

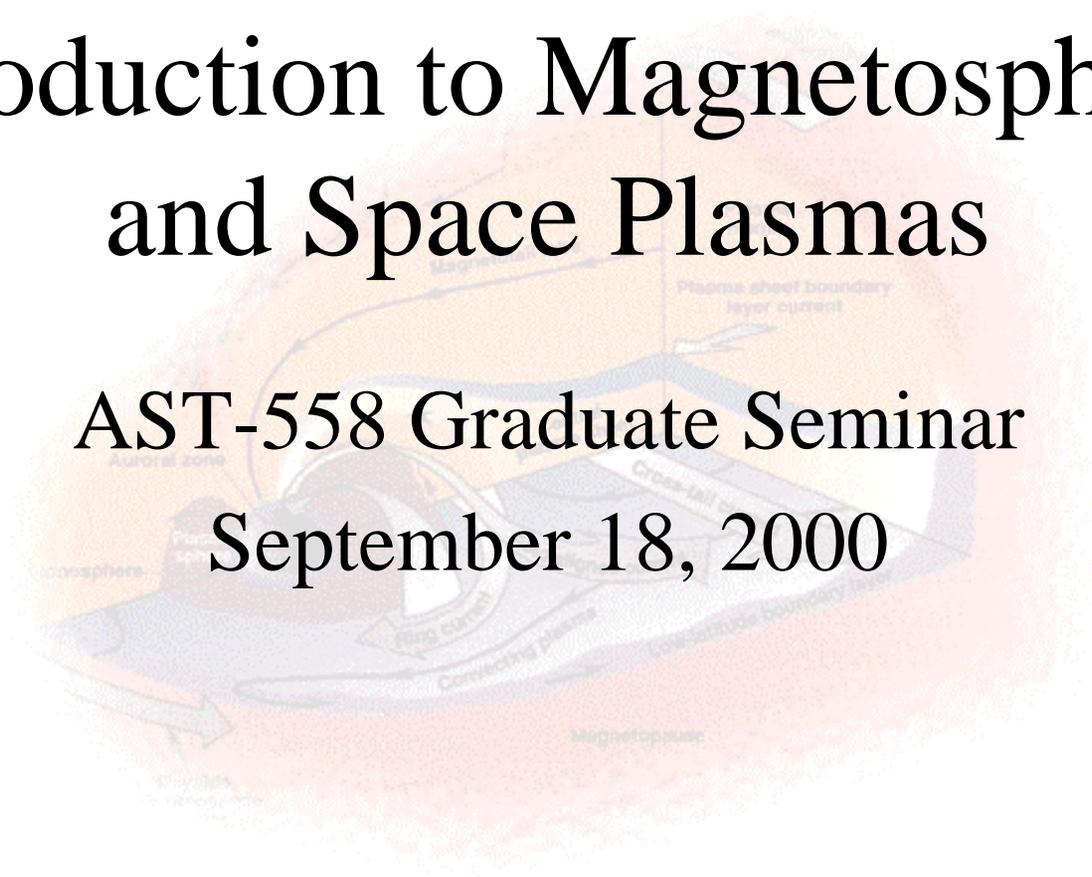
# Auroral Arcs



# Introduction to Magnetospheric and Space Plasmas

AST-558 Graduate Seminar

September 18, 2000

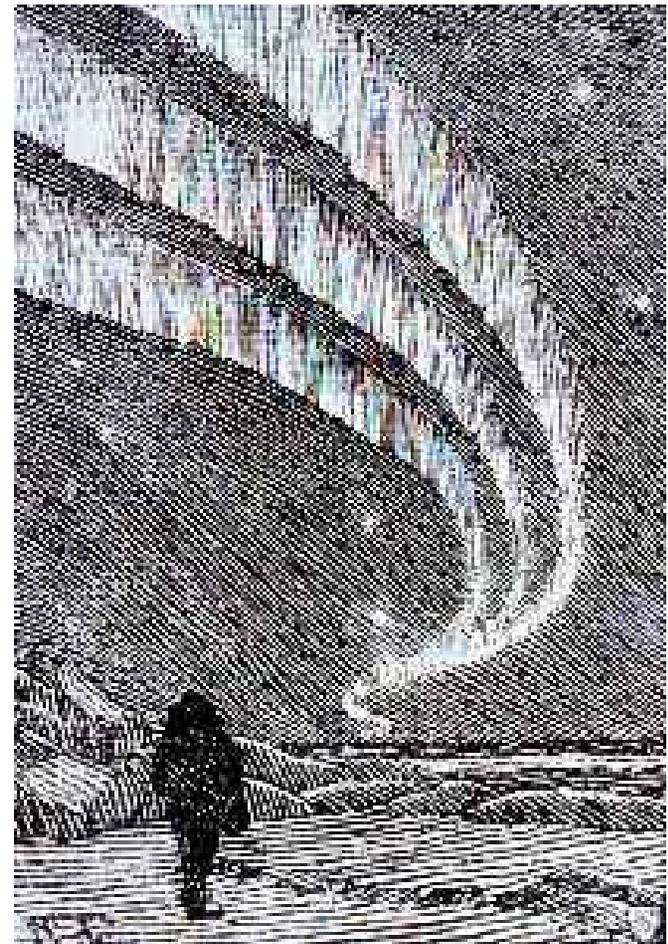


# Aurora in Antiquity



- Fires
- Bad Omen (Julius Ceasar, Attila ...)
- Dancing Animals or Dragons
- Swords of Heaven
- Red Spear Shafts
- Cracks in the Sky

