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

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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^{max}) and total electron content (TEC) vary considerably with season and solar cycle as the scale height of the atmosphere changes

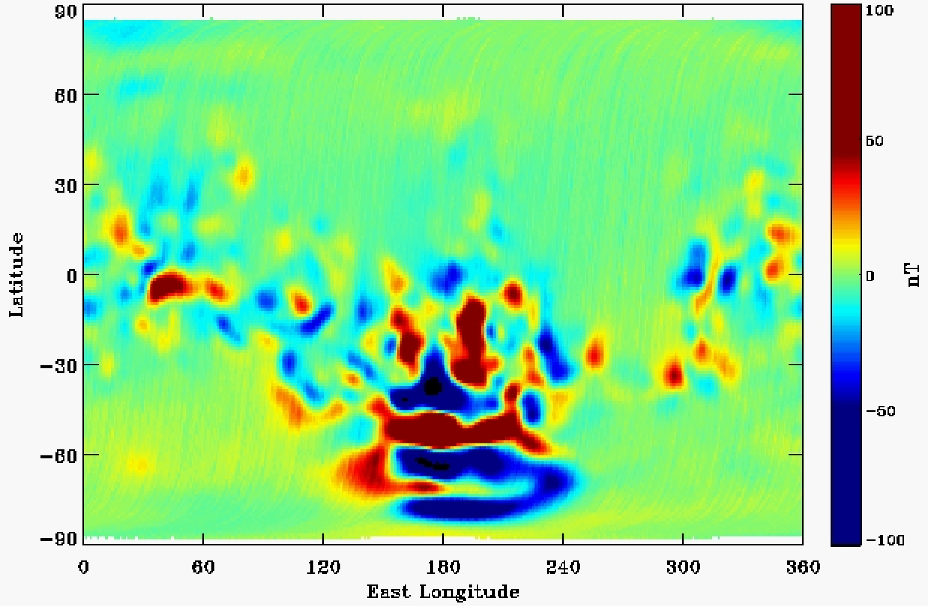
- Both n_e^{max} and TEC impact subsurface science that can be done from orbit:

  higher n_e^{max} → lower penetration depths

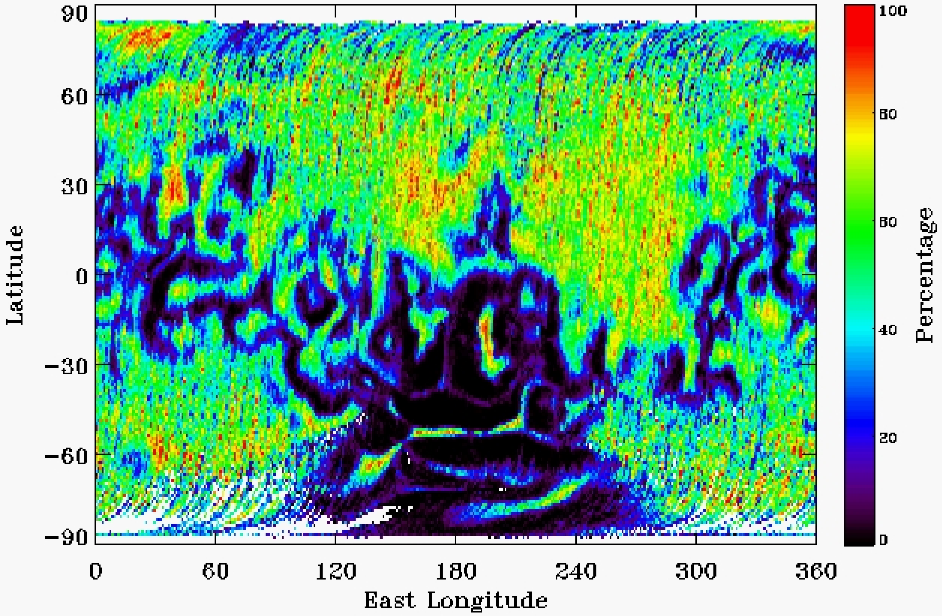
Martian Magnetic Field and Cusps

- 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"

