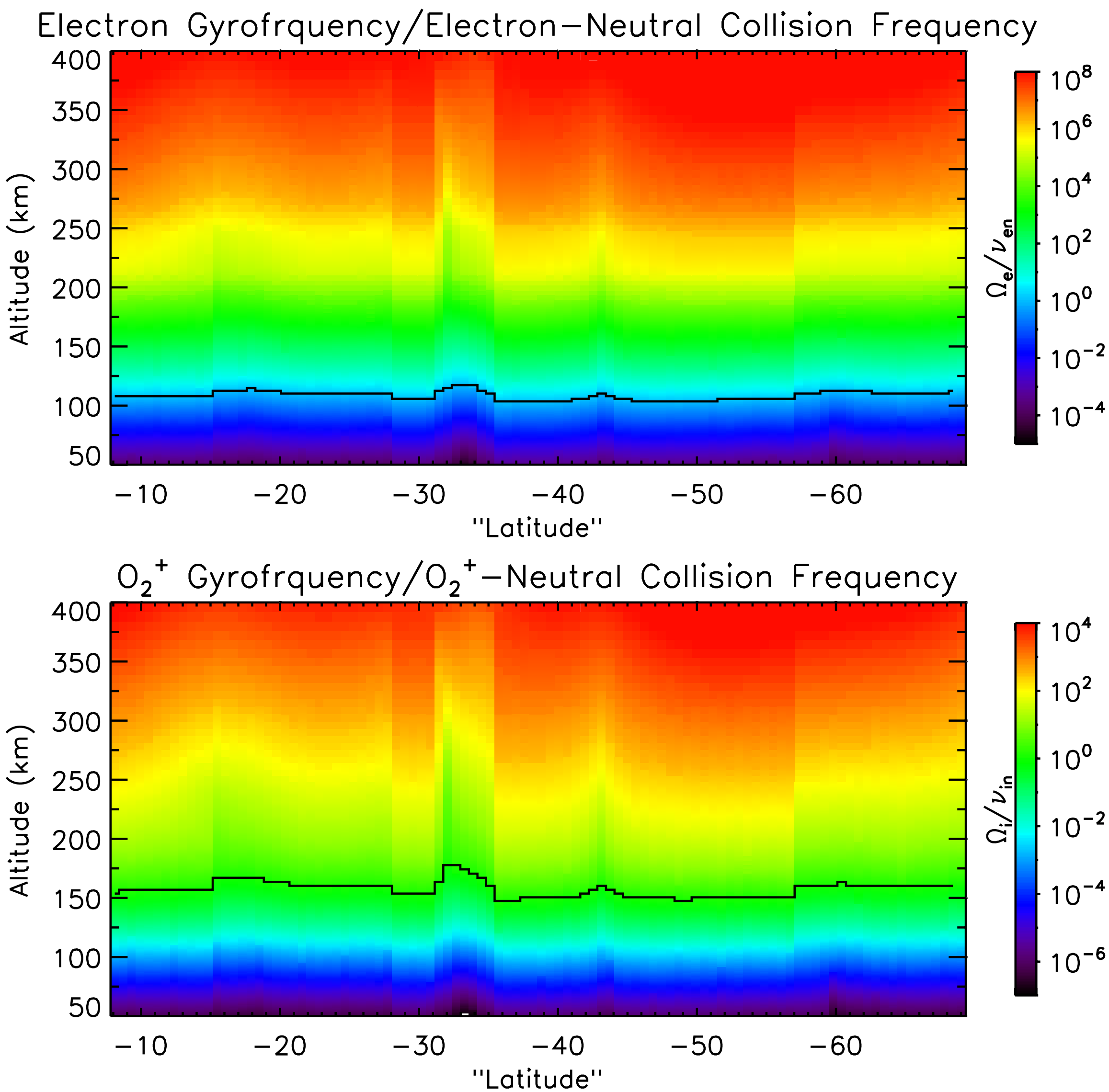
Modeled electron density as a function of altitude and latitude

Peak $n_e^{max} = 3.1\times10^4$ cm^{-3}

Peak TEC = 1.4×10^{15} m^{-2} = 0.14 TECU

> 10% of dayside values

Ionospheric Electrodynamics



Ratio of gyrofrequency to collision frequency, $f = \Omega/\nu$

For electrons,
$f_e = \Omega_e/\nu_{en} \sim |\mathbf{B}|/n_n/T_e^{\alpha}$,
where $\alpha \approx 0.5 – 3$
depending upon neutral species