# Historical Recording of Aurorae



# Auroral Spiral



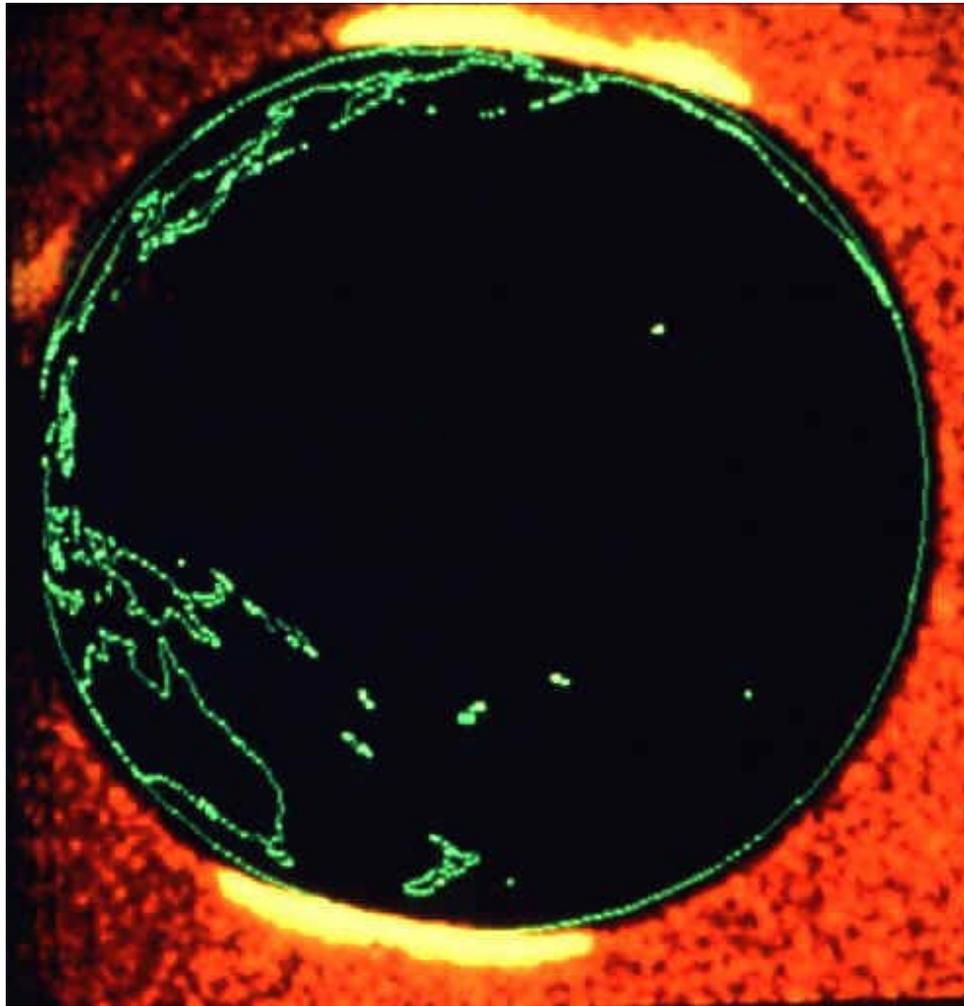
# Auroral Arcs



# Auroral