Map of the radial component of B

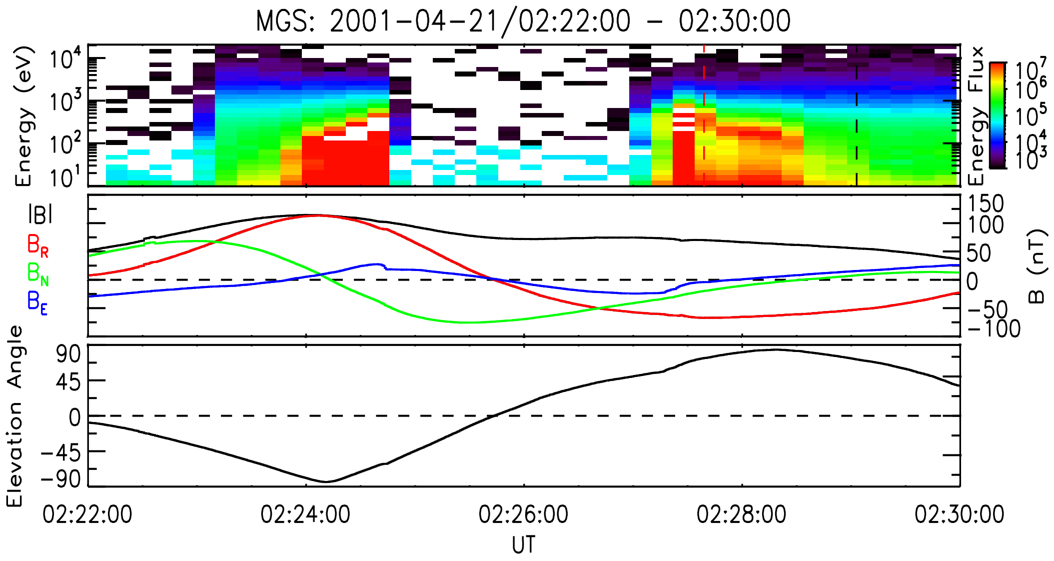


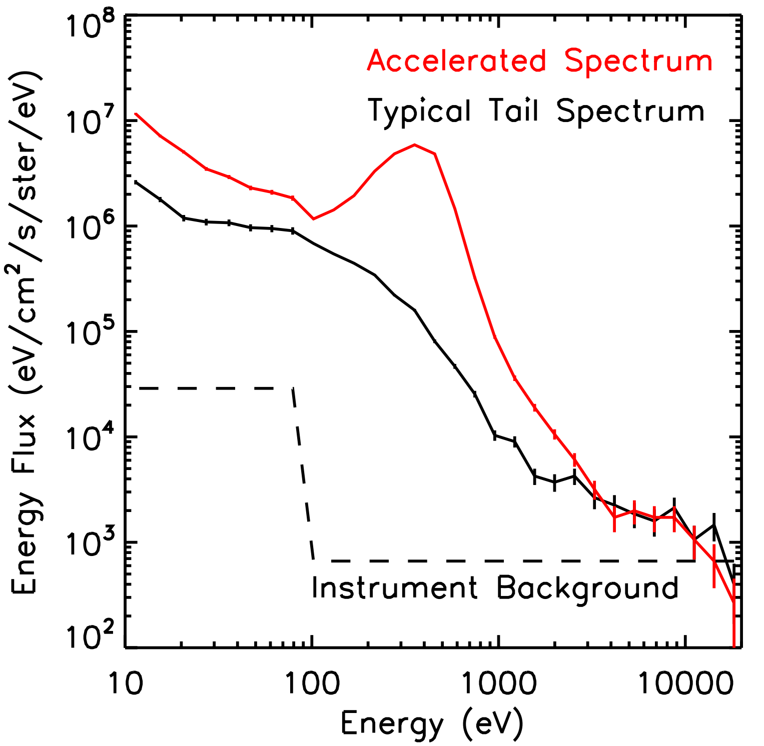
Map of the probability of observing upward loss cones on the nightside

