Ionospheric Physics

C. E. Valladares

Institute for Scientific Research/Boston College

Lima, September 23, 2014

Outline

The Earth's Ionosphere: Definition. Origin. Different layers.

Absorption of Solar Radiation. Continuity equation. Ionization rate. Chapman layers. E-region ionization and Recombination. F-region ionization.

Plasma Dynamics: Momentum equation. Conductivities. Fountain effect.

The High-latitude Ionosphere. Processes: Polar Cap patches, Theta auroras and Polar cap arcs.

The Ionosphere during Storms conditions

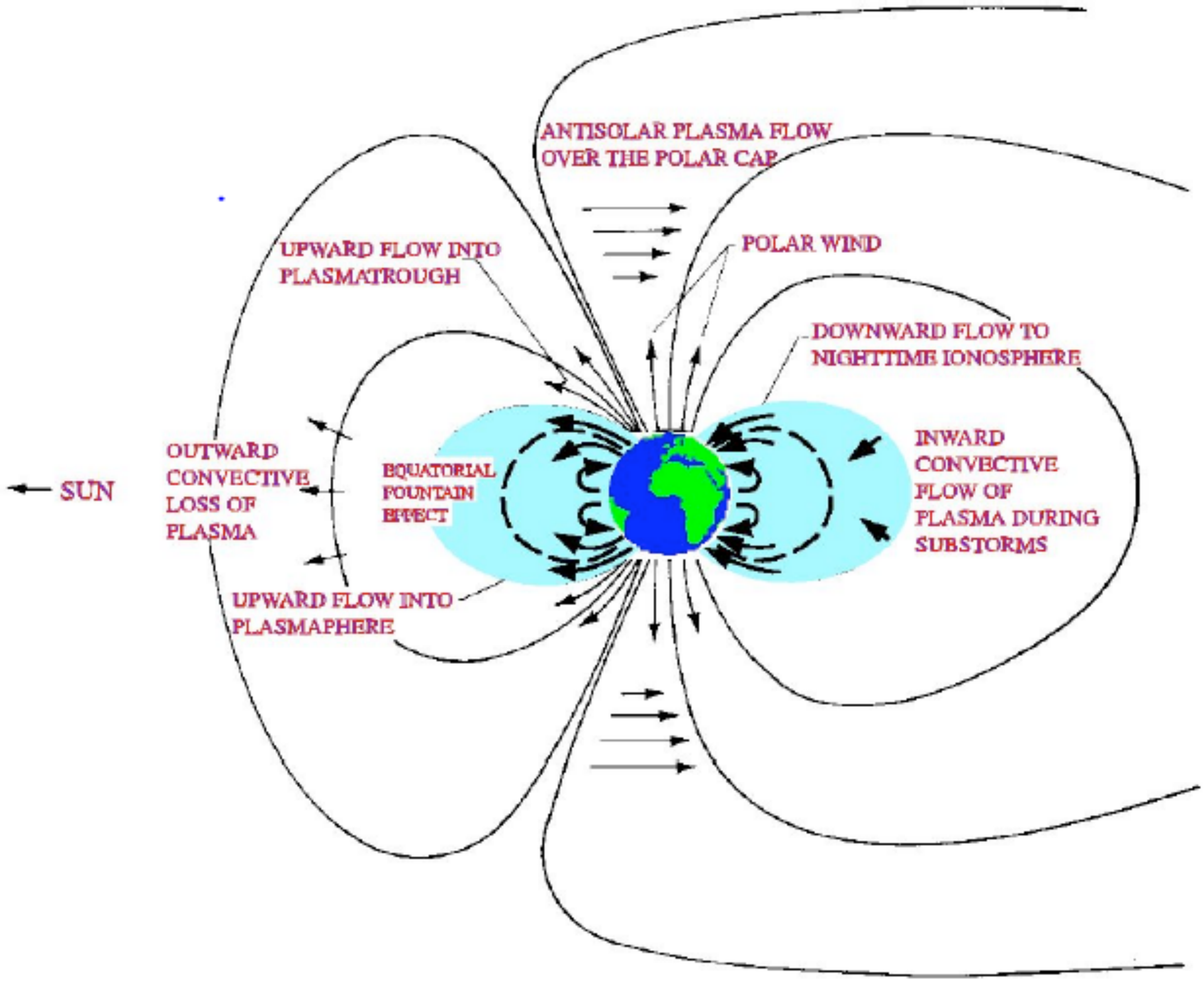
The Ionosphere: Definition

The ionosphere is a weakly ionized region in the upper part of the atmosphere (of the order of 10^{-5} of the atmospheric molecules).

The ionosphere is electrically conducting and can support strong electric currents. The ionized medium also affects radio waves and, as magnetized plasma, it can support and generate a variety of waves, interactions and instabilities.

What produces the ionosphere: The continuum spectrum in the far UV region originates from the uppermost layer of the photosphere. The radiation in this wavelength band is completely absorbed by molecular oxygen at altitudes between 80 and 120 km in the terrestrial atmosphere.

Ionospheric Plasma Motions



Ionosphere Regions

The main regions are designated D, E, F1 and F2, with the following daytime characteristics:
D region, 60 - 90 km: 10^8-10^{10} m^{-3} (10^2 - 10^4 cm^{-3});
E region, 105 - 160 km: several 10^{11} m^{-3} (10^5 cm^{-3});
F1 region, 160 - 180 km: several 10n-10^{12} m^{-3} (10^5-10^6 cm^{-3});
F2 region, maximum variable around 300 km: up to several 10^{12} m^{-3} (10^6 cm^{-3}).

The D and F1 regions vanish at night, and the E region becomes much weaker. The F2 region, however, tends to persist though at reduced intensity.

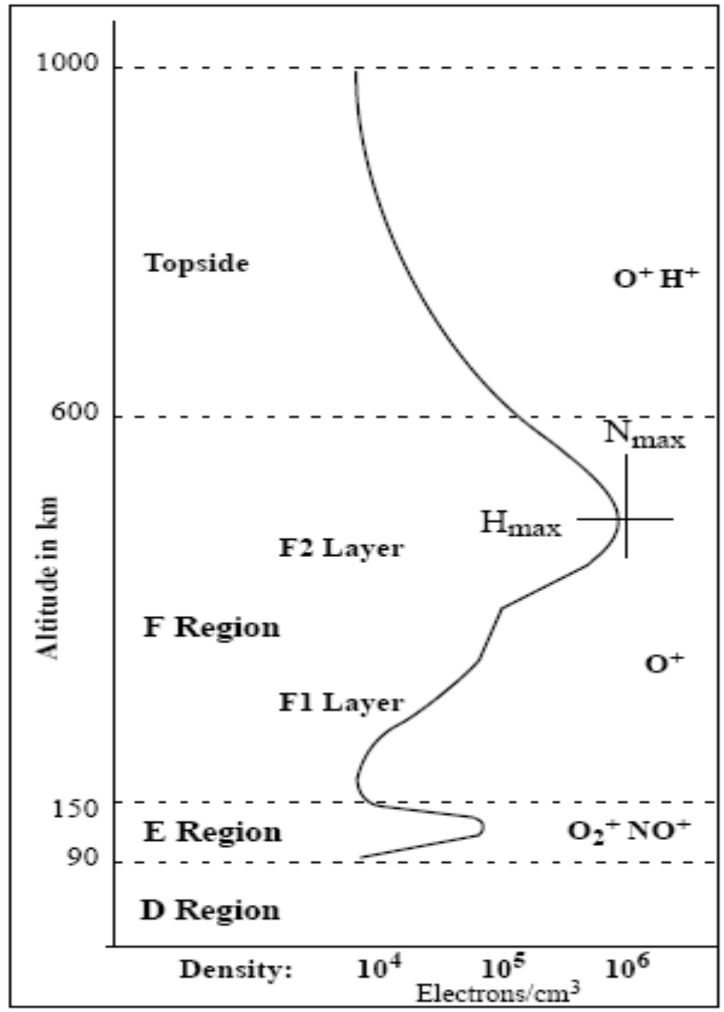
At high latitudes the E-region electron densities may increase drastically during the nighttime exceeding even the F-region peak due to auroral particle precipitation.

Ionosphere Vertical Electron Density Profile

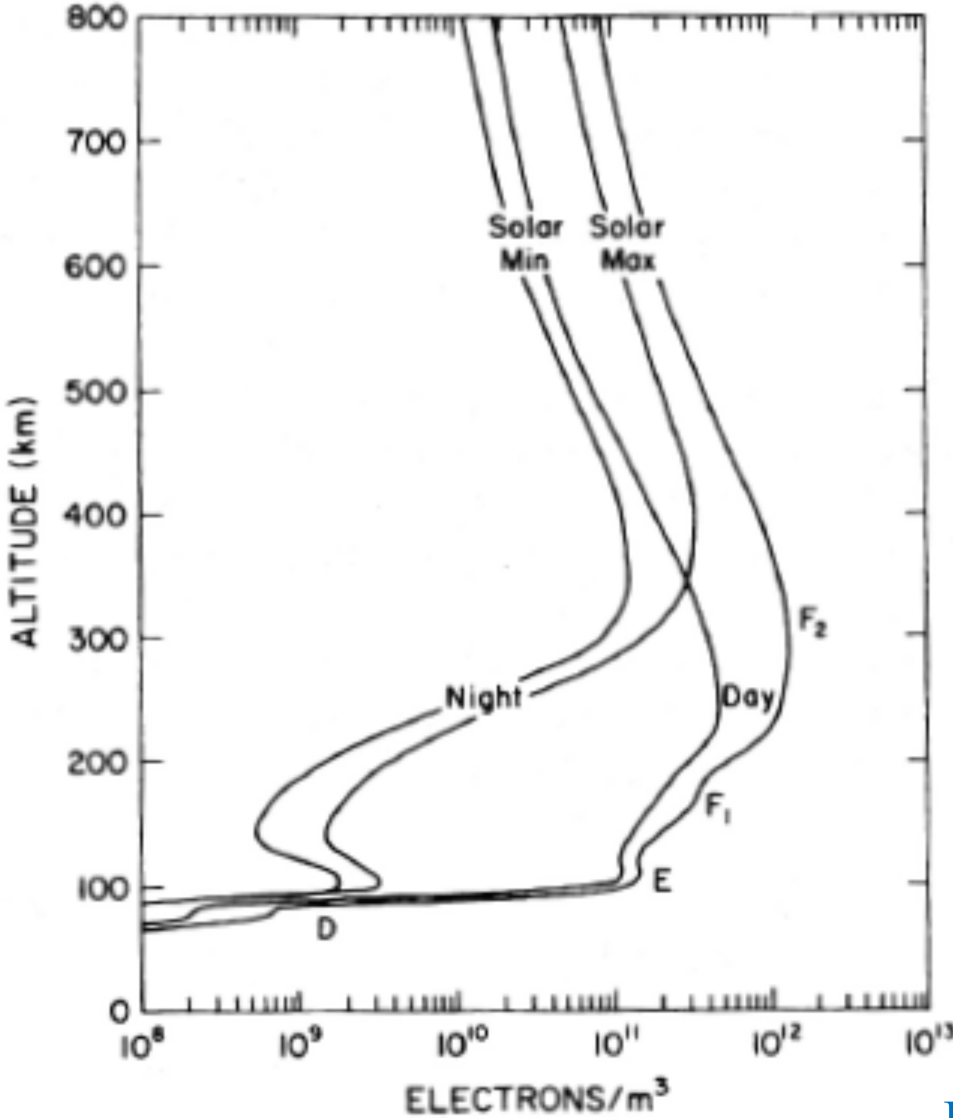
The F2 region varies by 3-5X diurnally, highest just after noon, lowest before dawn.

The F1 region and E region dissipate at night.

The D region is present only during daytime and in times of high activity.

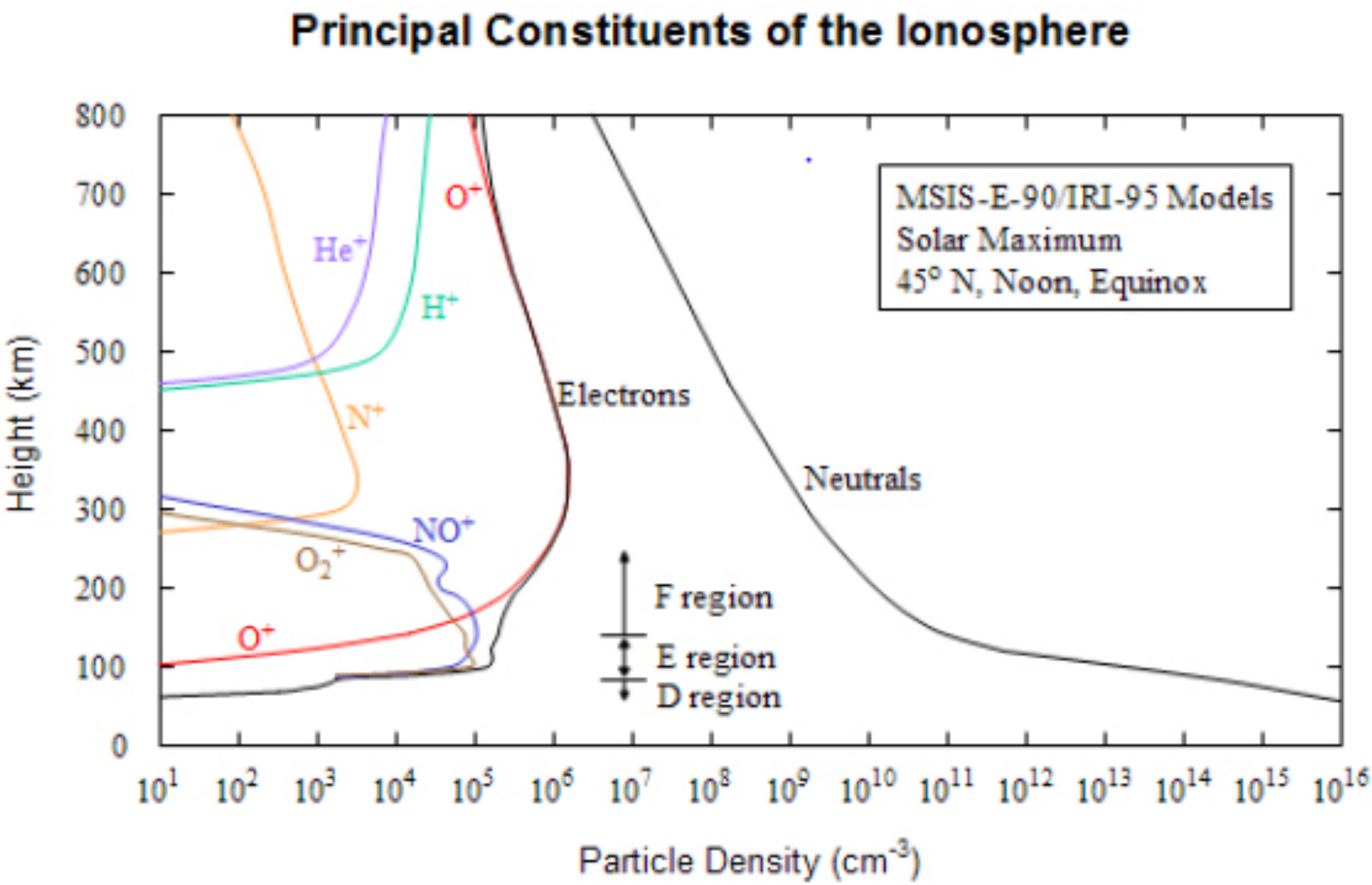


Typical ionospheric electron density profiles for solar maximum and minimum conditions for daytime and nighttime