For ions (O_2^+ in this case),
$f_i = \Omega_i/\nu_{in} \sim |\mathbf{B}|/n_n$

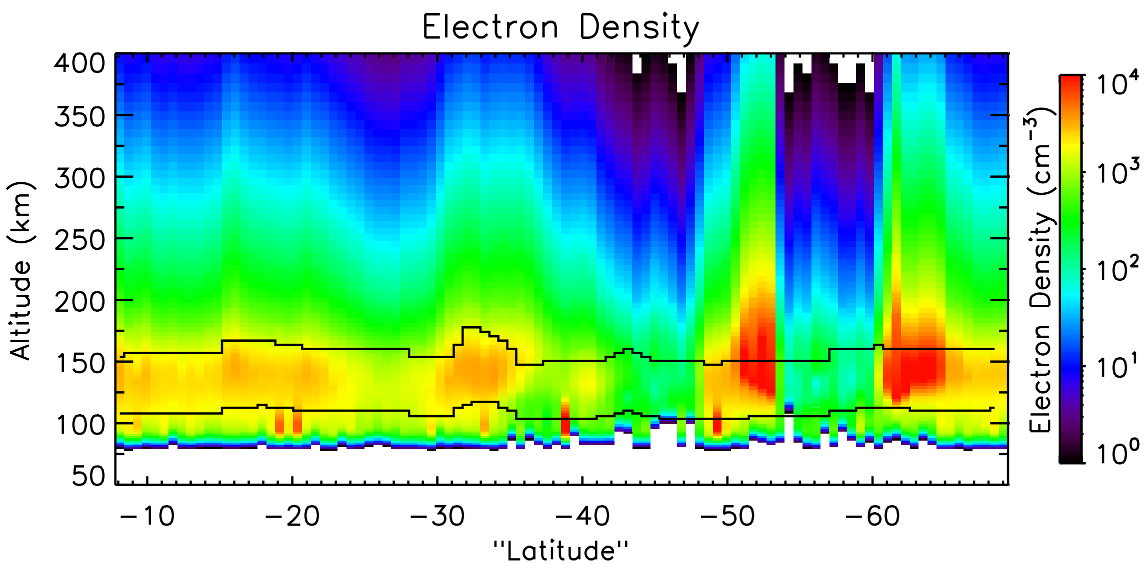
$f < 1$: collisions dominate

$f > 1$: magnetic field effects dominate

$f_e = 1$ at about 110 km

$f_i = 1$ at about 160 km

Ionospheric Electrodynamics

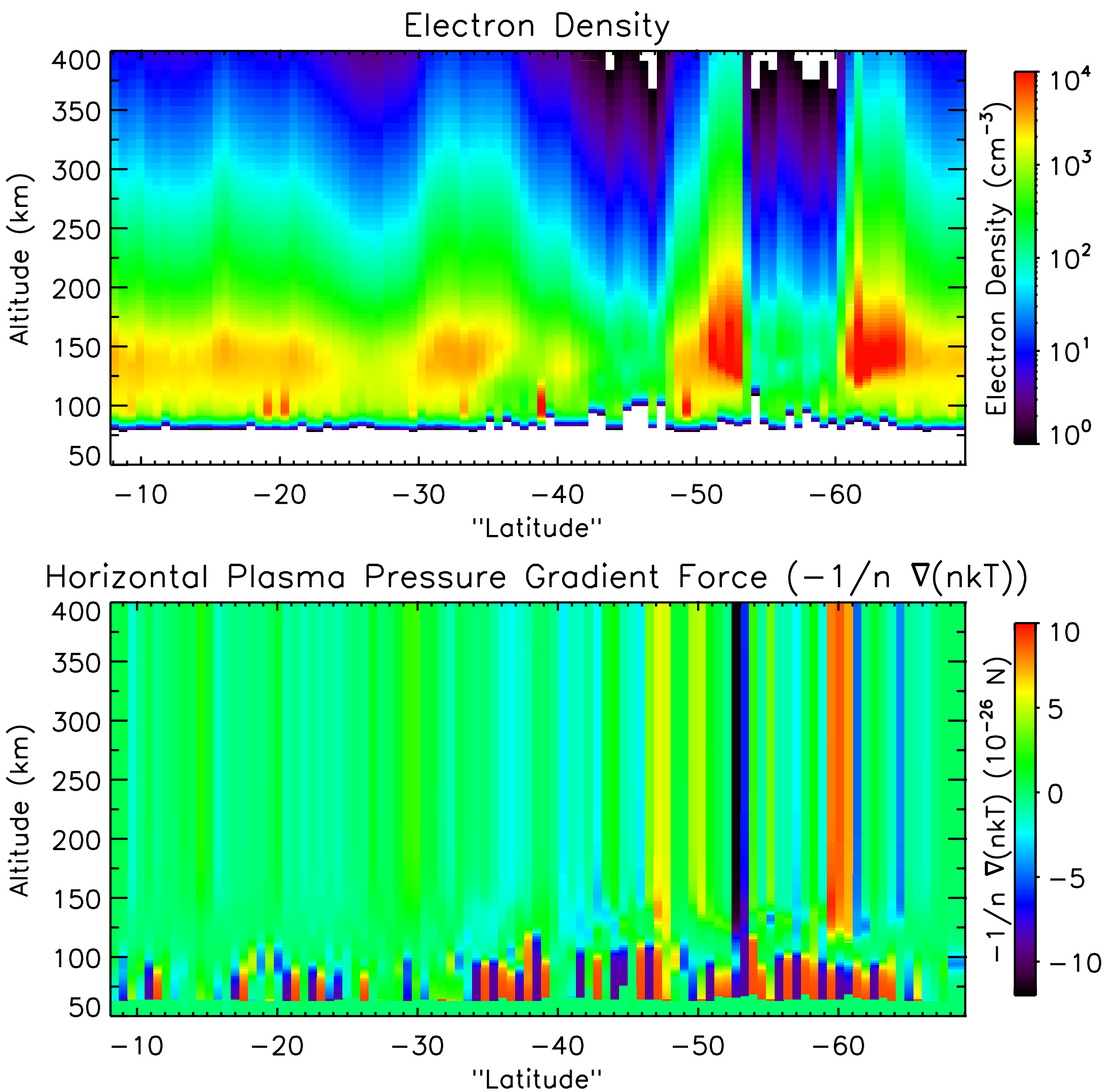


The altitude range where ions are collisionally coupled to the atmosphere but electrons are not coincides with the peak in ionospheric density

current density:
$\mathbf{j} = ne(\mathbf{v}_i - \mathbf{v}_e)$

Since plasma density, n, and $(\mathbf{v}_i - \mathbf{v}_e)$ are large in this region, **currents should also be large**

Plasma Pressure Gradient



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: $-1/n_i \nabla(n_i k T_i) + m_i \mathbf{g} + e(\mathbf{E} + \mathbf{V}_i \times \mathbf{B}) - m_i \nu_{in}(\mathbf{v}_i - \mathbf{u}) = 0$

Electrons: $-1/n_e \nabla(n_e k T_e) + m_e \mathbf{g} - e(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) - m_e \nu_{en}(\mathbf{v}_e - \mathbf{u}) = 0$

- First, consider only the pressure gradient term:

let $\nabla \rightarrow d/dx$; ignore **E**, **u**; and assume $\mathbf{B} = B_Z$