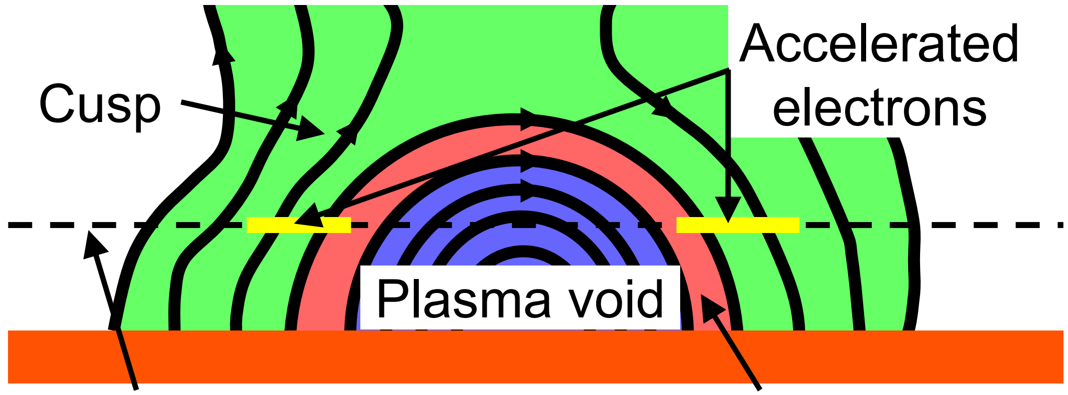


Accelerated (Auroral) Electrons

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

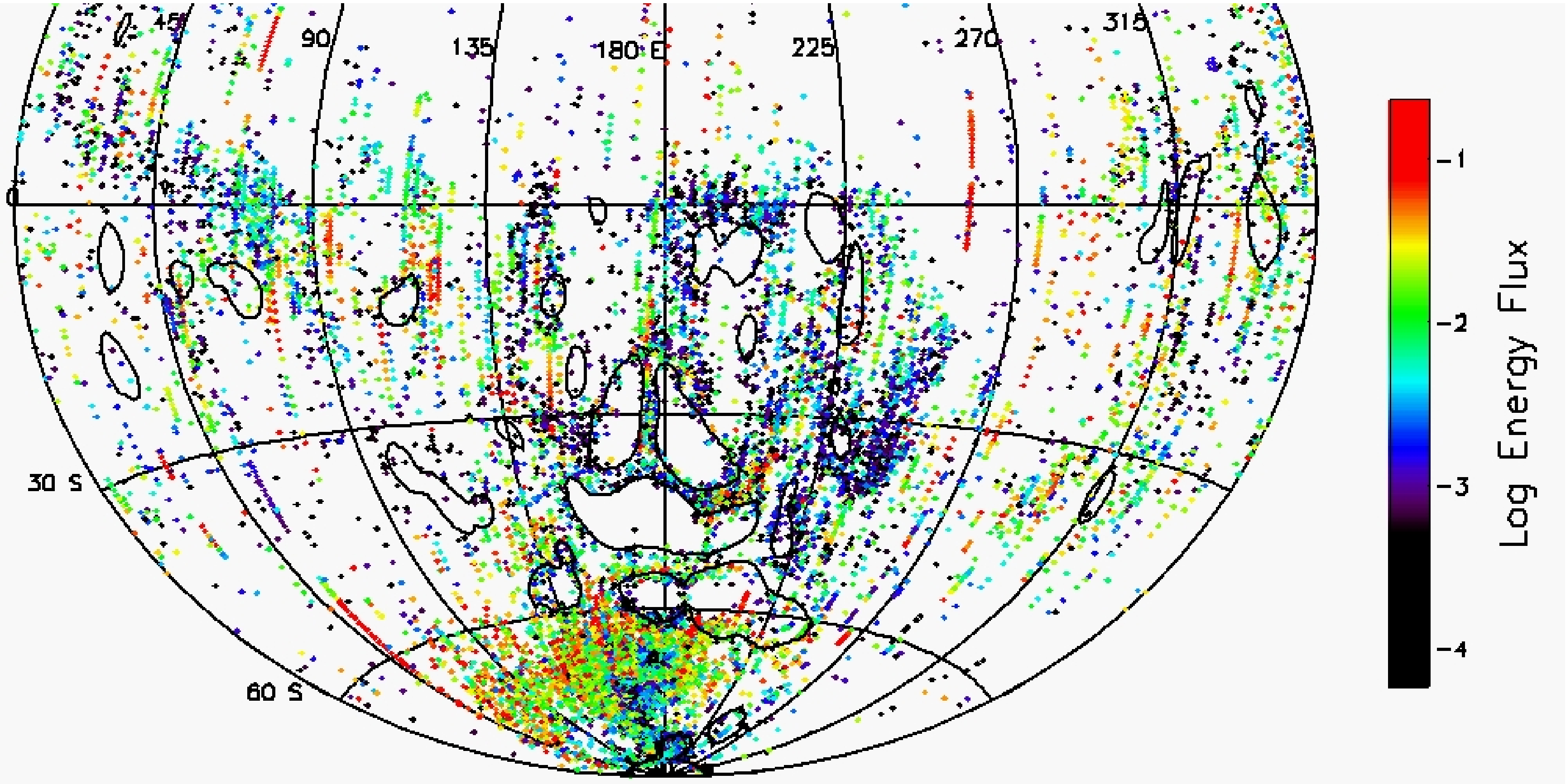






- MGS at 400 km at SZA ~ 125°
- Downward energy flux for **accelerated spectrum** 10 X greater than that for **typical tail spectrum**