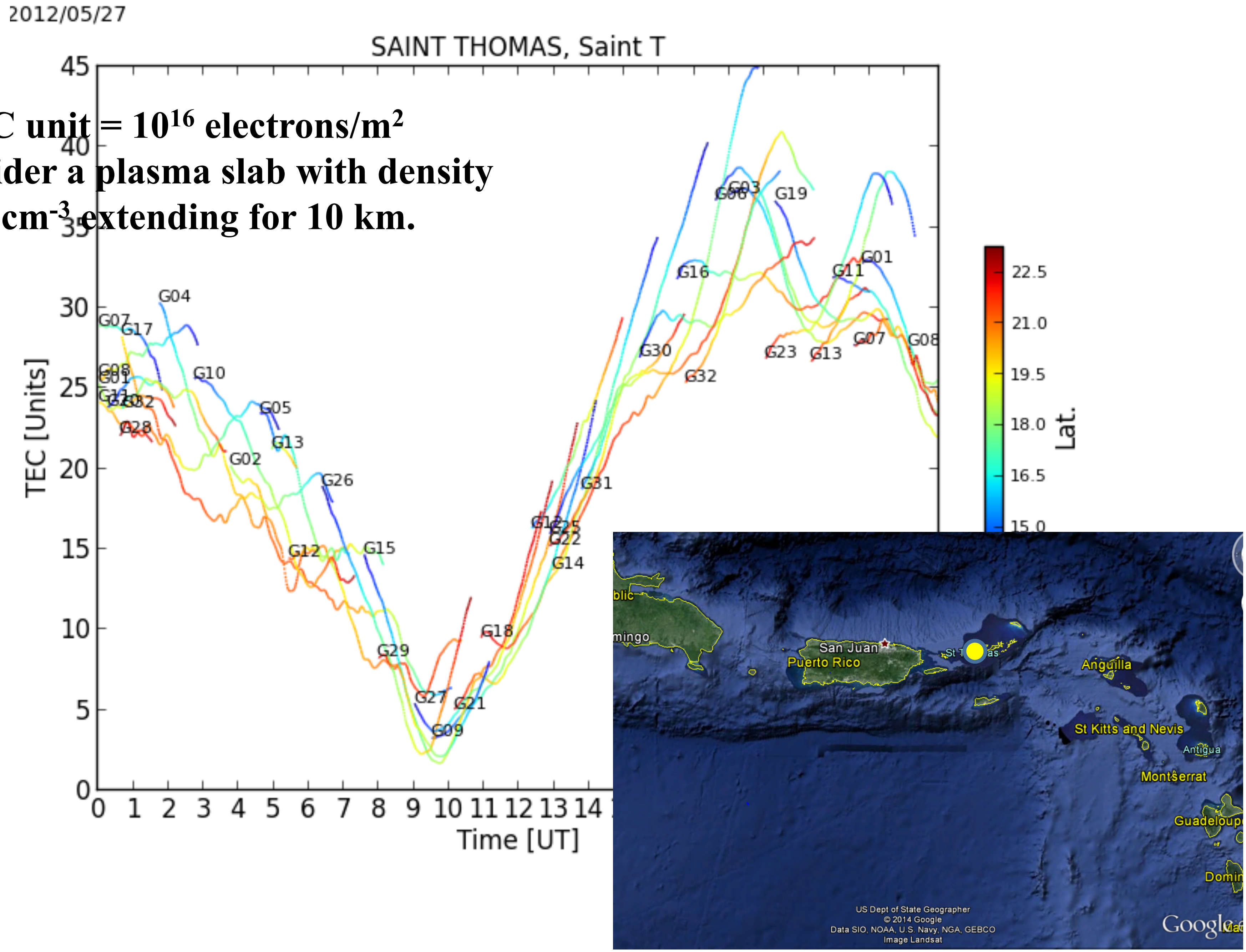
Richmond, 1987

The Earth's Ionosphere

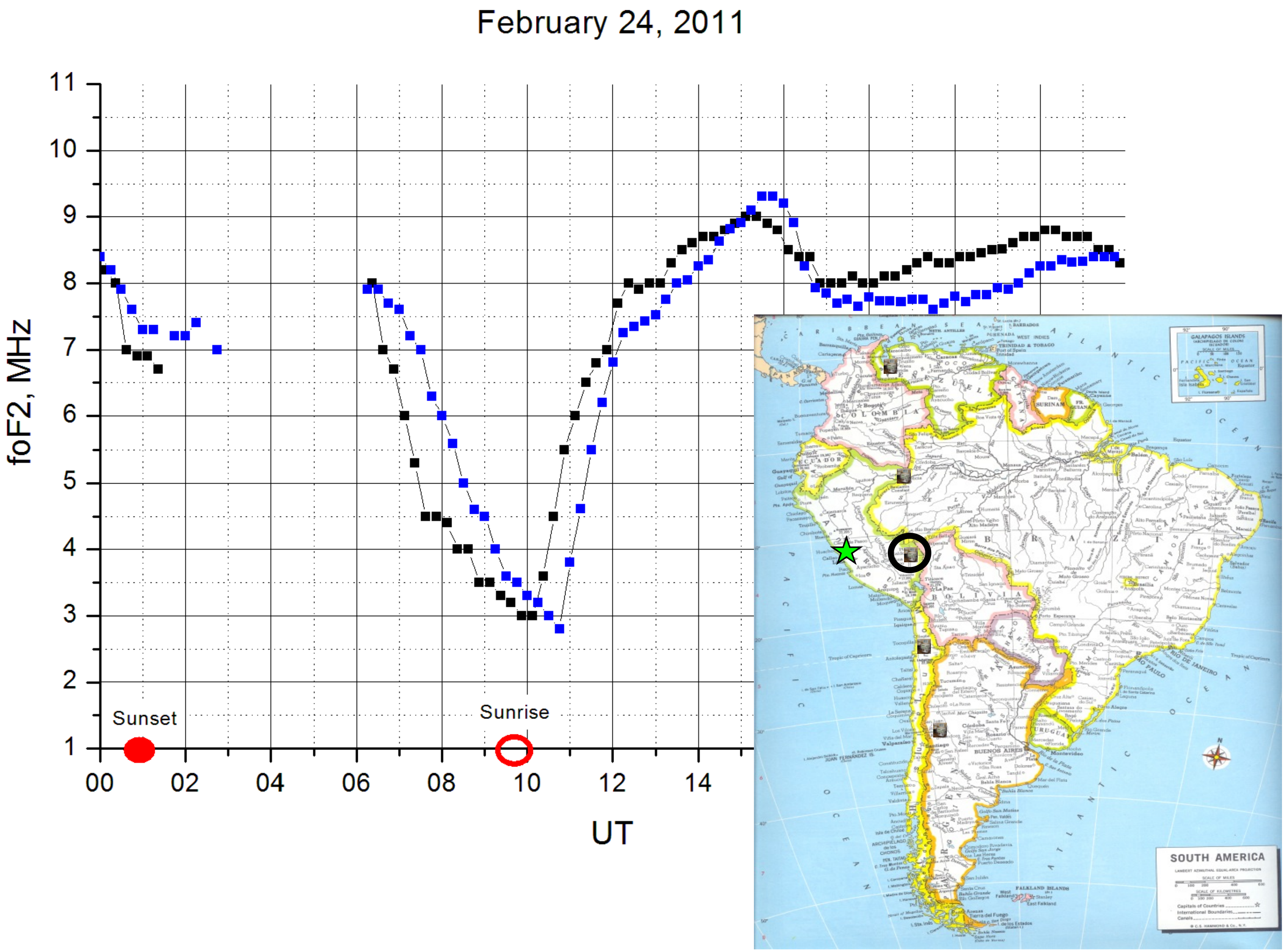


24-hour variation of TEC observed on May 27, 2012 at St. Thomas

1 TEC unit = 10^{16} electrons/m^2
Consider a plasma slab with density = 10^6 cm^{-3} extending for 10 km.



Jicamarca - Puerto Maldonado f_oF_2 comparison



Ionization sources

Day: Ionization by solar EUV

Night: Geocorona, scattered Lyman-α at 121.6 nm, ionizes only NO.

Galactic X-rays, mostly penetrate to about 100 km altitude

Photoelectrons, local or from the conjugate hemisphere, F-region ionization

Solar energetic protons, polar cap D-region ionization

Aurora, electron and proton precipitation from the magnetosphere

Production and Loss processes

The ionosphere is formed by the ionization of atmospheric gases such as N2, O2 and O. At middle and low latitude the energy required comes from solar radiation in the extreme ultra-violet (EUV) and X-ray parts of the spectrum. The rate of change of electron density is expressed by a continuity equation:

$$\delta N/\delta t = q - L - \mathrm{div}(Nv)$$

where q is the production rate, L the loss rate by recombination, and div(Nv) expresses the loss of electrons by movement, v being their mean drift velocity.

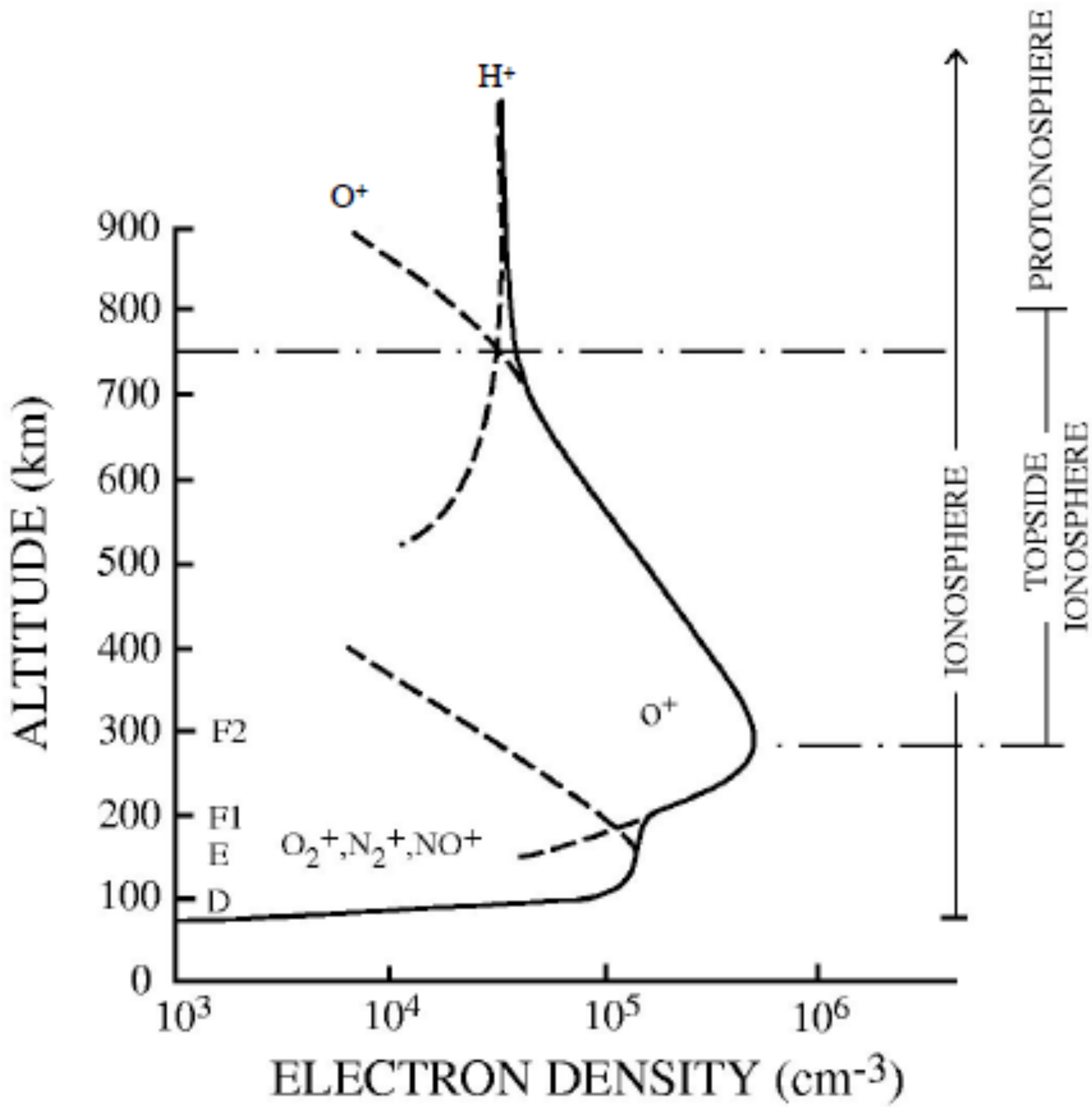
Photoionization

E > 12 eV

Loss Processes

The important loss processes are : atomic ion and electron (radiative) recombination and molecular ion and electron (dissociative) recombination.

Some Ionospheric Processes



F-Region

$O + h\nu \rightarrow O^+ + e^*$

$O^+ + N_2 \rightarrow NO^+ + N$

$O^+ + O_2 \rightarrow O_2^+ + O$

Topside

$O^+ + H \Leftrightarrow H^+ + O$

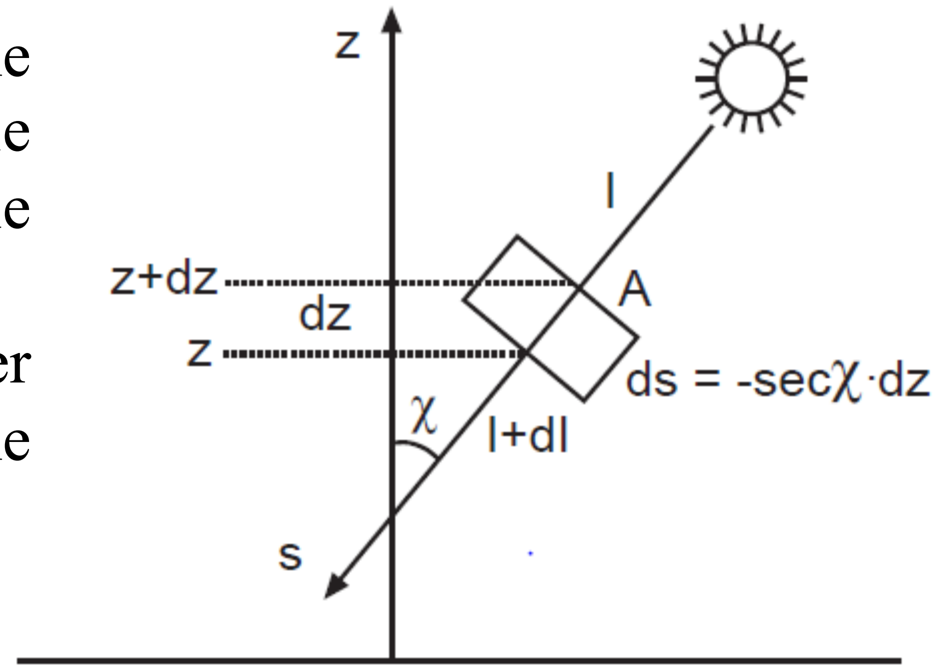
Chapman's Equations for Production of Ionization

Total absorption cross section of the slab is $\sigma nAds$, where σ is the absorption cross section of a single molecule.

The number of absorbed photons per unit time is $I\sigma nAds$. And, the decrease in intensity as unit of area:

I is the intensity of radiation $I(\lambda,z)$

$$dI = \sigma nI \sec\chi \, dz \qquad (1)$$



$$I(z) = I_\infty \exp\left[-\sigma \sec\chi \int_z^\infty n(z)dz\right] = I_\infty \exp(-\sigma \sec\chi \, N_T)$$

For a multi-component atmosphere:

$$I(z) = I_\infty \exp\left[-\sec\chi \sum_j \sigma_j \int_z^\infty n_j(z)dz\right] = I_\infty \exp(-\tau)$$

Chapman's Equations (continued)

The rate of production per unit volume is given by:

$$q = \eta n \sigma I = \eta n \sigma I_\infty \exp\left[-\sigma \sec\chi \int_z^\infty n(z)dz\right]$$

The ionization efficiency η is the number of photo electrons produced per photon absorbed. And, assuming that the neutral density varies as:

$$n = n_m \exp\left(-\frac{z - z_m}{H}\right) = n_m e^{-h}$$

The ionization rate is:

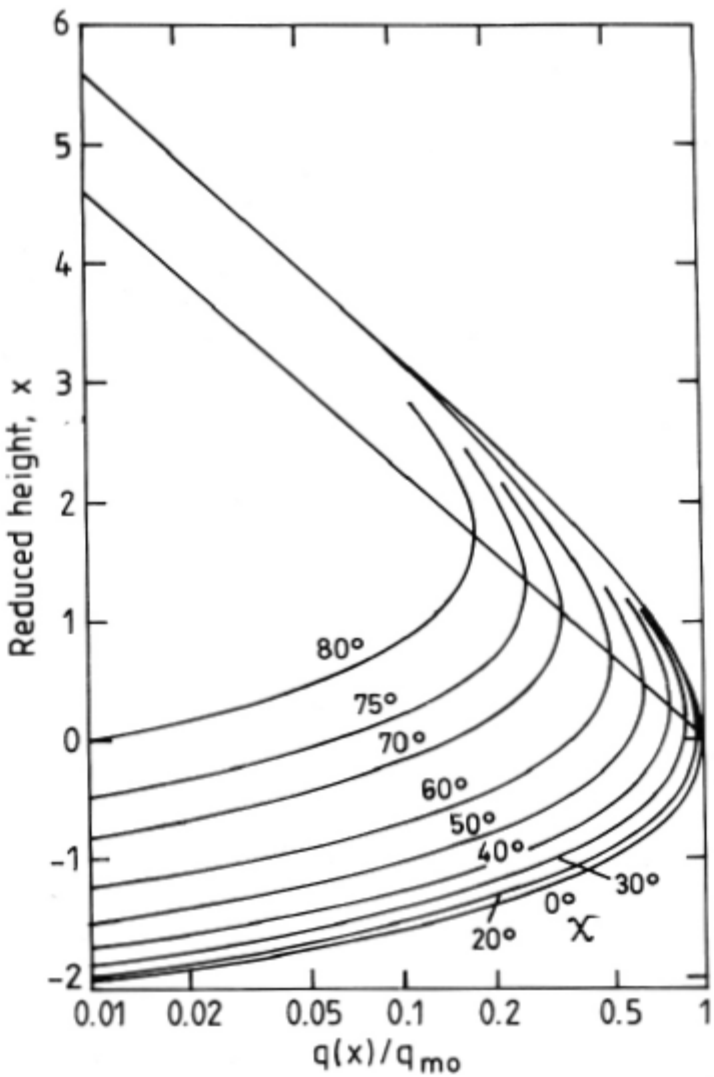
$$q(\chi, h) = \frac{\eta I_\infty \sigma H n_m}{H} \exp\left[-h - \sec\chi \cdot \sigma H n_m e^{-h}\right]$$

Making $\sigma H n_m$ equal to 1 introducing exp (e) in both num and den.

$$q(\chi, h) \;=\; \frac{\eta I_\infty}{He} \exp\left[1 - h - \sec\chi e^{-h}\right]$$

Chapman's Equations (continued)

Normalized Chapman's production function:



after Van Zandt and Knecht, 1964

photo ionization (EUV, X-ray)