- Then,

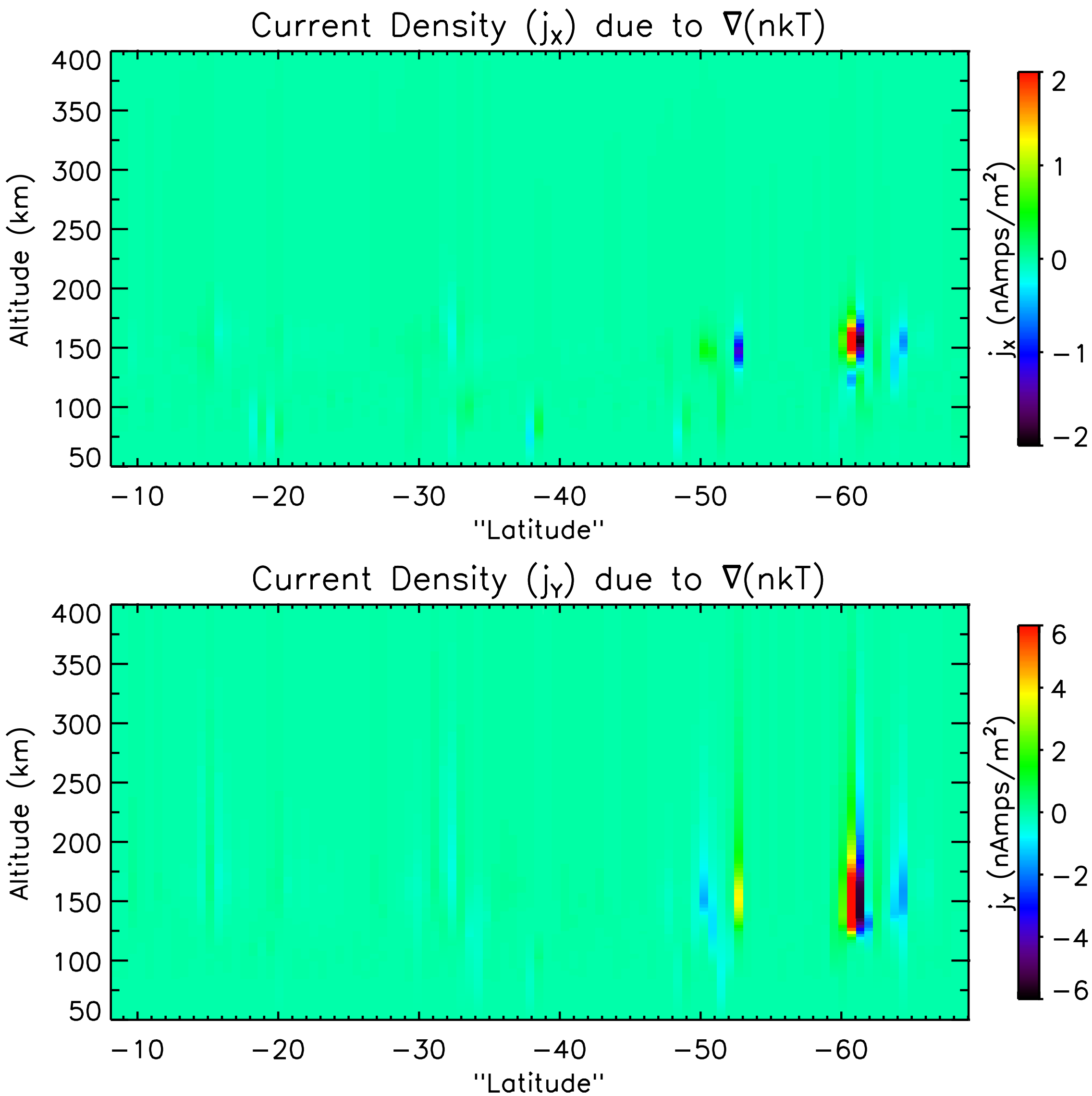
$$v_{ix} = -1/n_i \nabla(n_i k T_i)\, \nu_{in}/m_i(\Omega_i^2 + \nu_{in}^2);\; v_{iy} = -(\Omega_i/\nu_{in})\, v_{ix}$$
$$v_{ex} = -1/n_e \nabla(n_e k T_e)\, \nu_{en}/m_i(\Omega_e^2 + \nu_{en}^2);\; v_{ey} = (\Omega_i/\nu_{in})\, v_{ex}$$