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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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

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

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

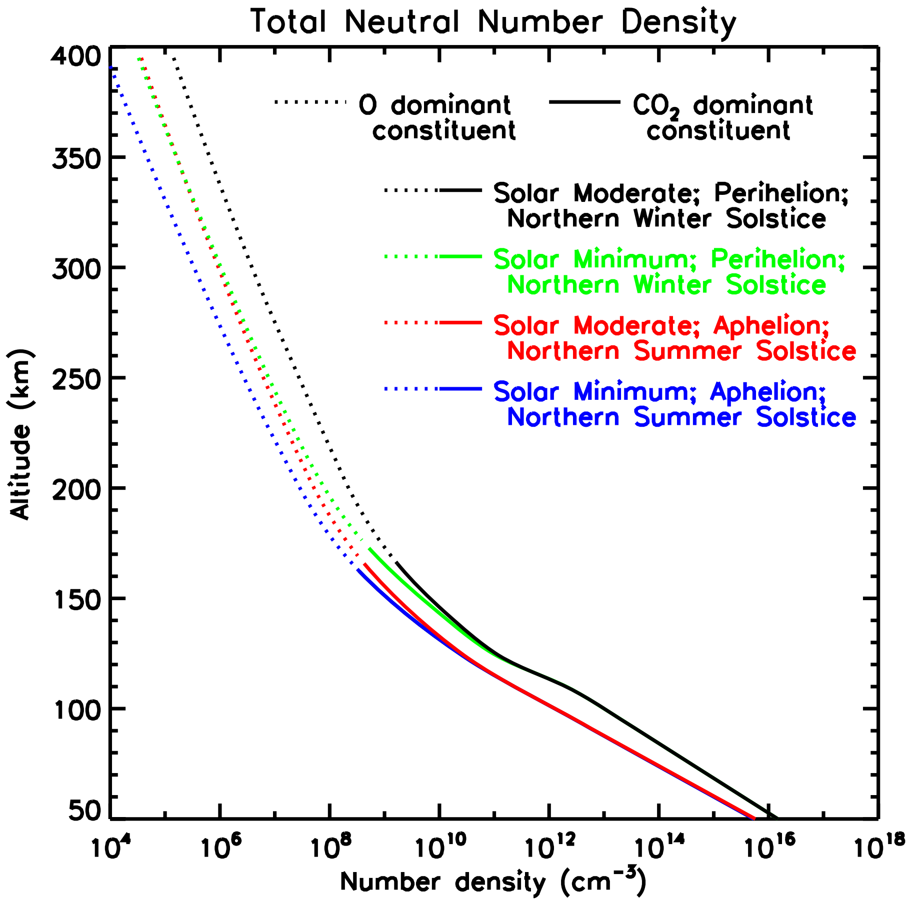
- Since O_2^+ is the dominant ionospheric ion due to rapid chemical reactions,