$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

$$O_2 + h\nu \rightarrow O^+ + O + e^-$$

$$O + h\nu \rightarrow O^+ + e^-$$

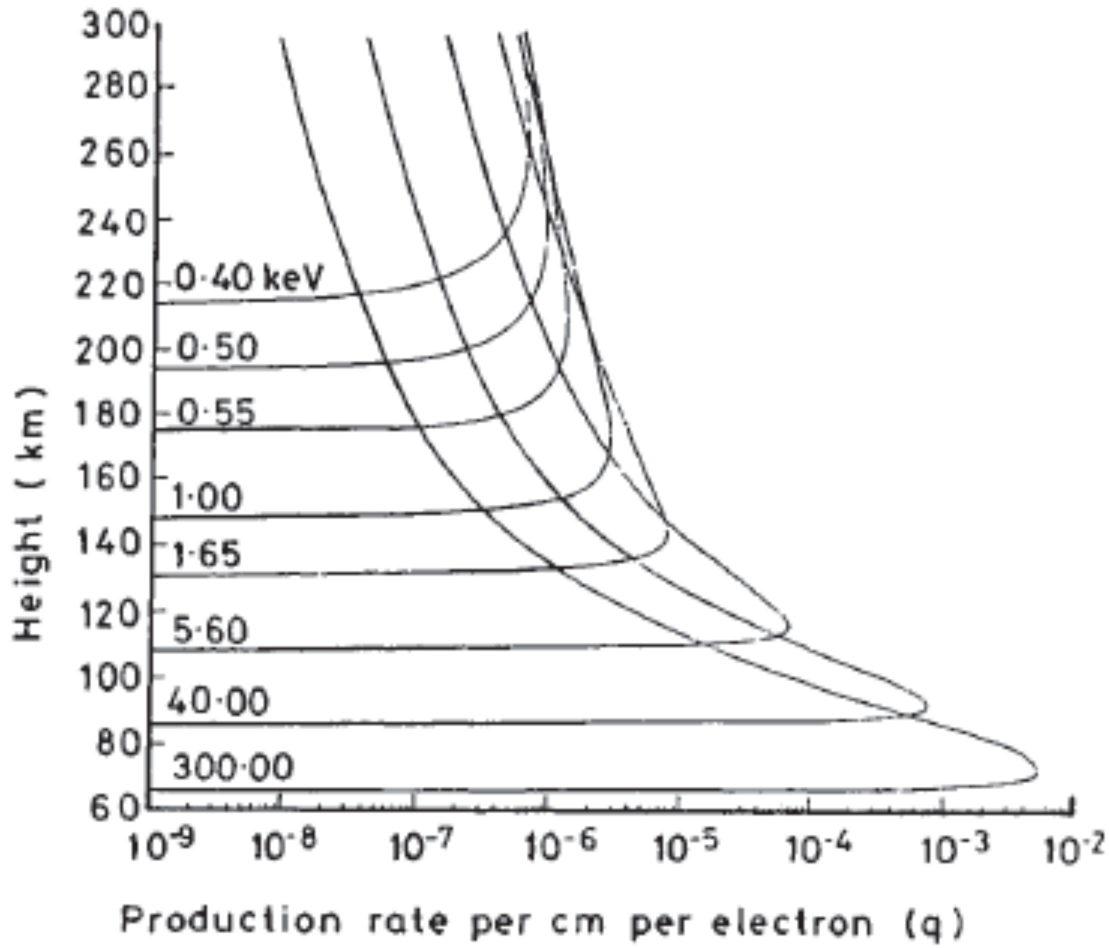
ionization by particle impact (aurora)

$$O_2 + e^* \rightarrow O_2^+ + 2e^-$$

$$O_2 + e^* \rightarrow O^+ + O + 2e^-$$

$$O + e^* \rightarrow O^+ + 2e^-$$

Production rates due to energetic electrons



M.H. Rees 1963

Chemistry of the E region

The E region is formed by the less strongly absorbed, and therefore a more penetrating part of the spectrum. EUV radiation between 800 and 1027 Å (the ionization limit of O_2) is absorbed by molecular oxygen.

The main primary ions produced in the E region are N_2^+, O_2^+, and O^+, but the most numerous are NO^+ and O_2^+.

The important recombination process is dissociative recombination of electrons and molecular positive ions. Recombination s in the E region are:

Charge exchange

$$O_2^+ + N_2 \rightarrow N_2^+ + O_2 \qquad \gamma_6 = 2.5\times10^{-10}\ \mathrm{cm^3 s^{-1}}$$

production of new ion species

$$O_2^+ + NO \rightarrow NO^+ + O_2 \qquad \gamma = 4.4\times10^{-10}\ \mathrm{cm^3 s^{-1}}$$

recombination

$$NO^+ + e \rightarrow O + N \qquad \alpha_3 = 4.2\times10^{-7}\left(T_e/300\right)^{-0.85}\ \mathrm{cm^3 s^{-1}}$$

Chemistry of the F region

A large proportion of the neutral atmosphere is atomic in the F region, atomic ions are produced by photoionization, but these do not recombine with electrons directly, except by the very slow radiative process. Instead , they undergo an ion-atom interchange reaction, and the molecular ions thus formed recombine with electrons.

only loss processes through charge transfer to N_2^+ and O_2^+

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad \gamma = 2\times10^{-11}\left(T_n/300\right)^{-0.4}$$

$$O_2^+ + e \rightarrow O + O\left({}^1D\right) \qquad \alpha = 1.9\times10^{-7}\sqrt{300/T_e}$$

Plasma Dynamics

The primary difference between ionospheric plasma dynamics and thermospheric neutral gas dynamics is the effect of electromagnetic forces. The plasma density does not become comparable to that of the neutrals until several thousand kilometers in altitude.

The various forces acting on charged particles drive electric currents that in turn create electric fields that modify the plasma dynamics.

It is extremely important the generation of electric fields in the ionosphere and the transmission of electric fields along magnetic field lines between the ionosphere and the magnetosphere (High Latitudes).

The forces that act on the ionospheric plasma are as follows:

Gravitational ($\rho_j g$);

Electric ($n_j q_j E$);

Magnetic $n_j q_j (V_j \times B)$

Frictional force is exerted on each specie by collisions with all of the other species.

Pressure forces: ($F = 1/n_j \nabla (n_j K T_j)$).

Ionospheric Forces

- **The following forces move charged particles:**

  Collisions with neutral particles: $-m_i v_{in}(V_i - U)$

  Partial pressure gradients: $-\ (N_i k T_i)/N_i$

  Gravity Force: $m_i g$

  Electric fields: $q\,E$

  Lorentz Force: $q\,(V_i \times B)$

- **Momentum Equation:**

$$0 = -\frac{1}{N_i}\nabla N_i k T_i \;+\; m_i\vec{g} \;+\; e\left(\vec{E} + \vec{V}_i \times \vec{B}\right) \;-\; m_i \upsilon_{in}\left(\vec{V}_i - \vec{U}\right)$$

Pressure Gradient	Gravity	Electric Field	Lorentz	Collisions with Neutrals

$$0 = m_i \frac{\partial V_i}{\partial t}$$

Inosphere Electrodynamics

Using the following variables to simplify solution:

$$\mathbf{F}_{\rm i} = -\frac{1}{N_{\rm i}}\nabla(N_{\rm i}kT_{\rm i}) + m_{\rm i}\mathbf{g} + e(\mathbf{E} + \mathbf{U}\times\mathbf{B}),$$

$$\Omega_{\rm i} = \frac{eB}{m_{\rm i}}$$ **Ion gyrofrequency**

Solving $\mathbf{V}_{\rm i}$:

$$\mathbf{V}_{\rm i}^{\perp} = \frac{1}{m_{\rm i}\upsilon_{\rm in}}\frac{1}{1+\left(\frac{\Omega_{\rm i}}{\upsilon_{\rm in}}\right)^2}\left[\mathbf{F}_{\rm i}^{\perp} + \frac{\Omega_{\rm i}}{\upsilon_{\rm in}}\mathbf{F}_{\rm i}^{\perp}\times\hat{\mathbf{b}}\right] + \mathbf{U}^{\perp},$$

This equation implies that the ions will move in a direction of the force and in a direction that is mutually perpendicular to the magnetic field and the force.

$$\mathbf{V}_{\rm i}^{\parallel} = \frac{1}{m_{\rm i}\upsilon_{\rm in}}\mathbf{F}_{\rm i}^{\parallel} + \mathbf{U}^{\parallel}$$

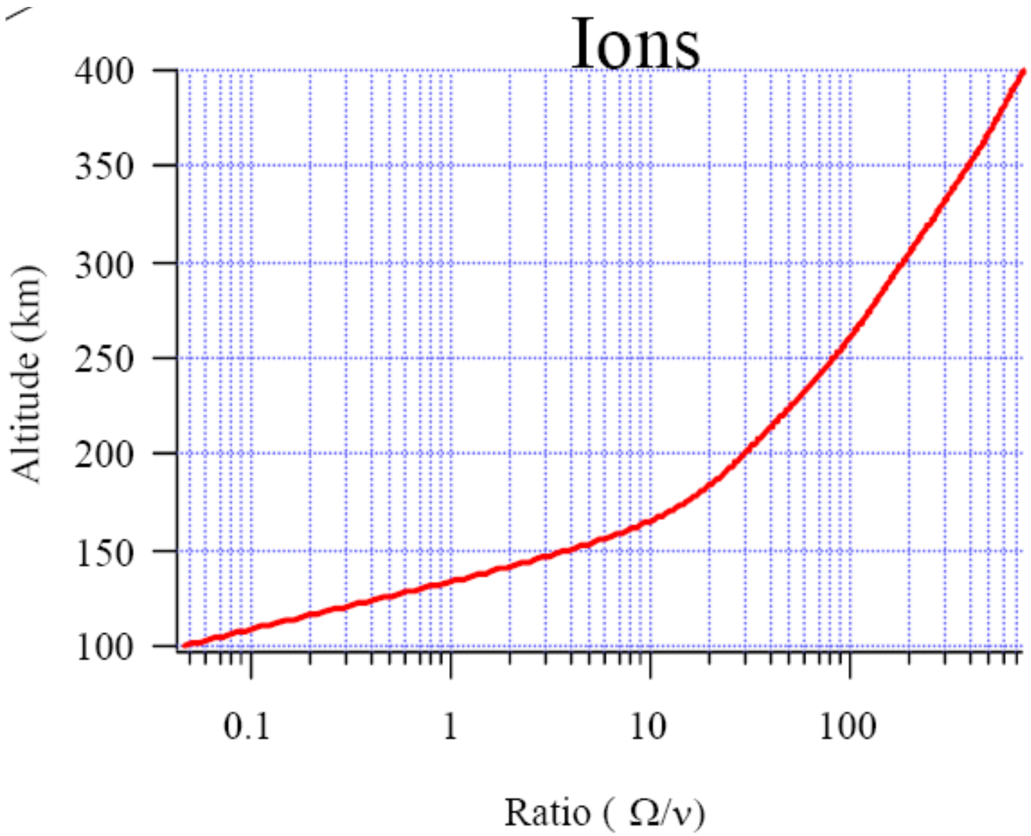
The ion velocity along the B field depends directly on the Force and the wind along B.

Ionosphere Electrodynamics

$$\mathbf{V}_i^{\perp} = \frac{1}{m_i \upsilon_{in}} \frac{1}{1 + \left(\frac{\Omega_i}{\upsilon_{in}}\right)^2} \left[\mathbf{F}_i^{\perp} + \frac{\Omega_i}{\upsilon_{in}} \mathbf{F}_i^{\perp} \times \hat{\mathbf{b}}\right] + \mathbf{U}^{\perp},$$

$$\mathbf{V}_i^{\parallel} = \frac{1}{m_i \upsilon_{in}} \mathbf{F}_i^{\parallel} + \mathbf{U}^{\parallel}$$

The magnitude of the velocity depends on the ratio of the gyrofrequency and collision frequency.



Ion Velocity equation

$$V_i = \frac{1}{m_i} \frac{\nu_{in}}{\nu_{in}^2 + \Omega_i^2} \left[F_i + \frac{\Omega_i}{\nu_{in}} F_i \times b \right] + U$$

$$F_i = -\frac{1}{N_i} \nabla \left(N_i k T_i \right) + m_i g + e \left(E + U \times B \right)$$

Electron Velocity drift equation

$$V_e = \frac{1}{m_e} \frac{\nu_{en}}{\nu_{en}^2 + \Omega_e^2} \left[F_e - \frac{\Omega_e}{\nu_{en}} F_e \times b \right] + U$$

$$F_e = -\frac{1}{N_e} \nabla \left(N_e k T_e \right) + m_e g - e \left(E + U \times B \right)$$

Conductivity Calculations

Conductivities relates the ionospheric current and the Force

$$\mathbf{j} = N_{\mathrm{i}} e(\mathbf{V}_{\mathrm{i}} - \mathbf{V}_{\mathrm{e}}) = \tilde{\sigma}\,\frac{\mathbf{F}}{e} = \sigma_0\,\frac{\mathbf{F}^{\parallel}}{e} + \sigma_{\mathrm{P}}\,\frac{\mathbf{F}^{\perp}}{e} - \sigma_{\mathrm{H}}\,\frac{\mathbf{F}^{\perp} \times \mathbf{b}}{e}.$$

Where:

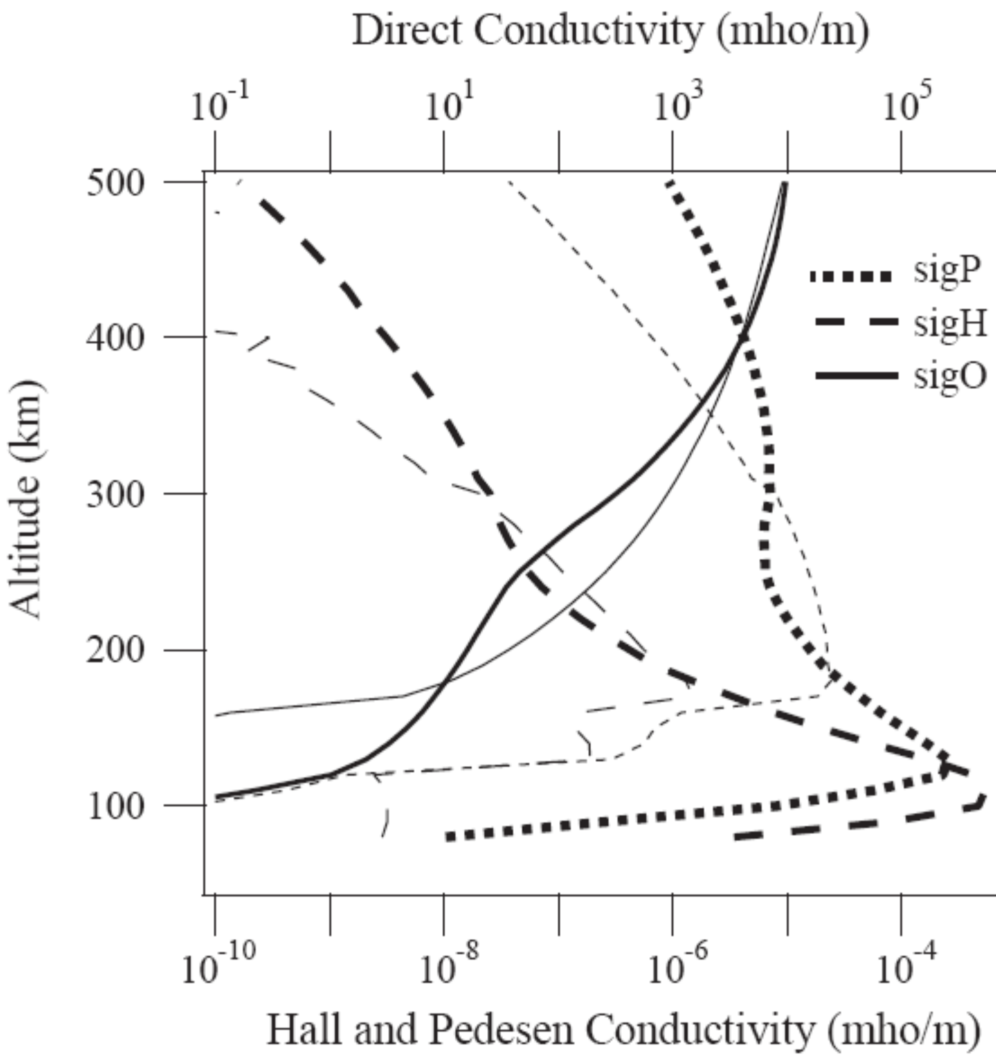
$$\sigma_0 = \frac{Ne^2}{m_{\mathrm{e}} \upsilon_{\mathrm{e}}} + \frac{Ne^2}{m_{\mathrm{i}} \upsilon_{\mathrm{i}}} \approx \frac{Ne^2}{m_{\mathrm{e}} \upsilon_{\mathrm{e}}},$$

$$\sigma_{\mathrm{p}} = Ne^2 \left[\frac{1}{m_{\mathrm{e}}}\,\frac{\upsilon_{\mathrm{e}}}{(\upsilon_{\mathrm{e}}^2 + \Omega_{\mathrm{e}}^2)} + \frac{1}{m_{\mathrm{i}}}\,\frac{\upsilon_{\mathrm{i}}}{(\upsilon_{\mathrm{i}}^2 + \Omega_{\mathrm{i}}^2)} \right],$$

$$\approx \frac{Ne^2}{m_{\mathrm{i}}}\,\frac{\upsilon_{\mathrm{i}}}{(\upsilon_{\mathrm{i}}^2 + \Omega_{\mathrm{i}}^2)},$$

$$\sigma_{\mathrm{H}} = Ne^2 \left[\frac{1}{m_{\mathrm{e}}}\,\frac{\Omega_{\mathrm{e}}}{(\upsilon_{\mathrm{e}}^2 + \Omega_{\mathrm{e}}^2)} - \frac{1}{m_{\mathrm{i}}}\,\frac{\Omega_{\mathrm{i}}}{(\upsilon_{\mathrm{i}}^2 + \Omega_{\mathrm{i}}^2)} \right].$$