- By using

$$\mathbf{j} = ne(\mathbf{v}_i - \mathbf{v}_e)$$

we can compute j_x and j_y…

Current Density due to ∇P



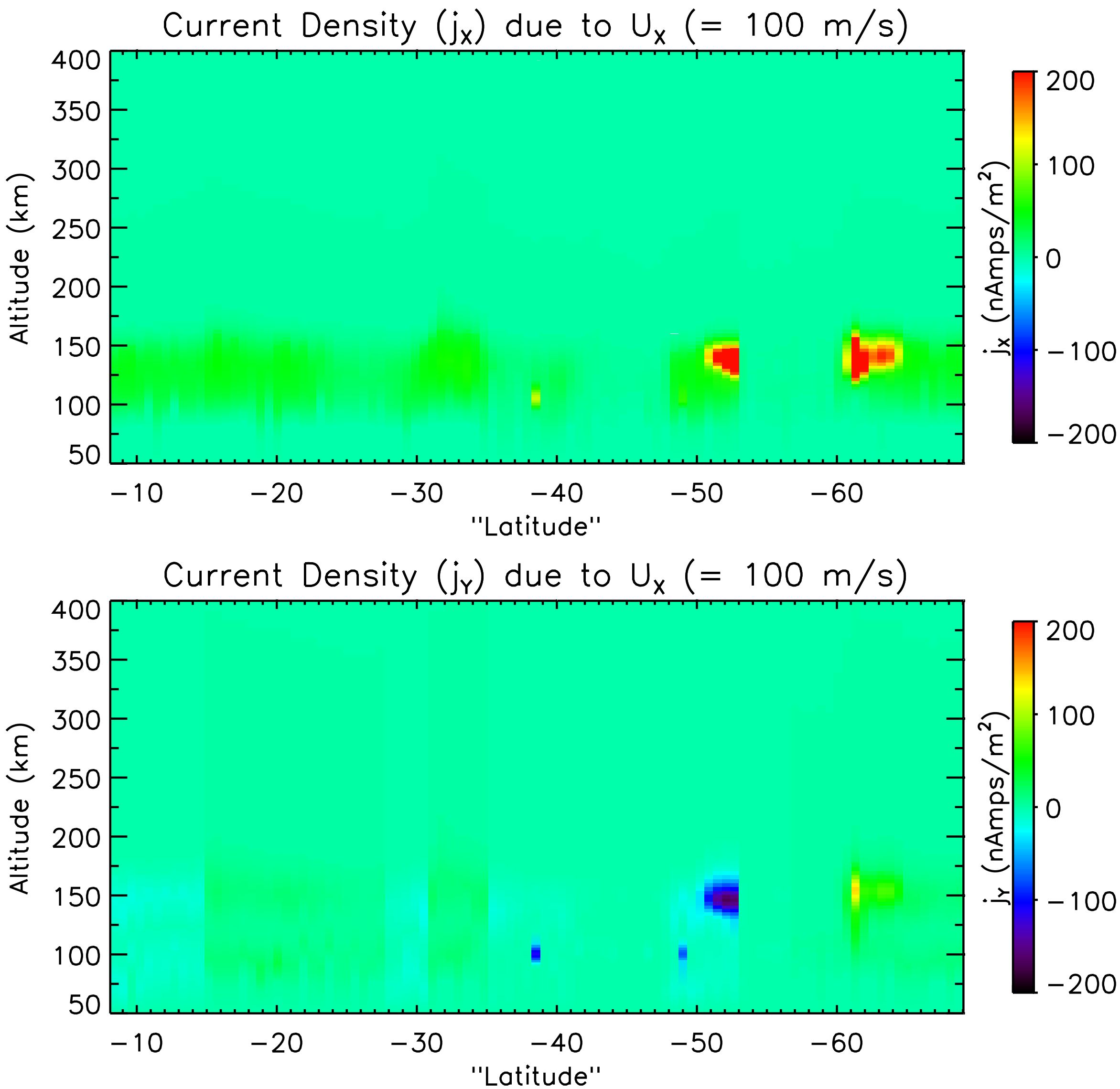
X- (top) and Y- (bottom) components of ionospheric currents driven by latitudinal pressure gradients