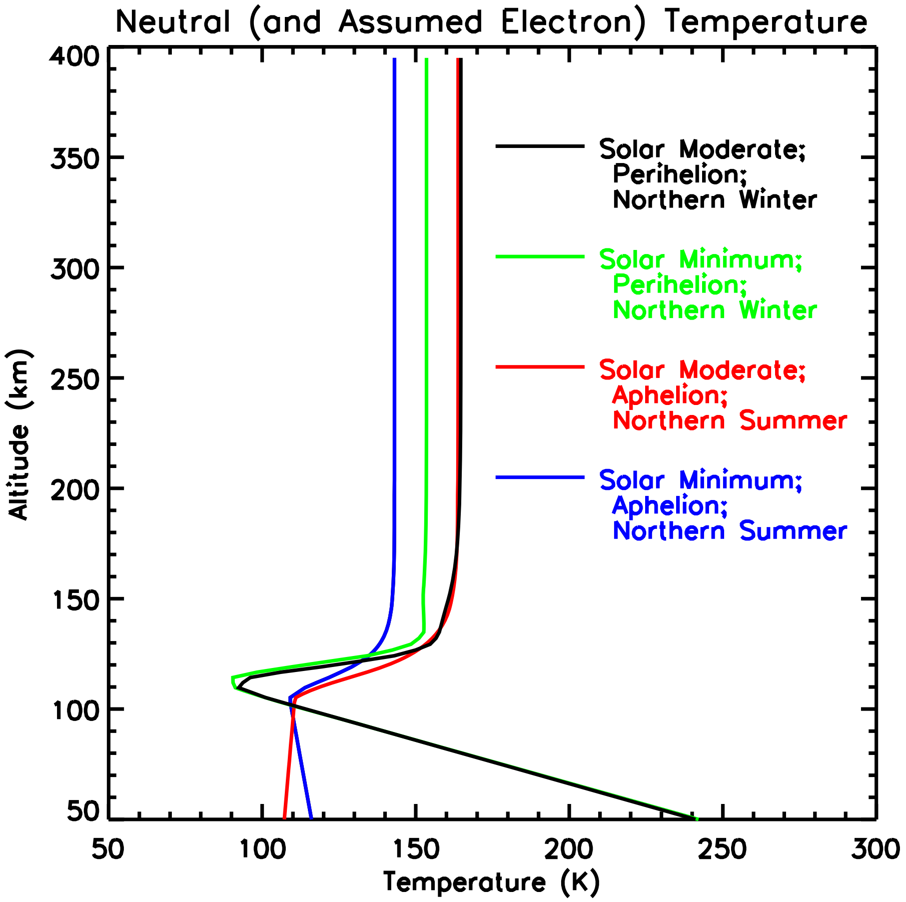
$$\boldsymbol{\alpha_{eff}(z)} = O_2^+ \text{ recombination rate} = \mathbf{1.95 \times 10^{-7}\ (300/T_e(z))^{0.7}\ cm^3\ s^{-1}},$$

  where T_e is the electron temperature (assume T_e = neutral temperature)

Neutral Atmosphere Profiles (MTGCM)