Direct and Perpendicular Conductivities

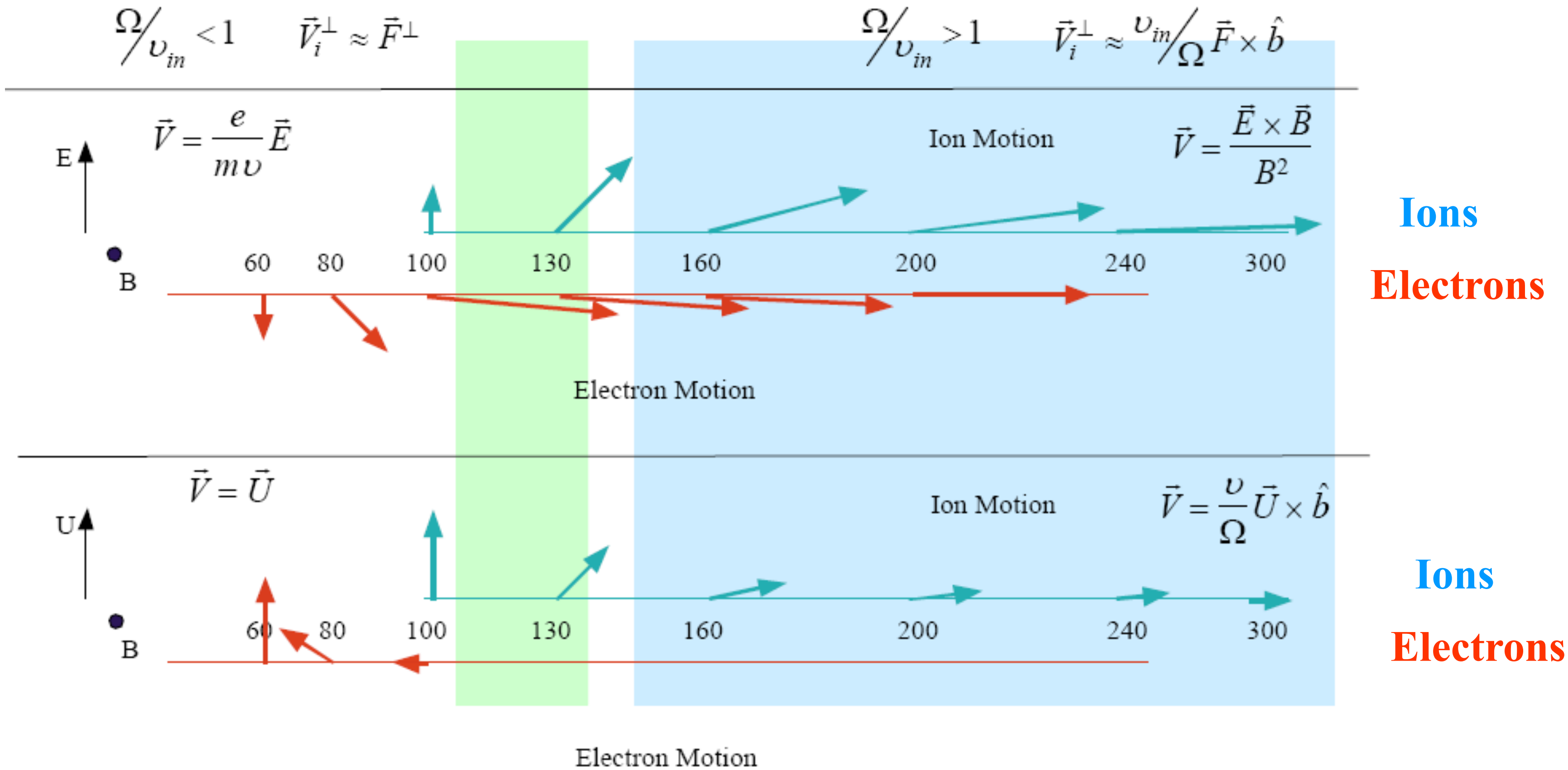


The Hall conductivity is practically a layer at 110 km. It is essentially removed during nighttime.

The Pedersen conductivity is divided in both regions. E region is much larger than F region during daytime. F region much greater that E region during daytime.

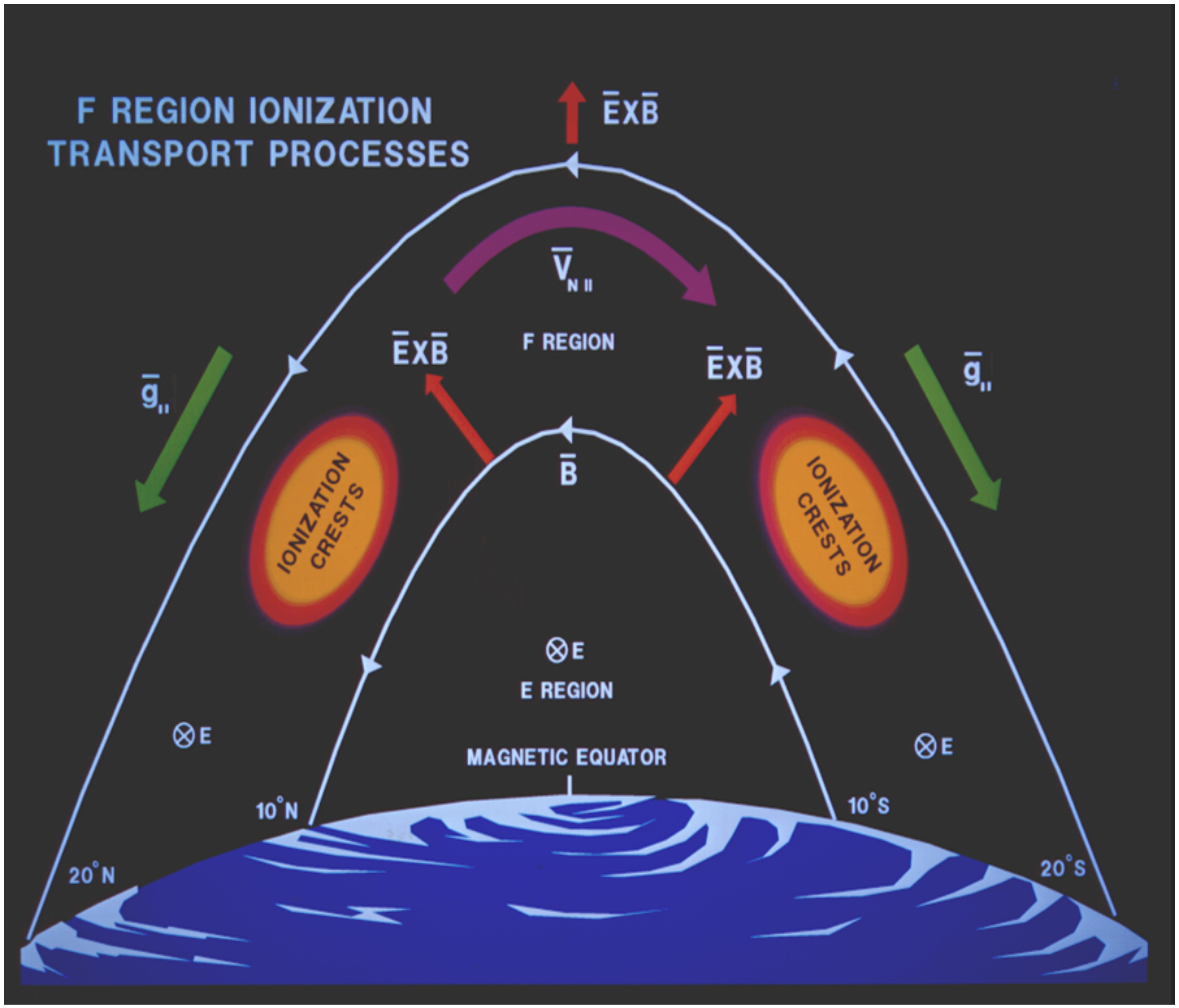
Direct conductivity larger than transverse conductivities above 90 km. Magnetic field lines are almost electric equipotentials.

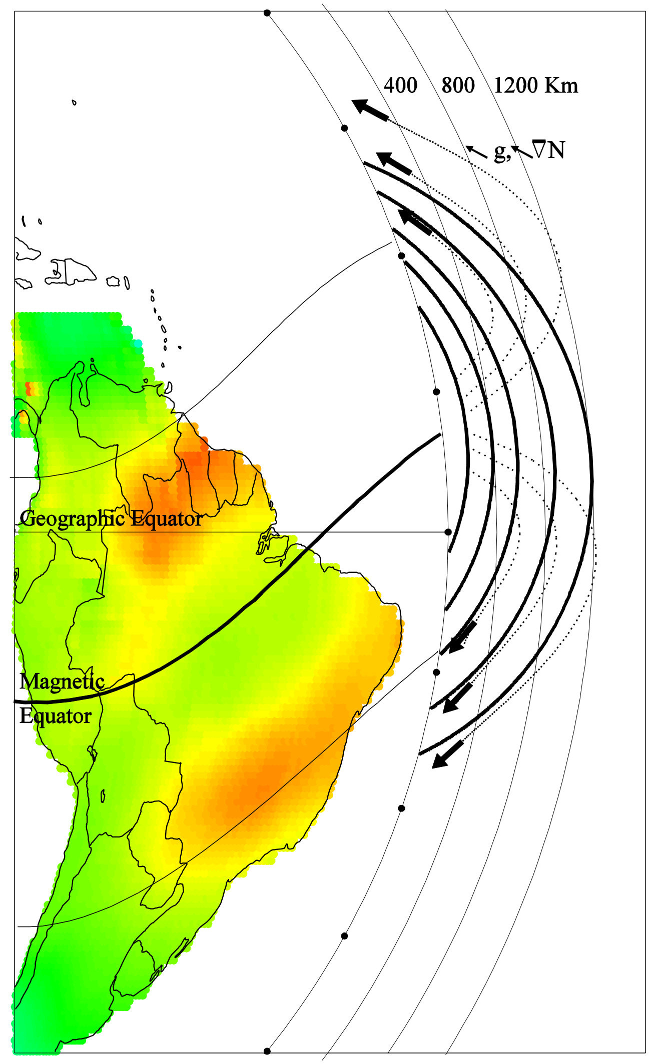
Particle Motions Perpendicular to B



Throughout the E and F region the ratio of Ω_e/ν_e for the electrons is very large, thus the electrons always move in the direction perpendicular to the force and magnetic field. For the ions, the direction of motion changes as a function of altitude.