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

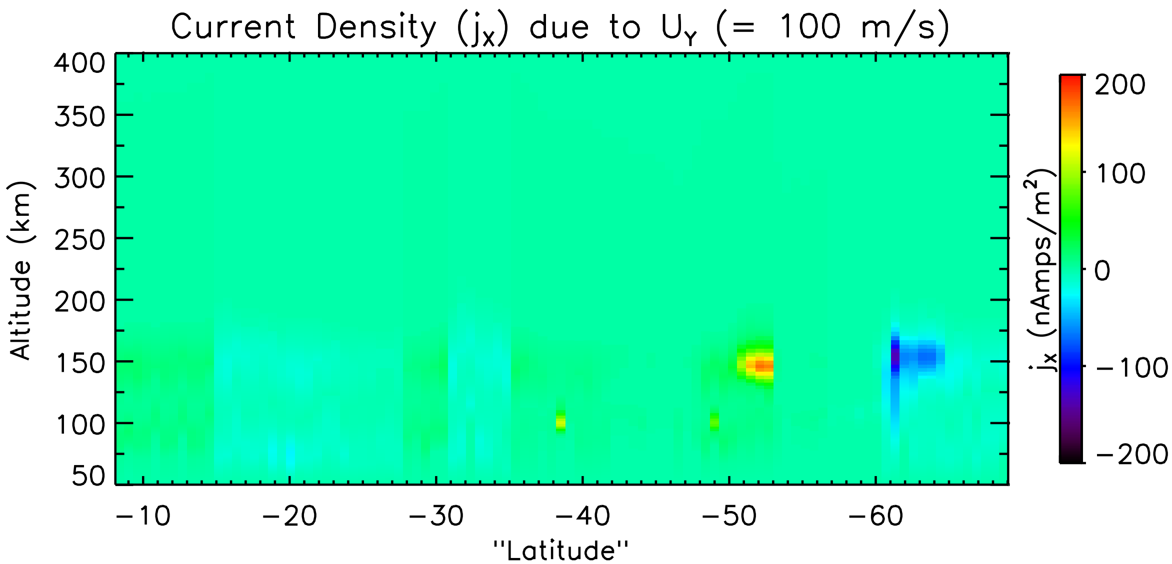


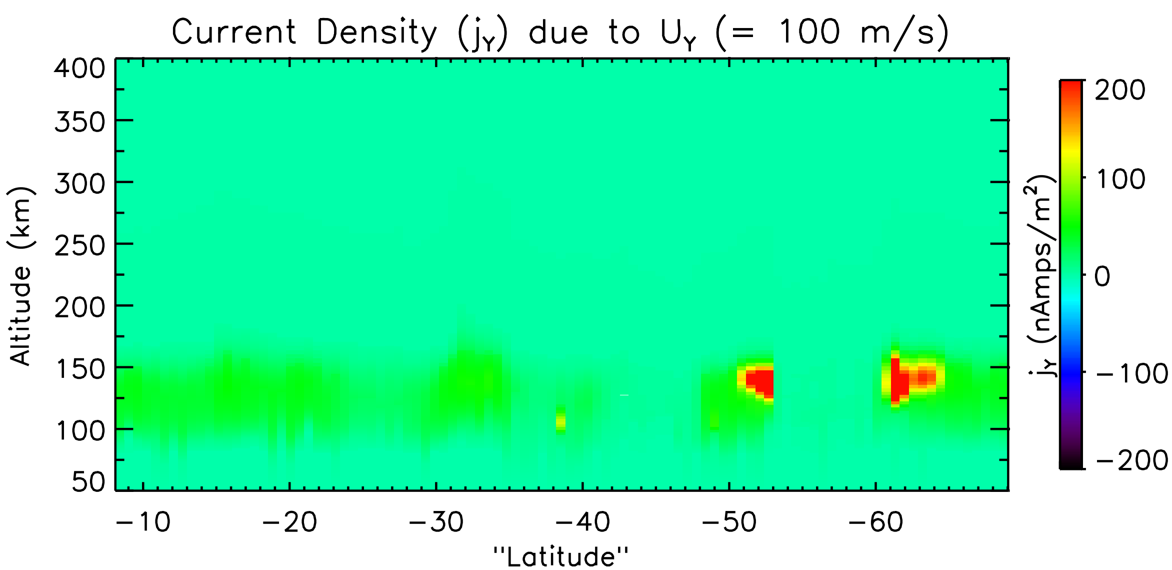
X- (top) and Y- (bottom) components of currents driven by latitudinal neutral wind:
u_x = 100 m/s **northward**

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

In these same regions, longitudinal (Hall-like) currents flow as electrons drift in the –**F** × **B** direction where **F** = $F_x = m\nu_{en}u_x$

Current Density due to Neutral Winds





X- (top) and Y- (bottom) components of currents driven by longitudinal neutral wind:
u_y = 100 m/s **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 **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 **B** structure → small scale ionization → small scale currents

- These currents will generate polarization electric fields; also external magnetospheric electric fields may be imposed (like at Earth)
- Where **J**·**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, ∇P, ν_{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)