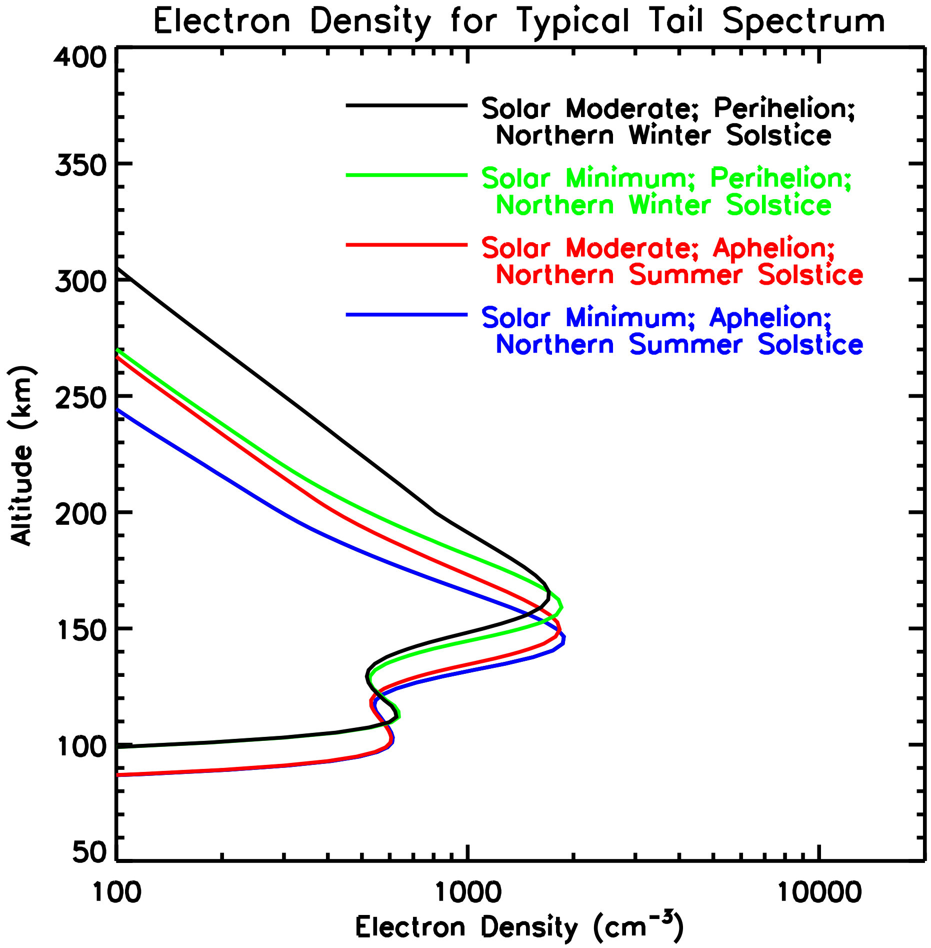
[*Bougher et al.*, 1999, 2000]


Total Neutral Number Density


Neutral (and Assumed Electron) Temperature

- Model contains CO_2, CO, O_2, O, & 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