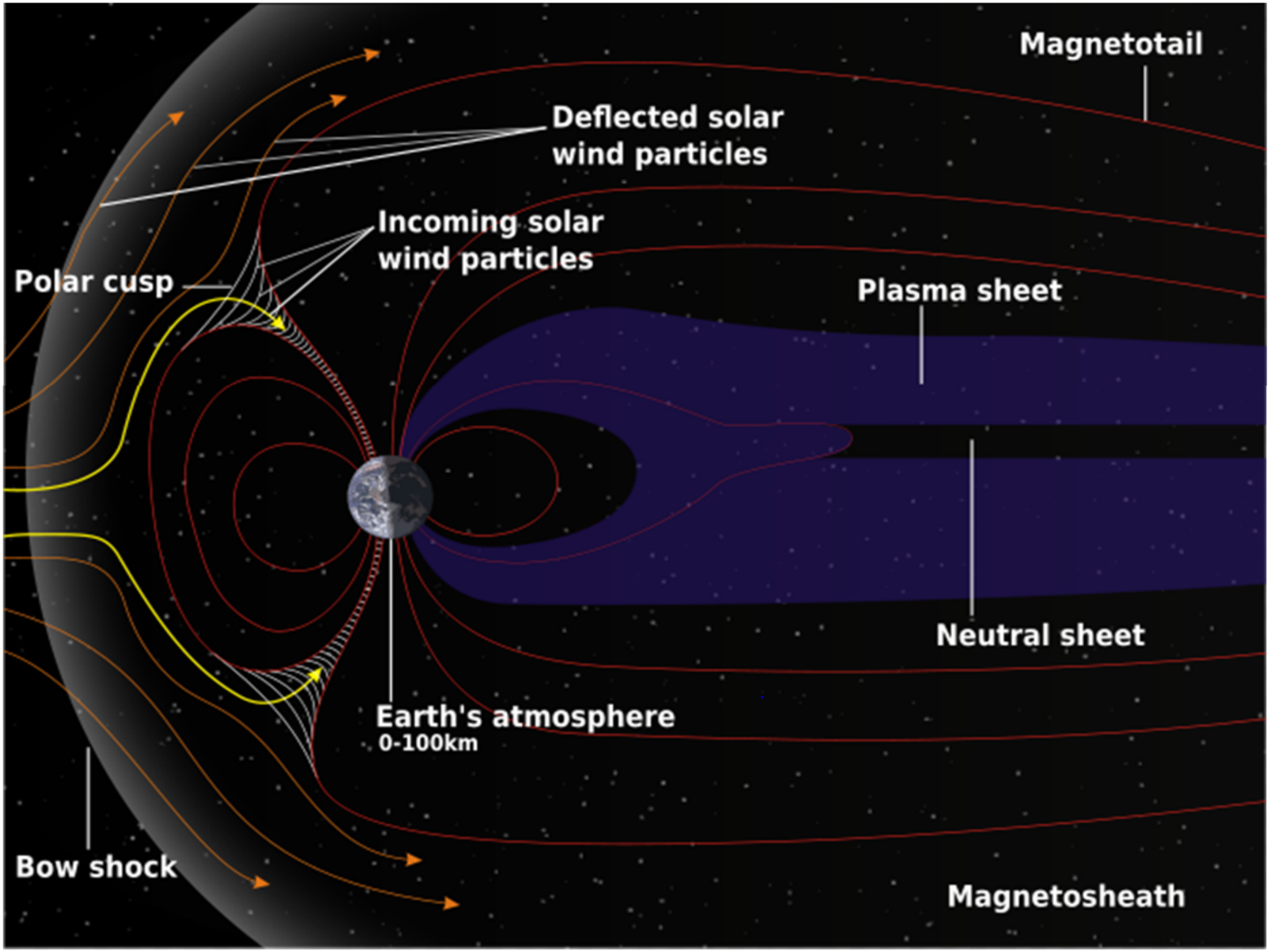
Fountain Effect and Equatorial Anomaly





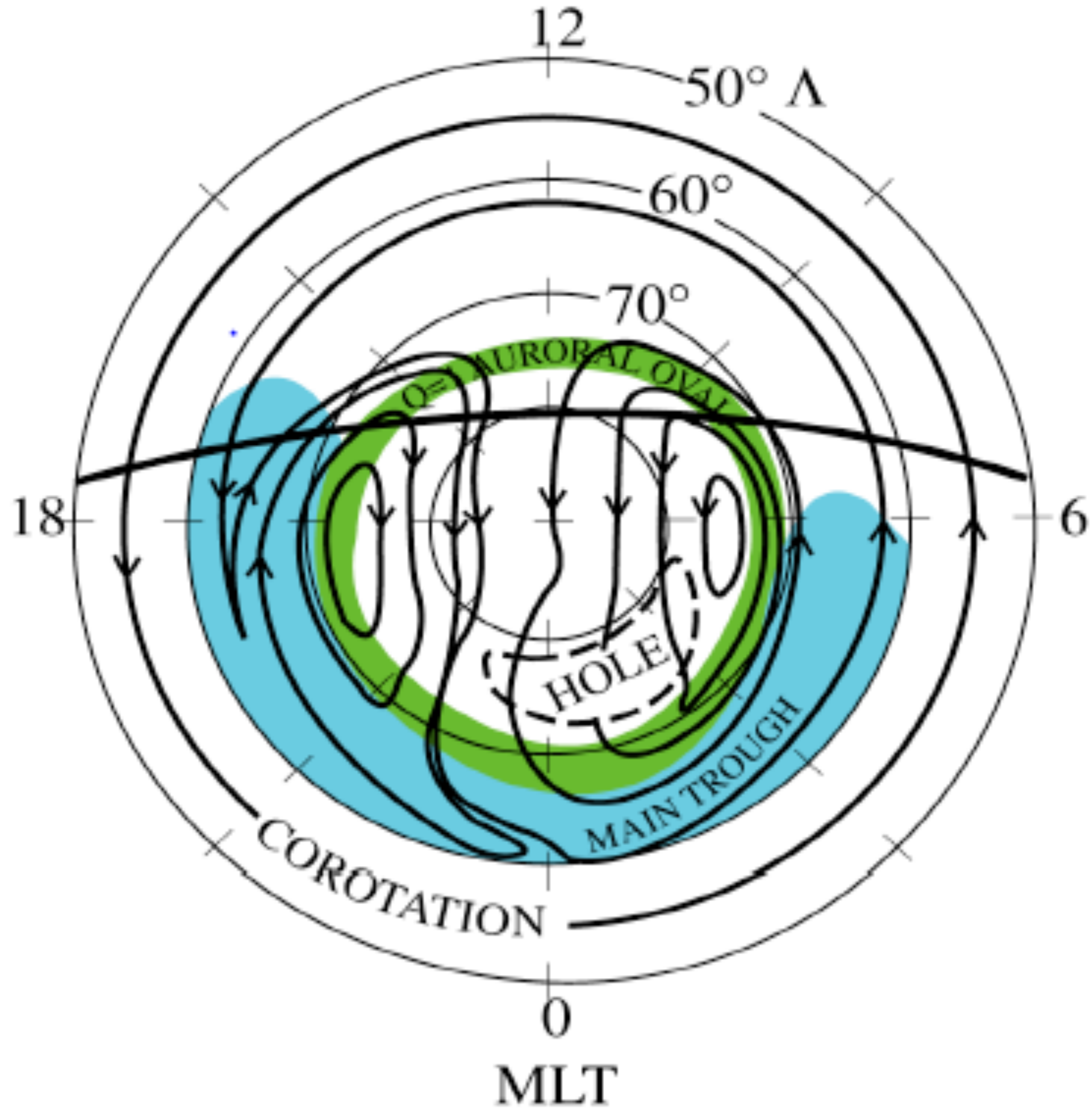
High Latitude Ionosphere

The Earth, the magnetosphere and solar wind

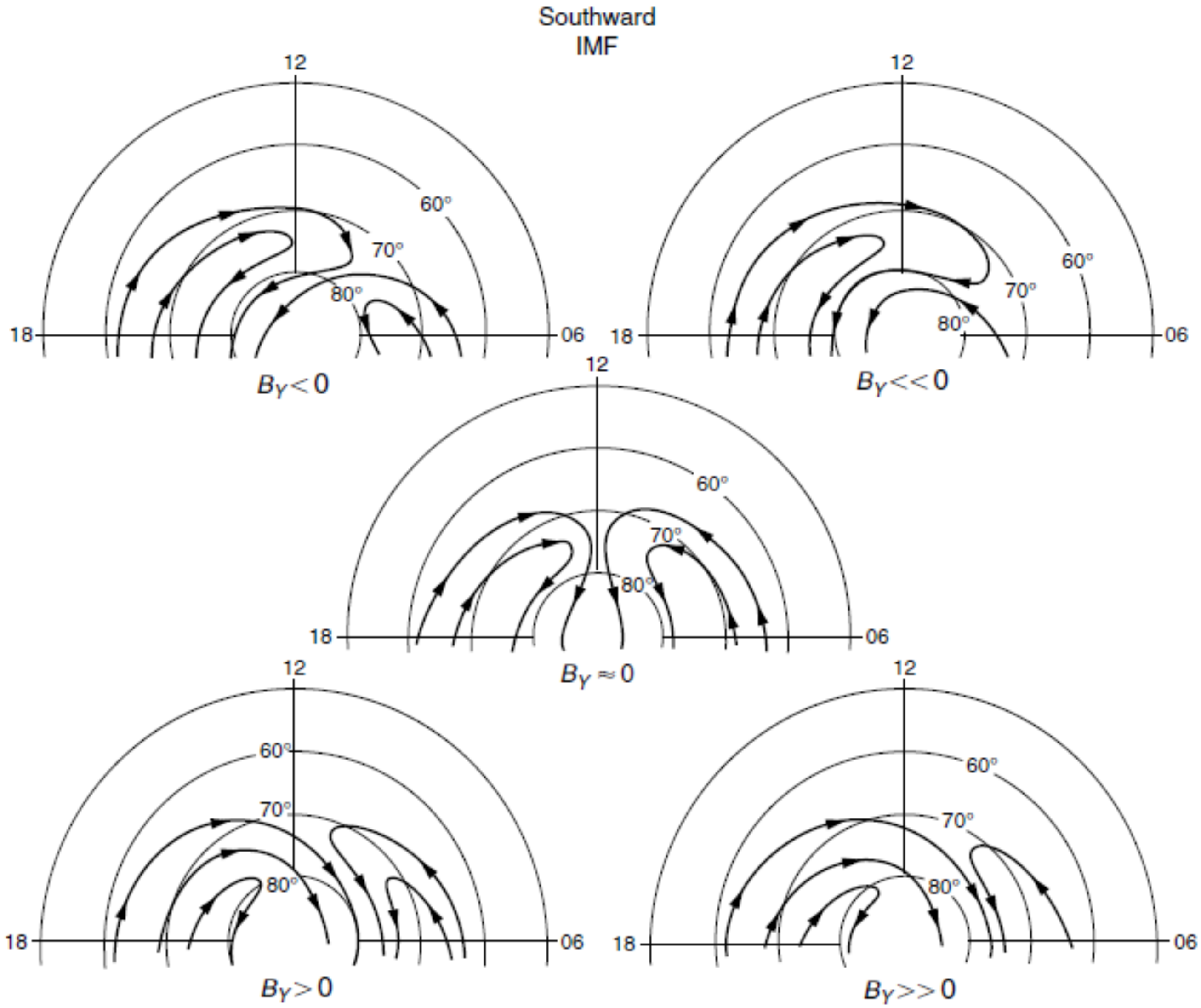


High-Latitude Ionosphere

The high-latitude ionosphere is dominated by the electric fields and currents that couple the ionosphere , outer magnetosphere and solar wind. The fields and currents are coupled along the Earth's magnetic field.



Daytime Polar Cap Convection during IMF B_z southward



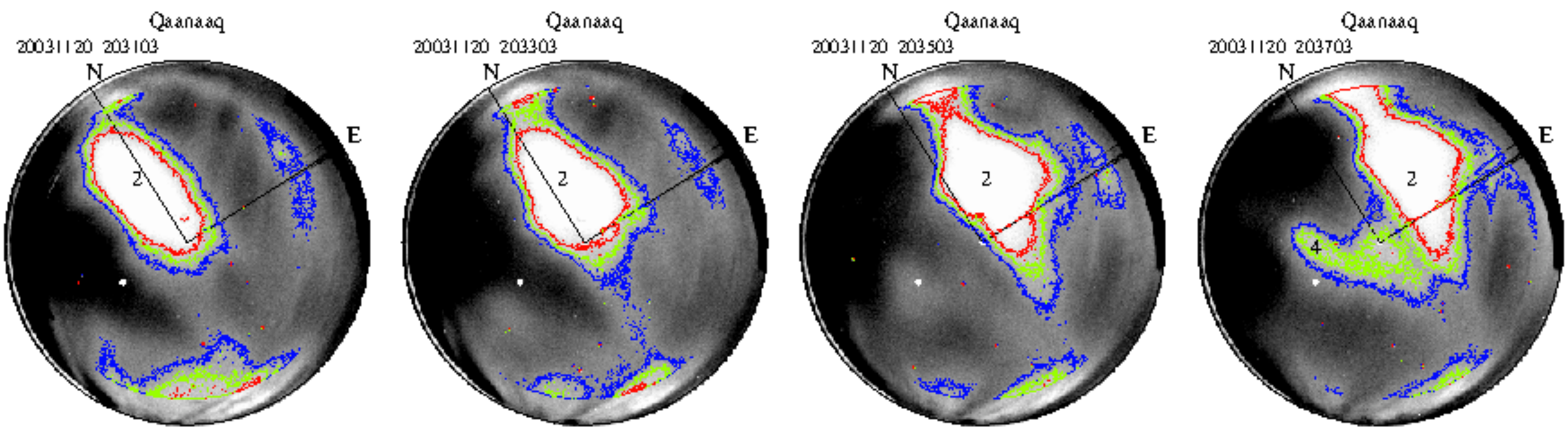
Heelis, 1984

High Latitude Meso-scale Structures

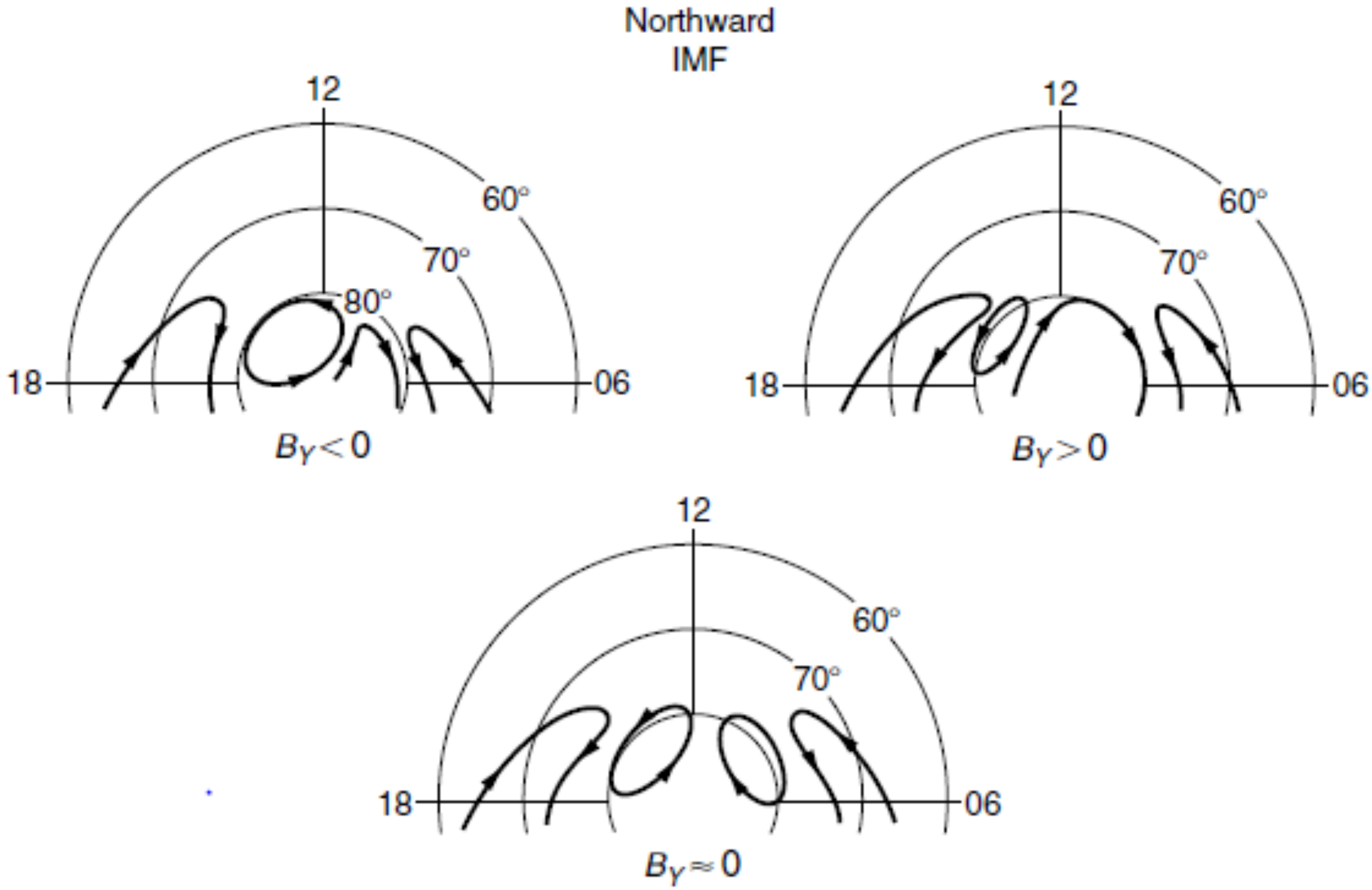
Propagating Plasma Patches
Propagating Atmospheric Hole
Propagating Polar Wind Jets
Propagating Neutral Streams
Sun-Aligned Polar Cap Arcs
Theta Aurora
Boundary and Auroral Blobs
Stationary Polar Wind Jets
Neutral Polar Wind Streams
Sub-Auroral Ion Drift Events (SAID)
Storm Enhanced Densities (SED) Ridges

Propagating polar cap patches

- Mesoscale Regions of Enhanced Plasma Density
- Created in or Equatorward of Noon Auroral Zone
- Antisunward Convection with Background Plasma
- Horizontal Extent of 200 - 1000 km
- Circular or Cigar-Shaped
- Single or Multiple Patches
- Density Enhancement of Few % to Factor 100
- Enhancement Extends Along B

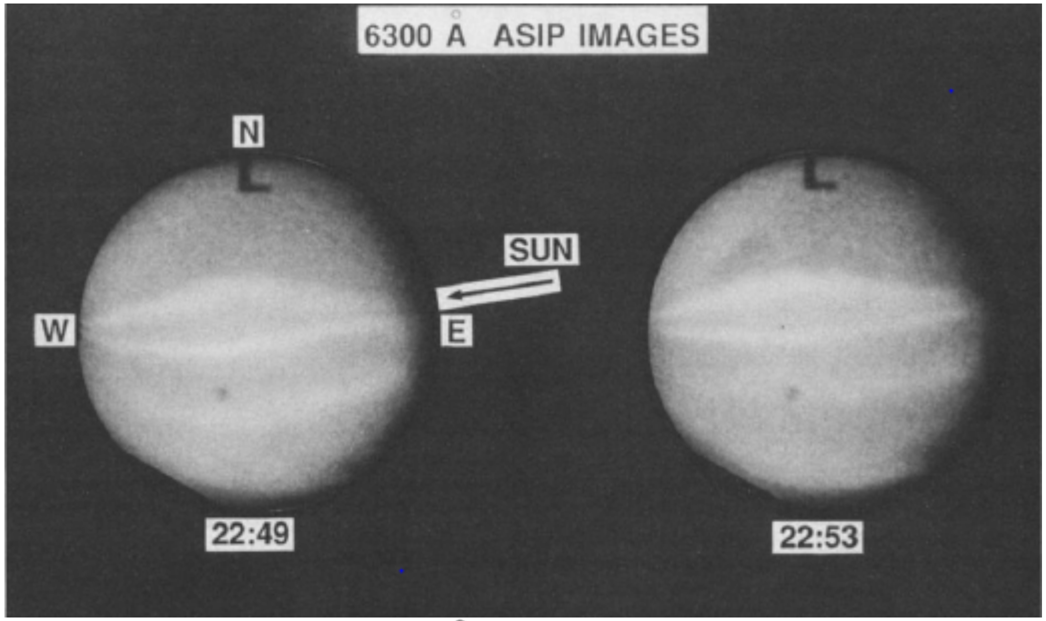


Daytime Polar Cap Convection during IMF B_z northward

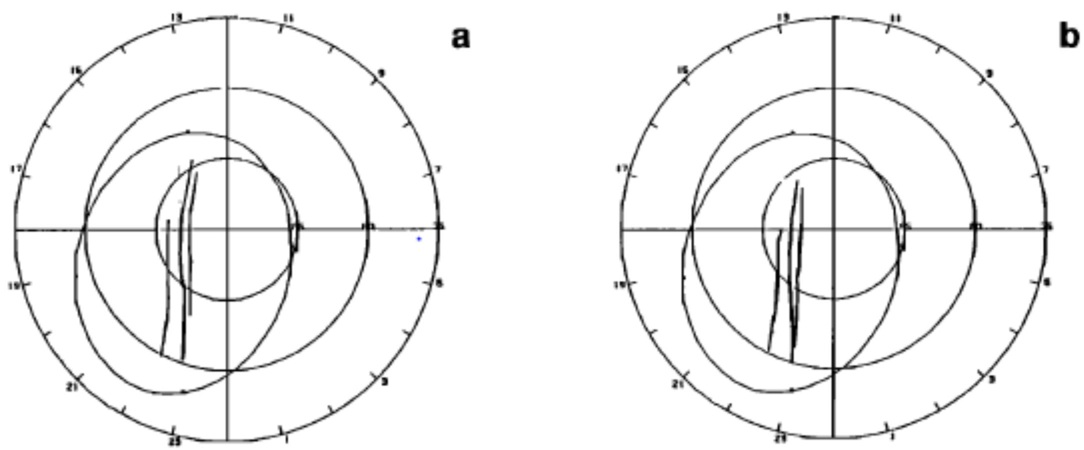


Heelis et al, 1986

Observations of Polar Cap (Sun-aligned) Arcs



6300 Å ASIP IMAGES
CORRECTED GEOMAGNETIC COORDINATE SYSTEM

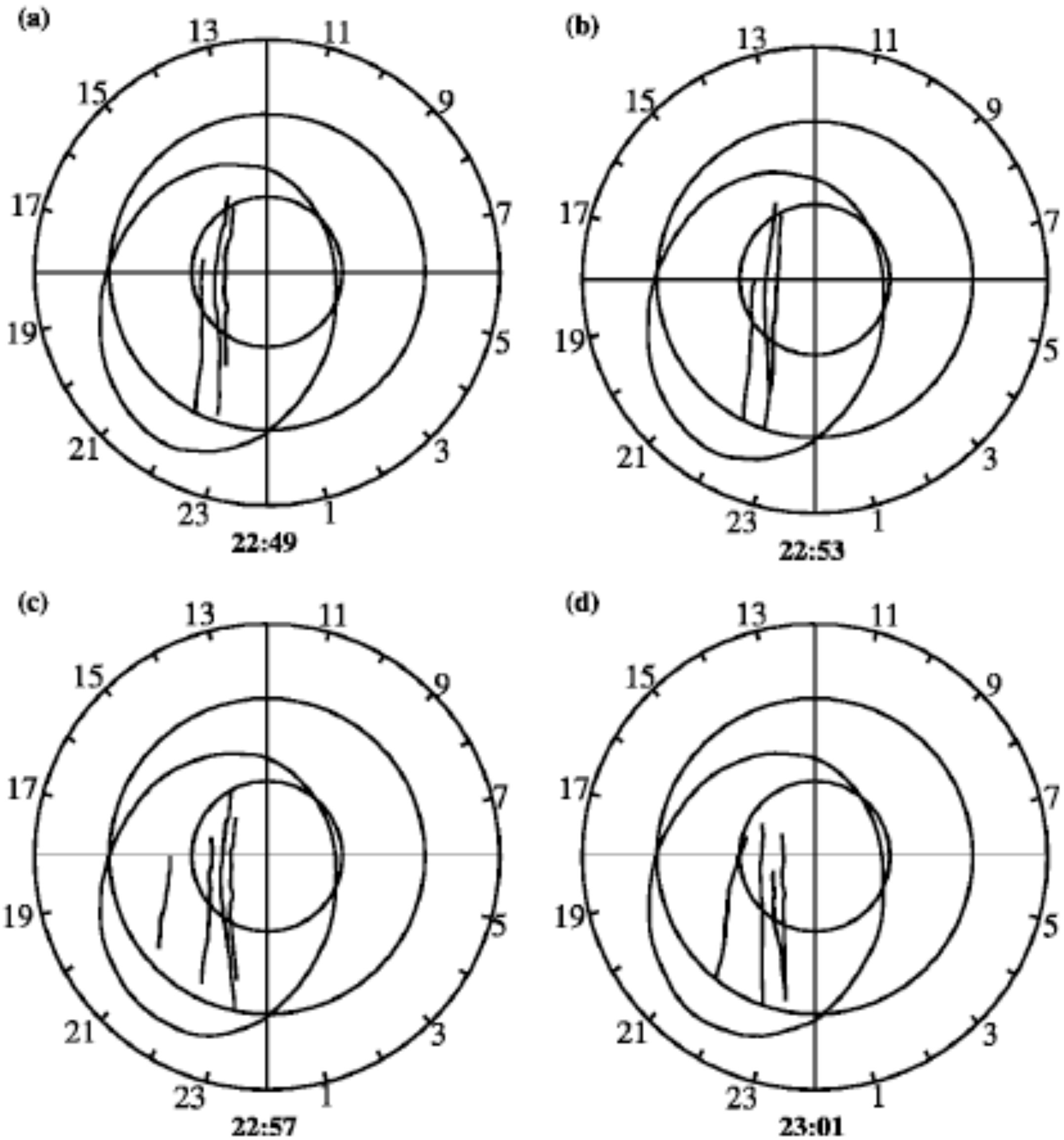


22:49 **22:53**

On the dawn-dusk motion of Polar Cap Patches

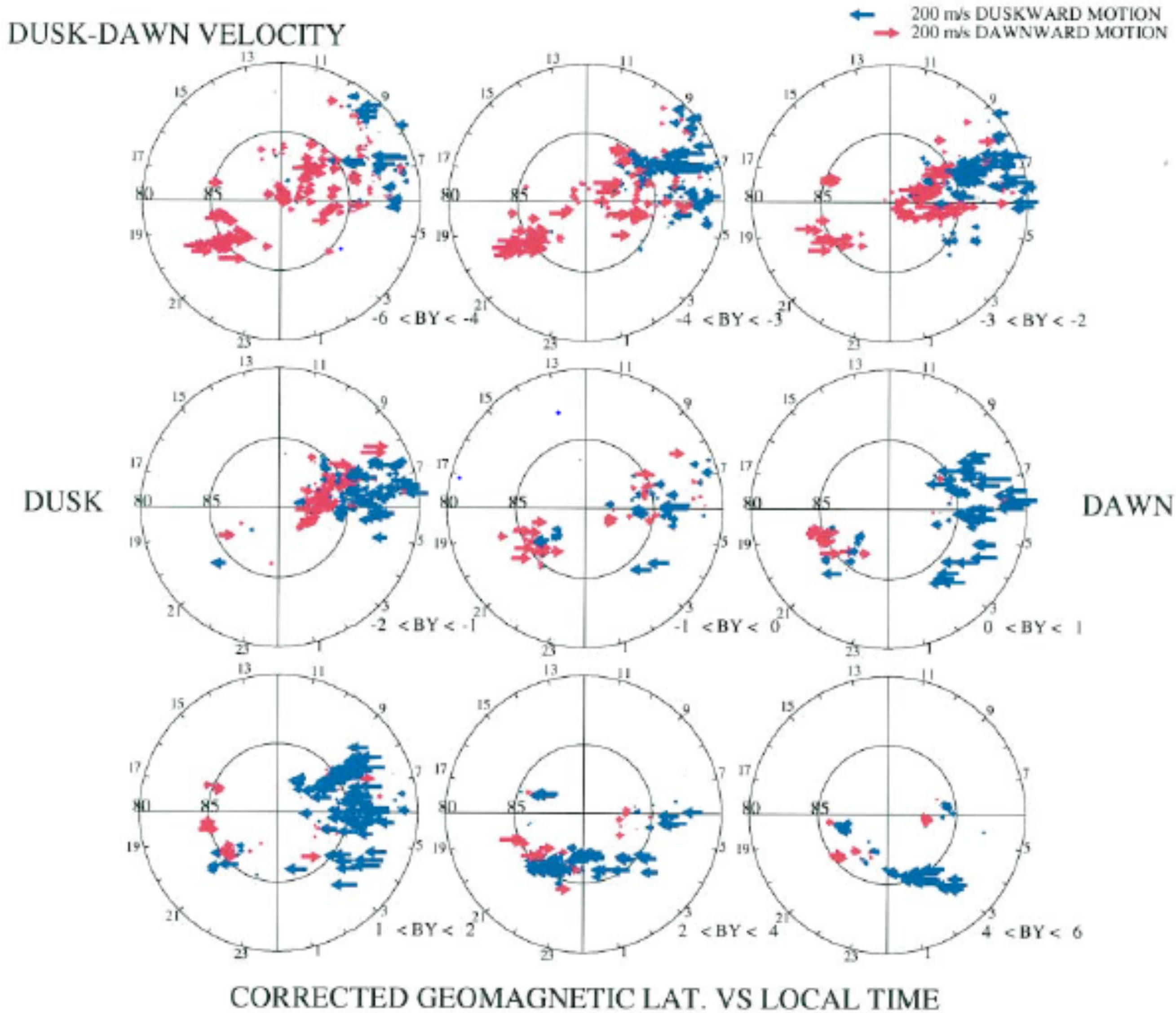
Greenland

100-300 km
by
1000-3000 km



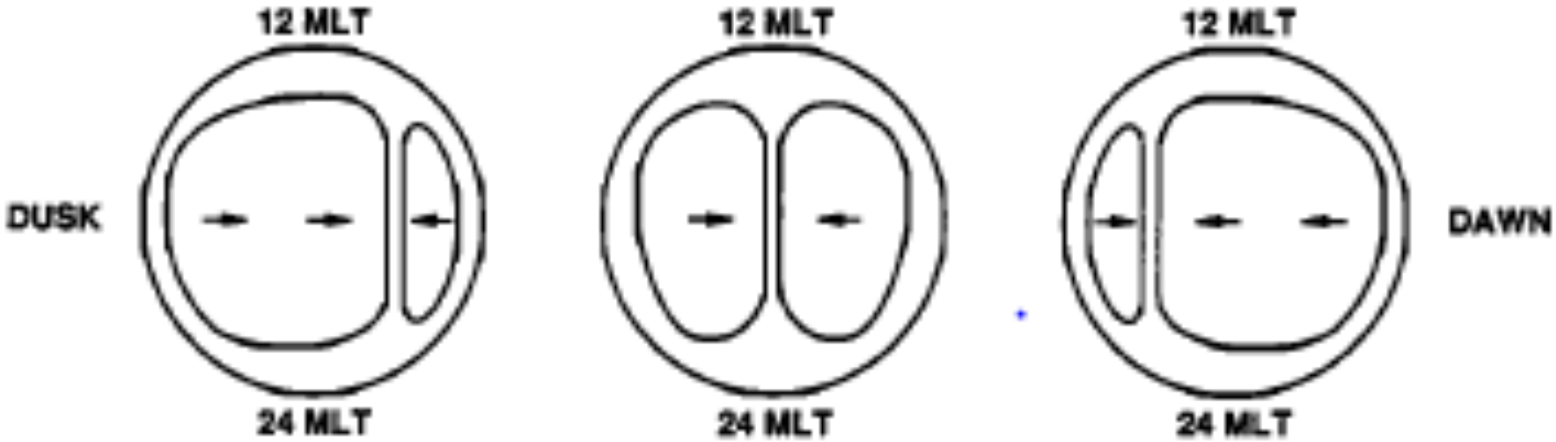
Valladares et al (1994)

Dawn-dusk motion of polar cap arcs (Sun-aligned)



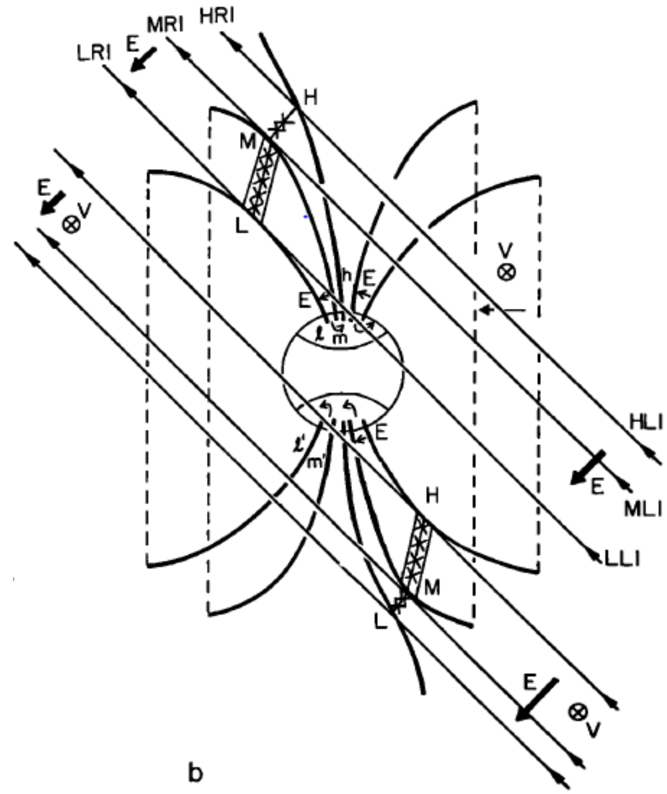
Valladares and Carlson, 1994

On the dawn-dusk motion of Polar Cap Patches

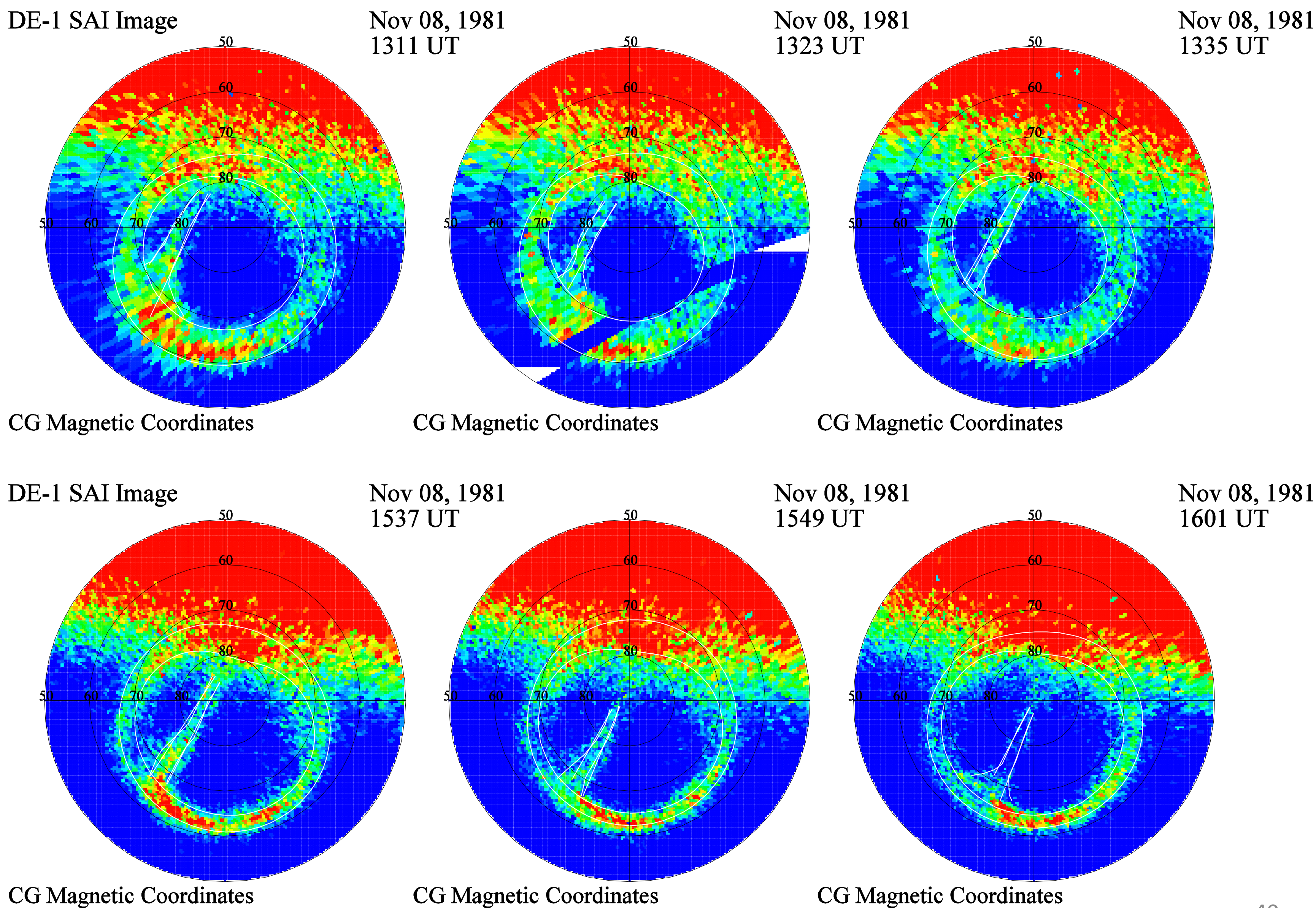


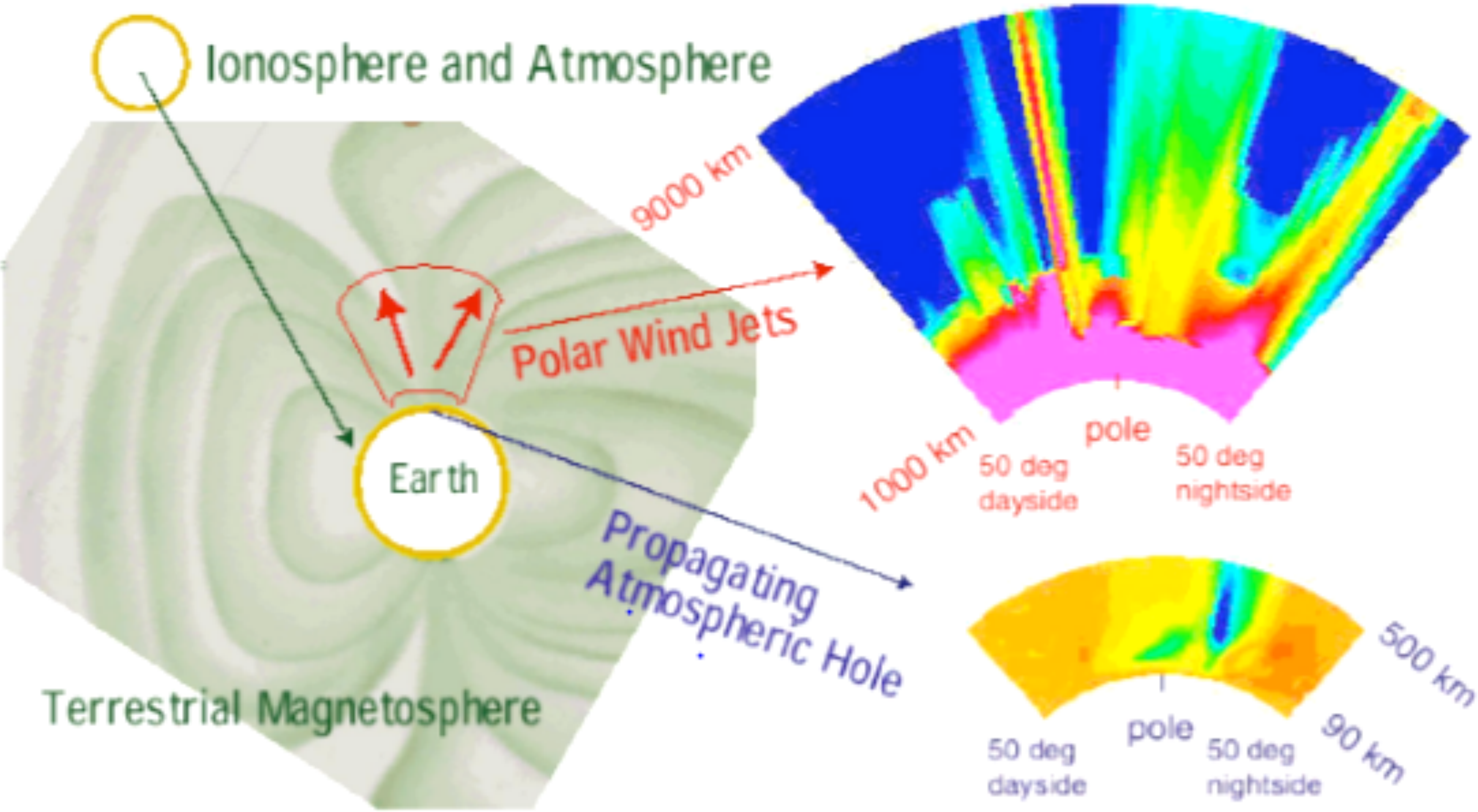
$B_y < 0$ $B_y = 0$ $B_y > 0$

If $B_y < 0$, $|B_y| \sim B_z$ and the magnetotail field lines are open, we recover the single lobe cell, whose direction of rotation is dependent on IMF By: counter- clockwise (clockwise) in the northern hemisphere for By < 0 (> 0). If the magnetotail field lines are closed, however, as shown here, (e.g., mMm') we predict two polar cap cells each with the same direction of flow. Merging of closed tail fields in the northern dawn cusp drives convection in the southern downside, and similarly for the southern dusk.