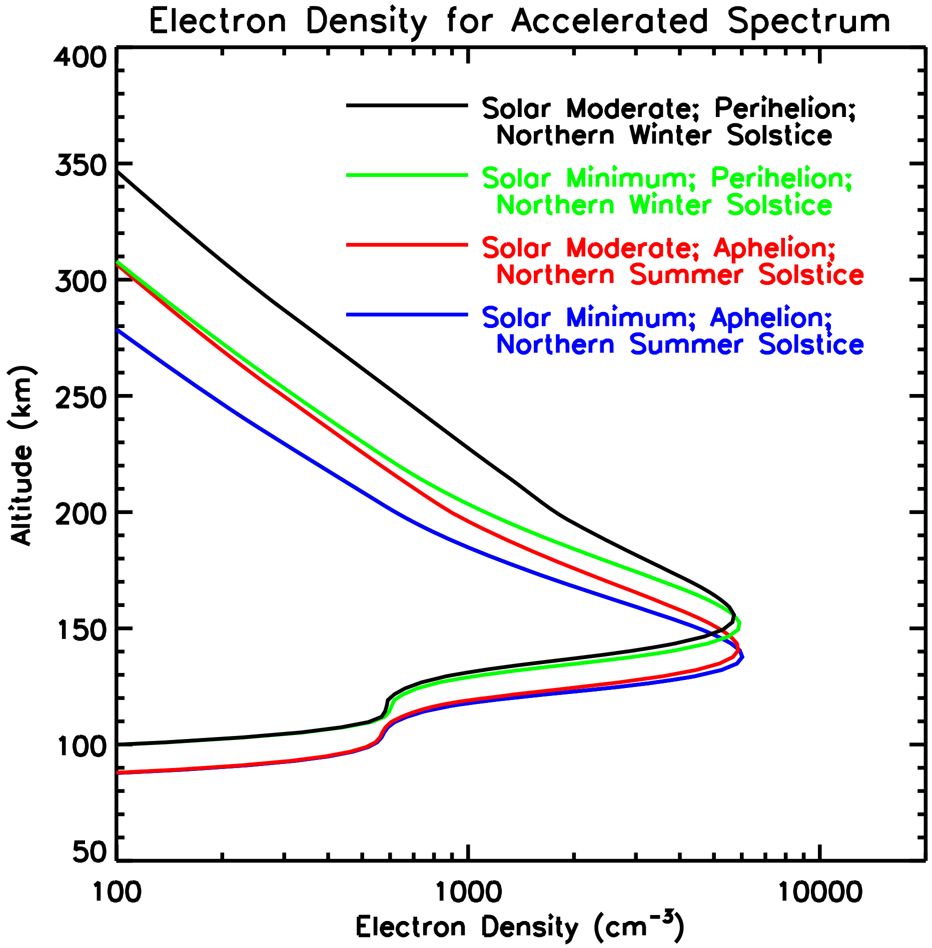
Electron Density (Typical Tail Spectrum)



	n_e^{max} (cm^{-3})	altitude of n_e^{max} (km)	TEC $(10^{14}\ m^{-2})$
Solar mod; perihelion	1700	166	1.35
Solar min; perihelion	1850	159	1.15
Solar mod; aphelion	1830	149	1.20
Solar min; aphelion	1880	146	1.07

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

Electron Density (Accelerated Spectrum)



	n_e^{max} (cm^{-3})	altitude of n_e^{max} (km)	TEC (10^{14} m^{-2})
Solar mod; perihelion	5700	156	3.47
Solar min; perihelion	5900	153	2.95
Solar mod; aphelion	5860	140	3.06
Solar min; aphelion	6020	138	2.72

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

Summary

- In all 4 cases, the accelerated spectrum increased $\mathbf{n_e^{max}}$ 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** $\mathbf{n_e^{max}}$ occur during **solar minimum at aphelion**
  Upper atmosphere **coolest** (smallest scale height) → **thinnest** ionosphere
  → **smallest TEC**
- **Smallest** $\mathbf{n_e^{max}}$ occur during **solar moderate at perihelion**
  Upper atmosphere **warmest** (largest scale height) → **thickest** ionosphere
  → **largest TEC**
- Between these two extremes, $\mathbf{n_e^{max}}$ changes by ~ **10%** → **observable**
  TEC changes by ~ **25%** → **changes!**

➔ **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^{max} and TEC impact subsurface science that can be done from orbit
- Penetration depth of radar soundings is inversely proportional to frequency

$$D_{penetration} \sim 1/f_{radar}$$

- To traverse the ionosphere, the signal frequency must be greater than the peak ionospheric electron plasma frequency which is determined by n_e^{max}

$$f_{radar} > f_p^{max} \sim \sqrt{n_e^{max}}$$

- Therefore, penetration depth is limited by the maximum electron density;
  → increased ionization leads to decreased penetration depths

$$D_{penetration} \sim 1/\sqrt{n_e^{max}}$$

- Dispersion, attenuation, & Faraday rotation of radar signals related to TEC
  → times of smallest n_e^{max} = times of largest TEC

➔ It is important to know not only <u>where</u> (geographically) but also <u>when</u> (season and solar cycle) n_e^{max} and TEC are optimal to enable deep subsurface soundings