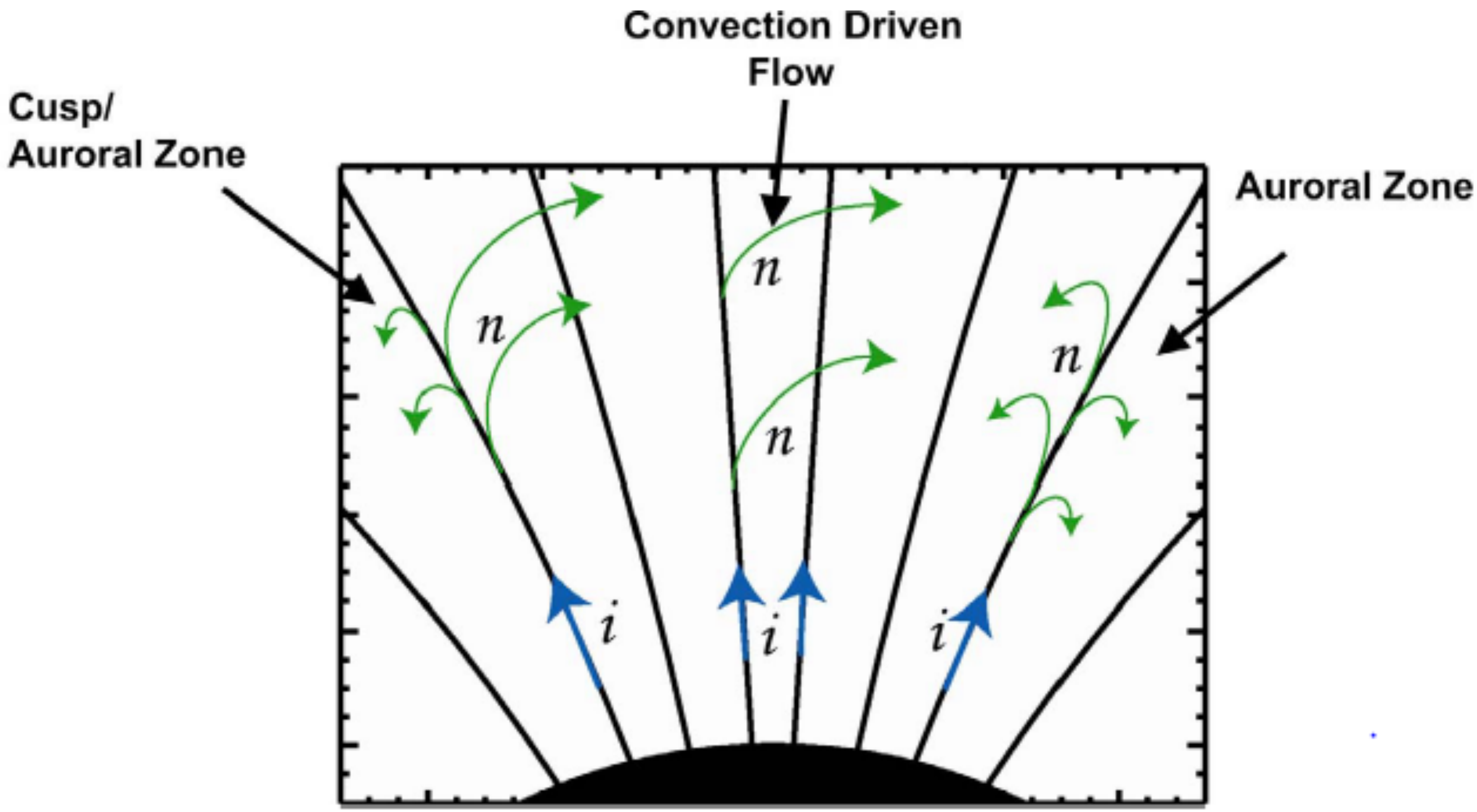
Transpolar (Theta) Aurora





The near Earth domain is composed of the magnetosphere polar wind, ionosphere and neutral atmosphere. Show are propagating supersonic polar wind jets, and propagating atmospheric holes.

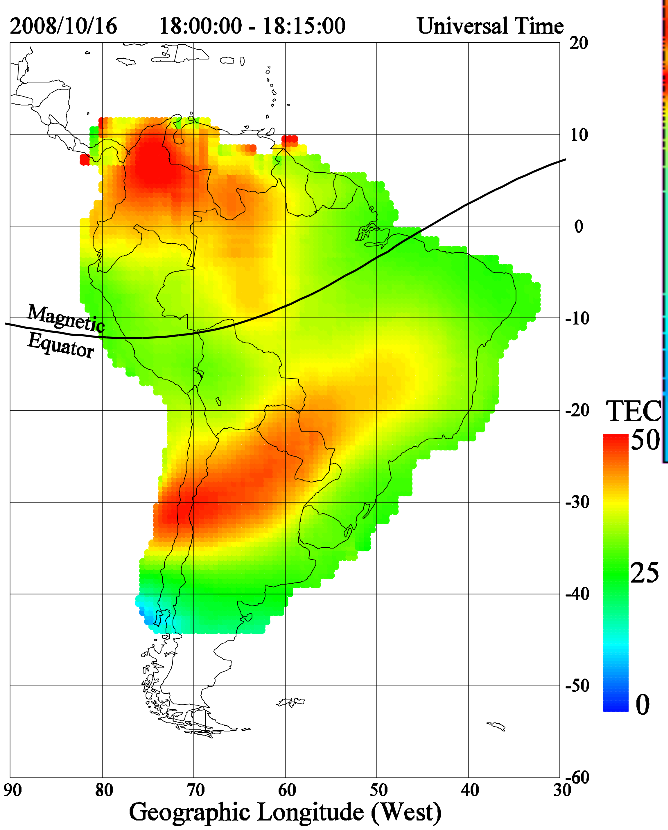
Schematic diagram showing the creation of streaming charge exchange neutrals (H_s and O_s; designated by n) created from up-flowing H^+ and O^+ ions (designated by i).

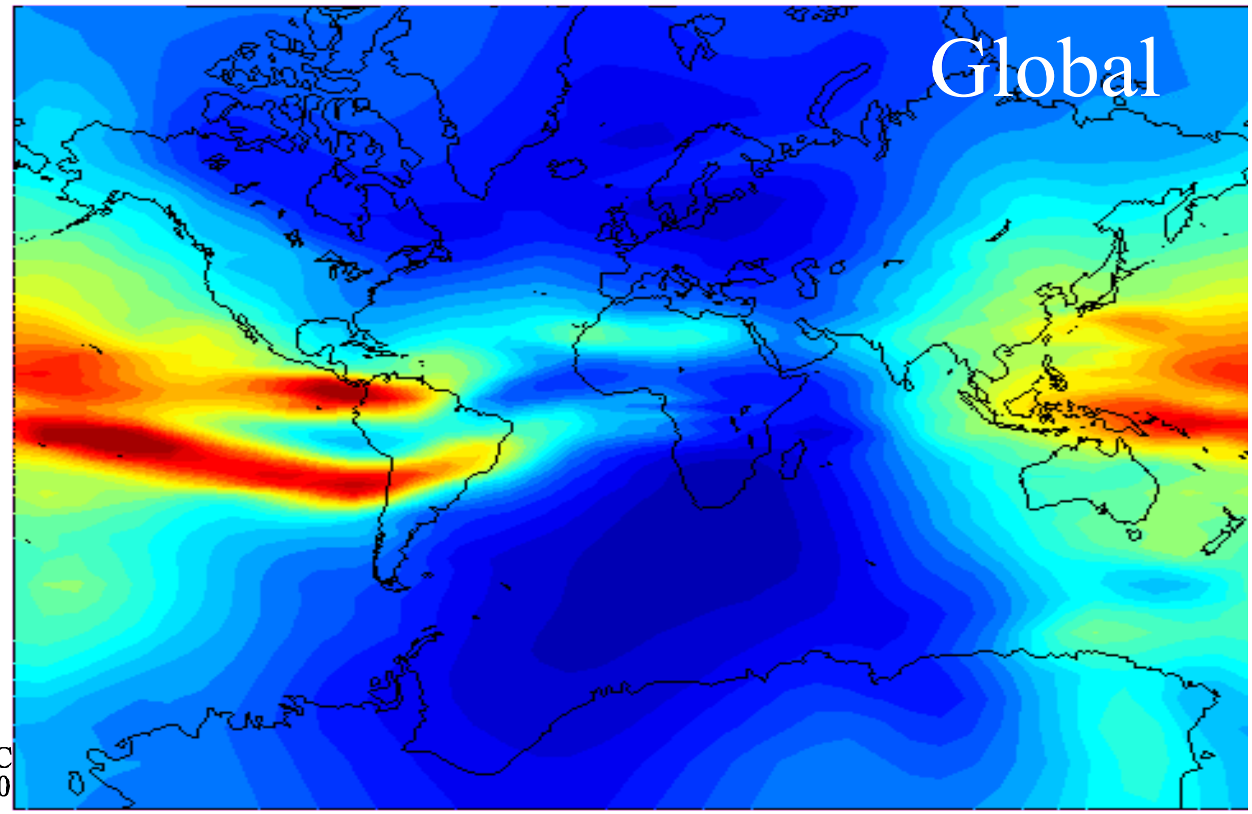


Gardner and Schunk [2005]

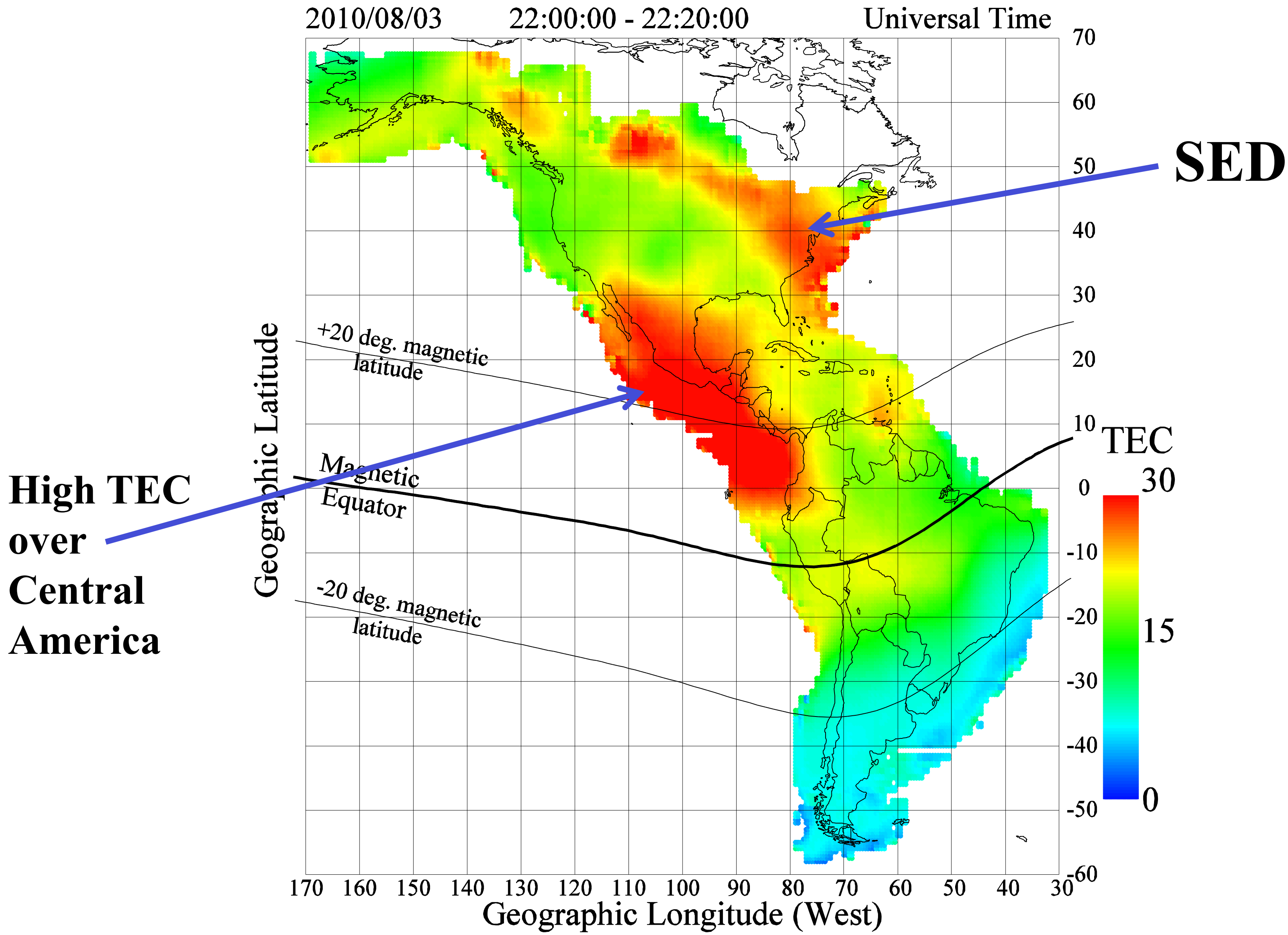
Ionosphere TEC values

Regional





Two channels of high TEC formed over the Americas on August 3, 2010, during a magnetic storm.



Summary

Status of Ionospheric Research

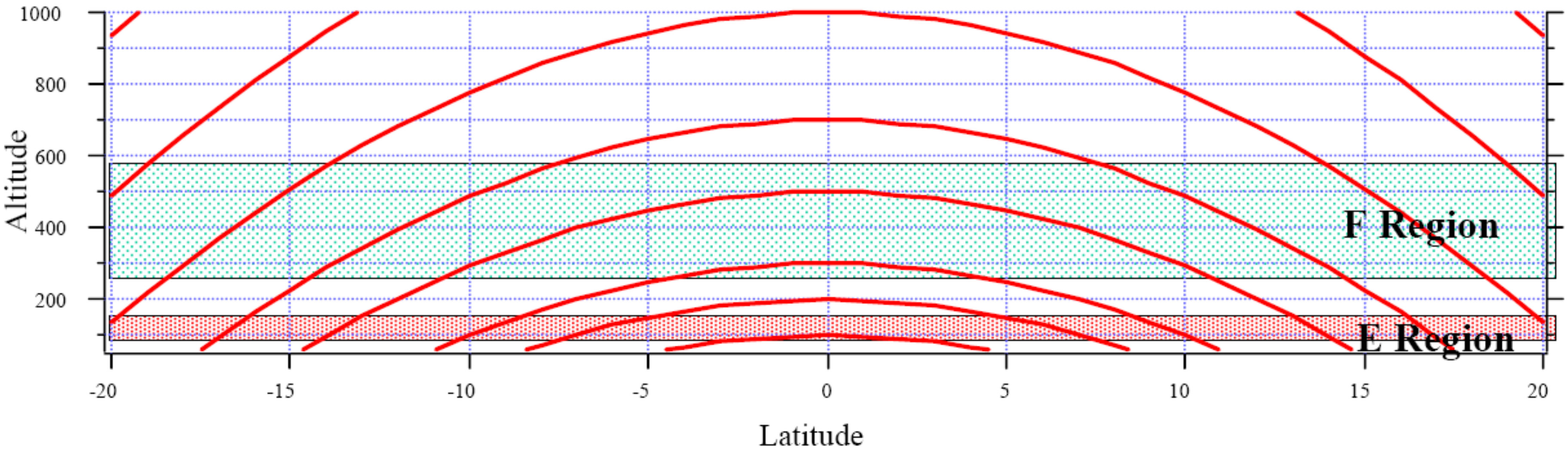
- Ionosphere has both a background State (Climatology) and a Disturbed State (Weather).
- Climatology is basically understood.
- Weather involves Storms, Substorms, Plasma Structures, Wave Activity, and Plasma Instabilities.
- Main research focus is on Weather

References

1. A. Brekke: Physics of the Upper Atmosphere, John Wiley & Sons, 1997.
2. H. Risbeth and O. K. Garriot: Introduction to Ionospheric Physics, Academic Press, 1969.
3. J. K. Hargreaves: The solar-terrestrial environment, Cambridge University Press, 1992.
4. M. C. Kelley: The Earth's Ionosphere, Academic Press, 1989.
5. R. A. Heelis: Electrodynamics in the low and middle latitude ionosphere: A tutorial, JASTP, 2004.
6. C. E. Valladares and H. Carlson: Interplanetary magnetic Field Dependency of stable Sun-Aligned Polar Cap Arcs, JGR, 1994.

Ionospheric Current Equations

$$\vec{J} = Ne\left(\vec{V}_i - \vec{V}_e\right) \qquad \nabla \bullet \mathrm{J} = 0 \qquad \frac{\partial \vec{J}^{\perp}}{\partial \perp} + \frac{\partial \vec{J}^{\|}}{\partial \|} = 0$$



Assume that: No current flows out of the bottom of the E region and above 1000 km the perpendicular current is negligible.

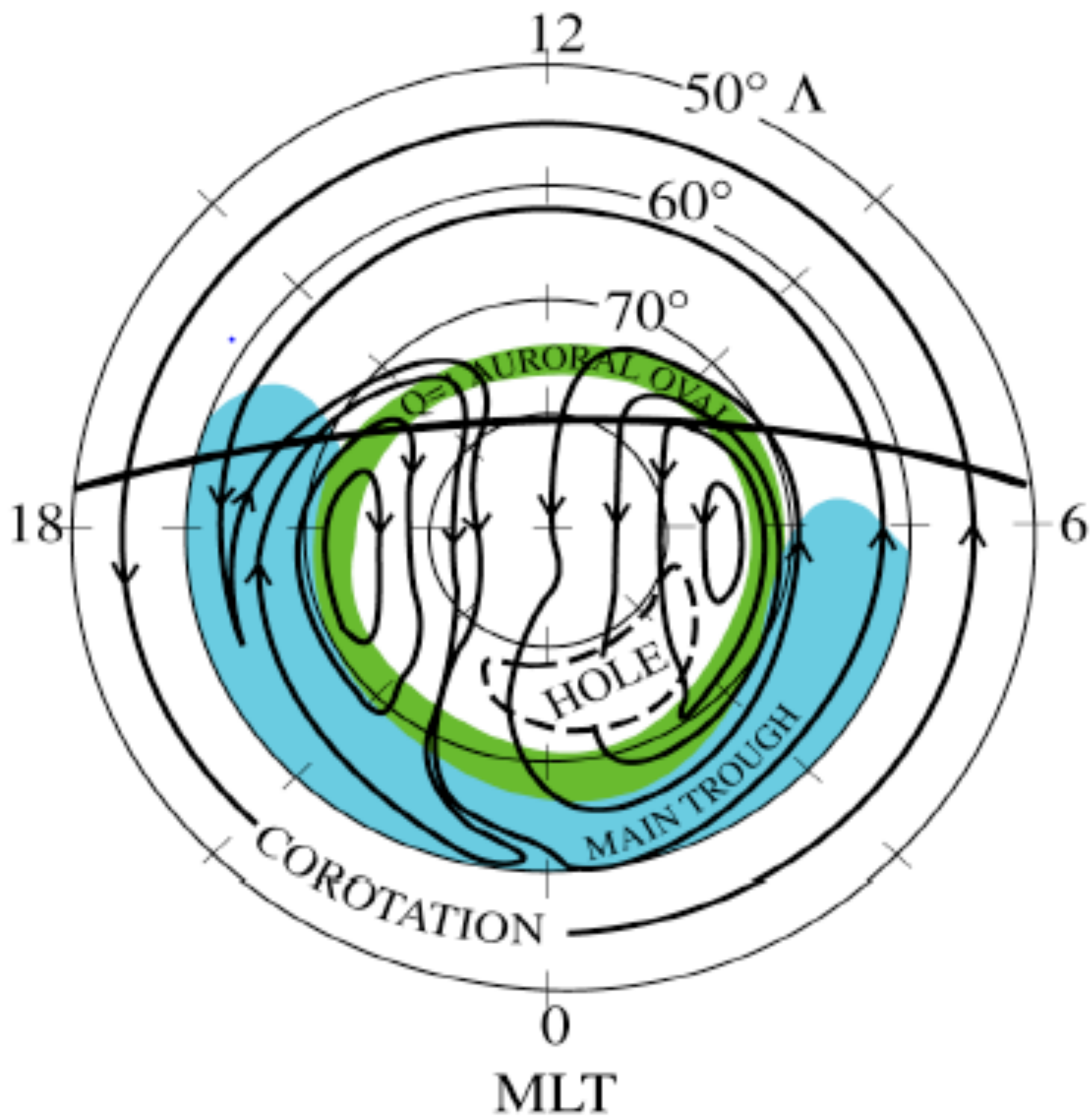
$$\int_{\text{base 1}}^{\text{base 2}} \nabla_{\perp} \cdot (\tilde{\sigma}\mathbf{E}^{\perp})\mathrm{d}s = -\int_{\text{base 1}}^{\text{base 2}} \nabla_{\perp} \cdot (\tilde{\sigma}(\mathbf{U} \times \mathbf{B}))\mathrm{d}s + j^{\|}_{\text{base 1}} - j^{\|}_{\text{base 2}}$$

Integration along the B field from the base of the E region to the E region in the other hemisphere,

The E and the UxB terms are taken out of the integral

$$\nabla_{\perp} \cdot \Sigma\mathbf{E} = -\nabla_{\perp} \cdot \Sigma(\mathbf{U} \times \mathbf{B}) + j^{\|}_{\text{base 1}} - j^{\|}_{\text{base 2}}.$$

High Latitude Climatology



Plasma Electrodynamics

- Collisions with neutral particles.

  Assume that neutral atmosphere and winds are given.
  Tidal oscillations that propagate up from below.
  In-situ circulation due to high-latitude energetic particles,
  Joule heating, and local heating from the sun.

- Electric Fields

  Externally applied from magnetospheric sources.
  Assume that they apply a potential difference across the region.
  Internally produced to make total current divergence free.

- Lorentz Force

  A charged particle in motion feels a force $q(\vec{V} \times \vec{B})$

- Gravity

  Most important for ions.

- Pressure Gradient

  Perpendicular to the magnetic field this current is divergence free.
  Parallel to the magnetic field is produces an ambipolar electric
  field to make ions and electrons move together.

Diffusion

Diffusion consists of gas transport due to thermal motion of the gas molecules. Diffusion takes place when two different gases occupy the same volume and there is a gradient in the density and/or temperature of one of the gas species.

If $v = -\frac{D}{n}\frac{\partial n}{\partial x}$

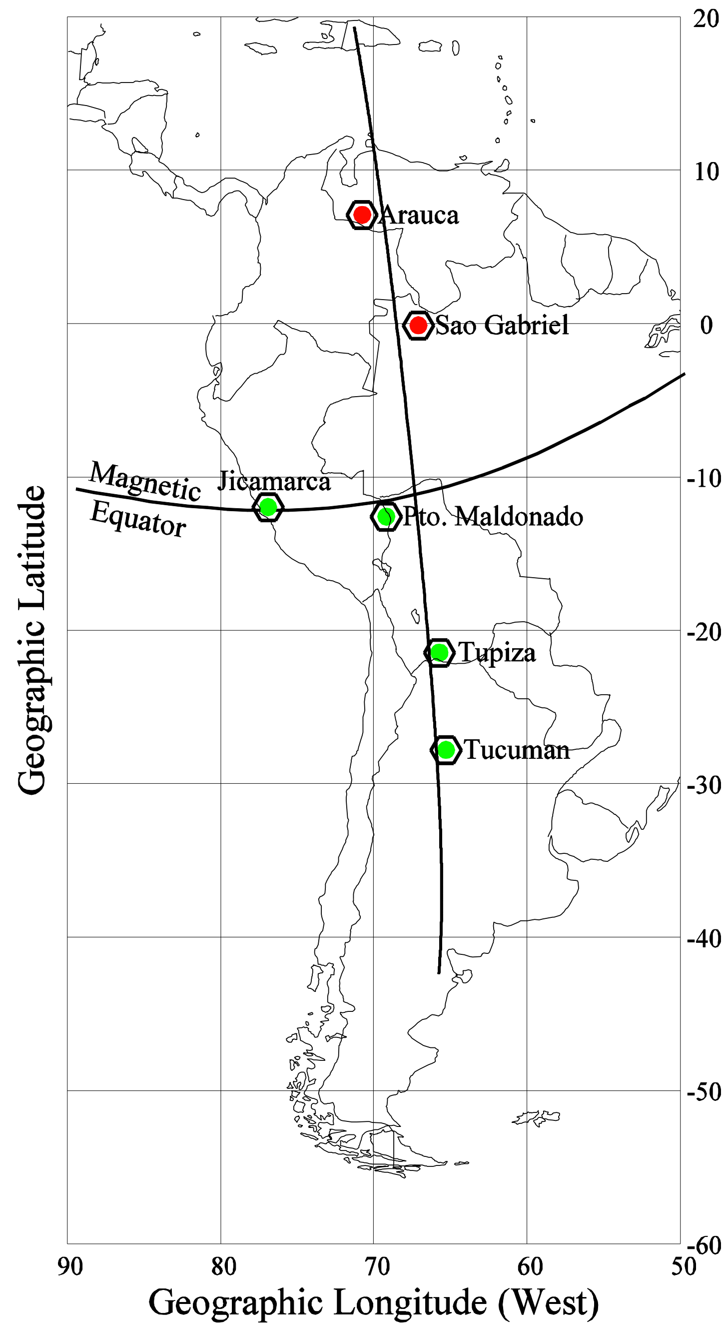
D-region ionization and recombination

Ionospheric diffusion. With and without magnetic Field

LISN network of VIPIRs

The low-latitude Ionosphere Sensor Network (LISN) is a distributed observatory designed to monitor and specify the condition of the ionosphere over South America in a regional context. LISN also includes a network of 5 VIPIR ionosondes. Three are presently operating, and a 4th is placed at Jicamarca. The last 2 VIPIRs will be installed in 2015. VIPIRs are able to interleave pulses doing a frequency sweep and an HF fixed frequency simultaneously.

http://lisn.igp.gob.pe



Ionospheric Regions

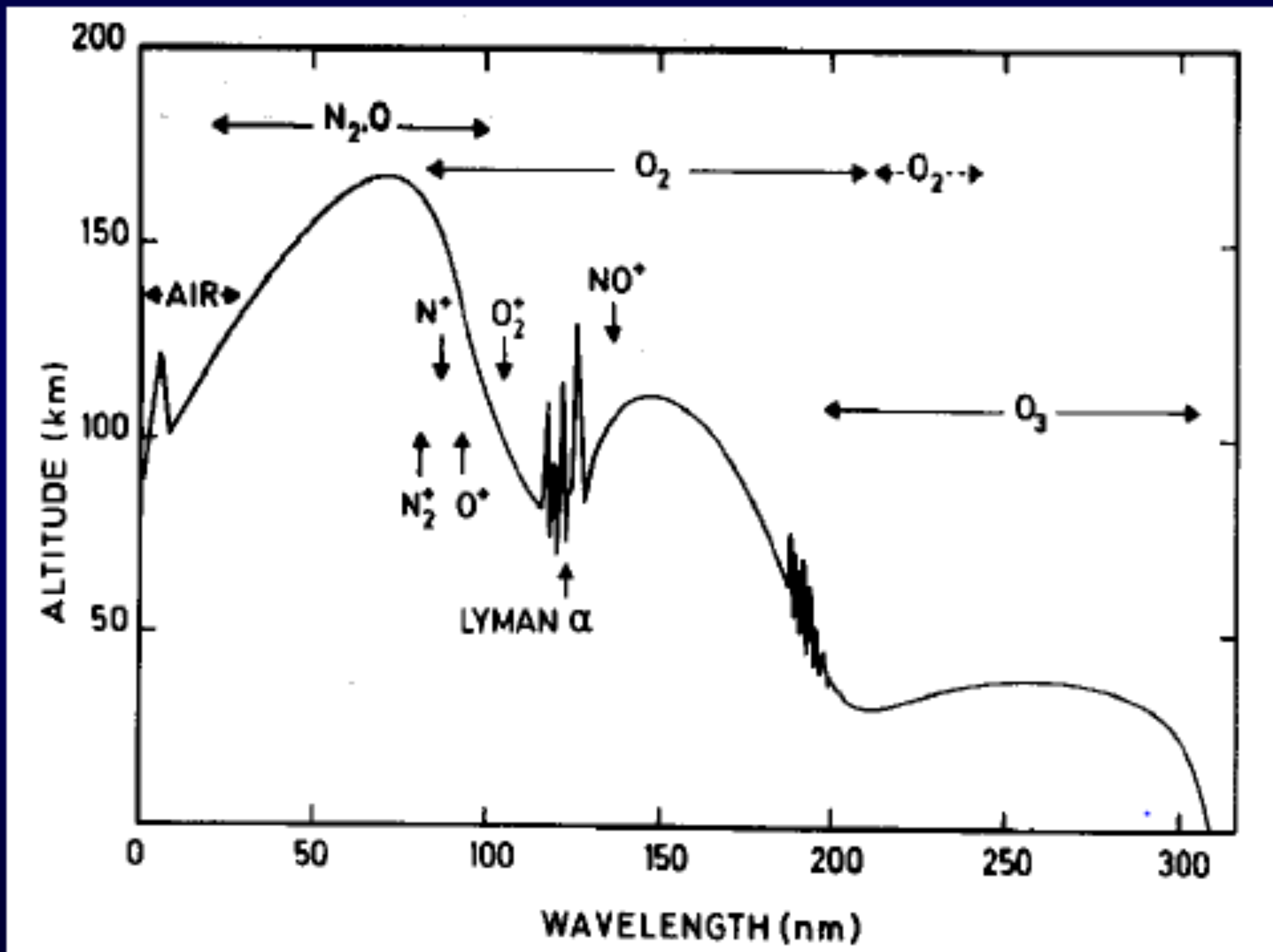
D–region: 60 – 90 km, $n_e = 10^8–10^{10}\ m^{-3}$
E–region: 90 – 150 km, $n_e = 10^{10}–10^{11}\ m^{-3}$
F–region: >150 km, $n_e = 10^{11}–10^{12}\ m^{-3}$.

These regions are physically different because of their different ion chemistry.

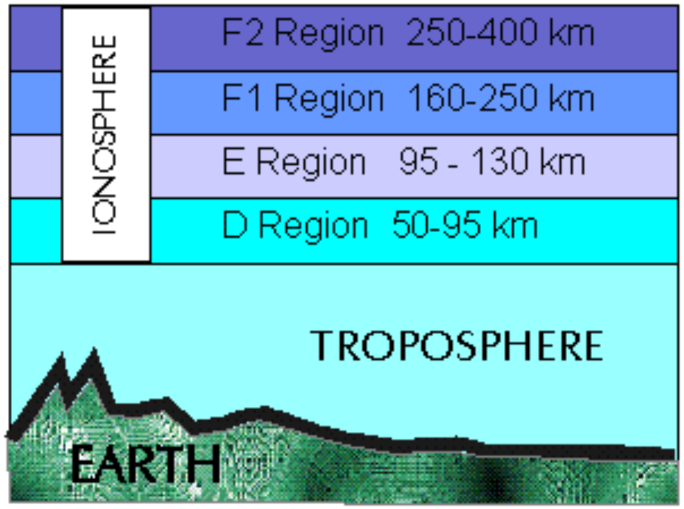
The F1 layer forms in the bottomside F-region electron density during day time in solar maximum conditions. The D-region disappears during night. Also the E-region becomes weaker in the nighttime, and the F-region slowly decays during the night.

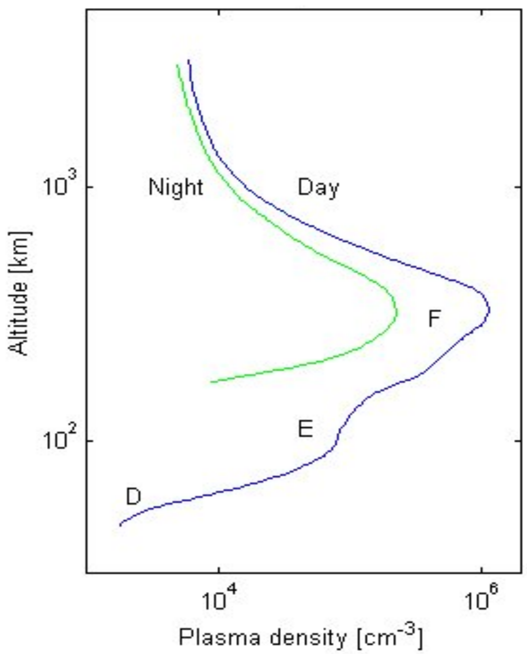
At high latitudes the E-region electron densities may increase drastically during the nighttime exceeding even the F-region peak due to auroral particle precipitation.

Penetration of solar radiation



The Ionosphere (continued)





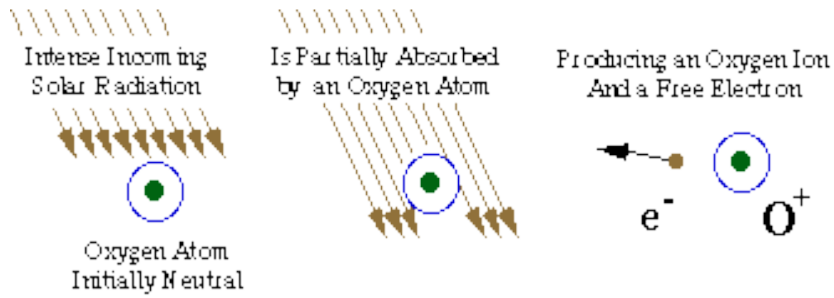
F Layer is most dense and highly variable.

The region of the atmosphere in which free electrons exist in sufficient quantities to affect the propagation of radio waves.

•Begins at about 50km and extends into space

•Produced by UV radiation from the Sun

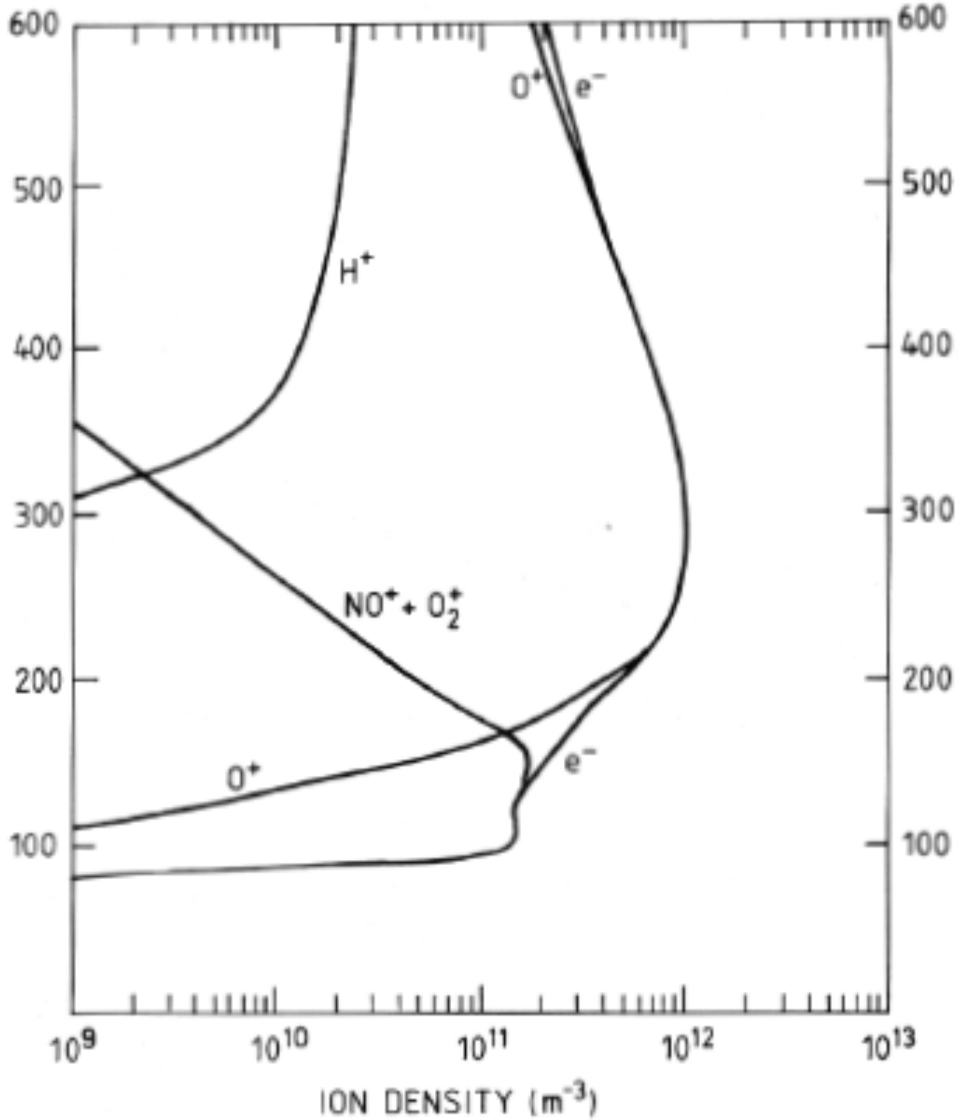
Photoionization



•Reverse process is *Recombination*

•Controlled by chemical composition and transport by neutral winds

The ion composition changes according to the molecular constituents in the neutral atmosphere. NO^+ and O_2^+ are the dominant ions below 150km. At greater heights O^+ ions are more abundant and the number of H^+ ions starts to increase rapidly above 300 km.



The distribution of ions depends on solar and magnetospheric activity.

Richmond, 1987