Arc from Space Shuttle



# Aurora from DE-1

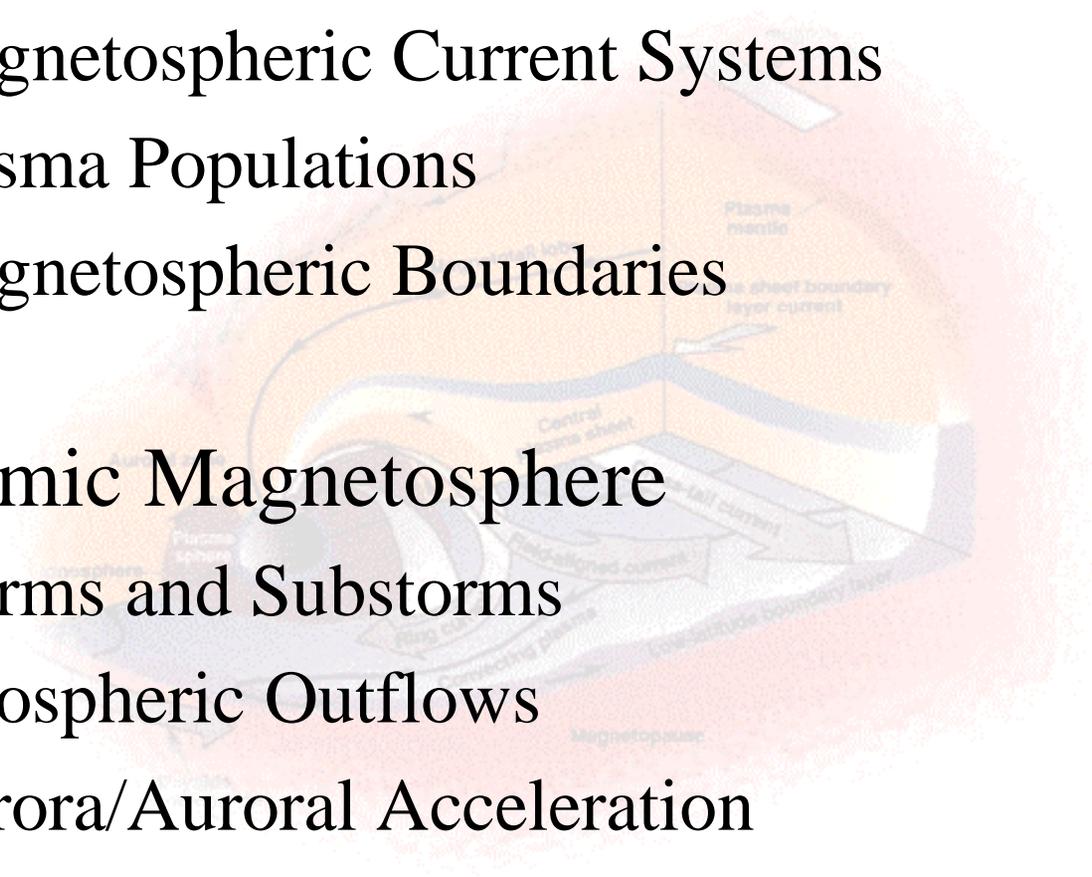


# Aurora over Fells Glacier

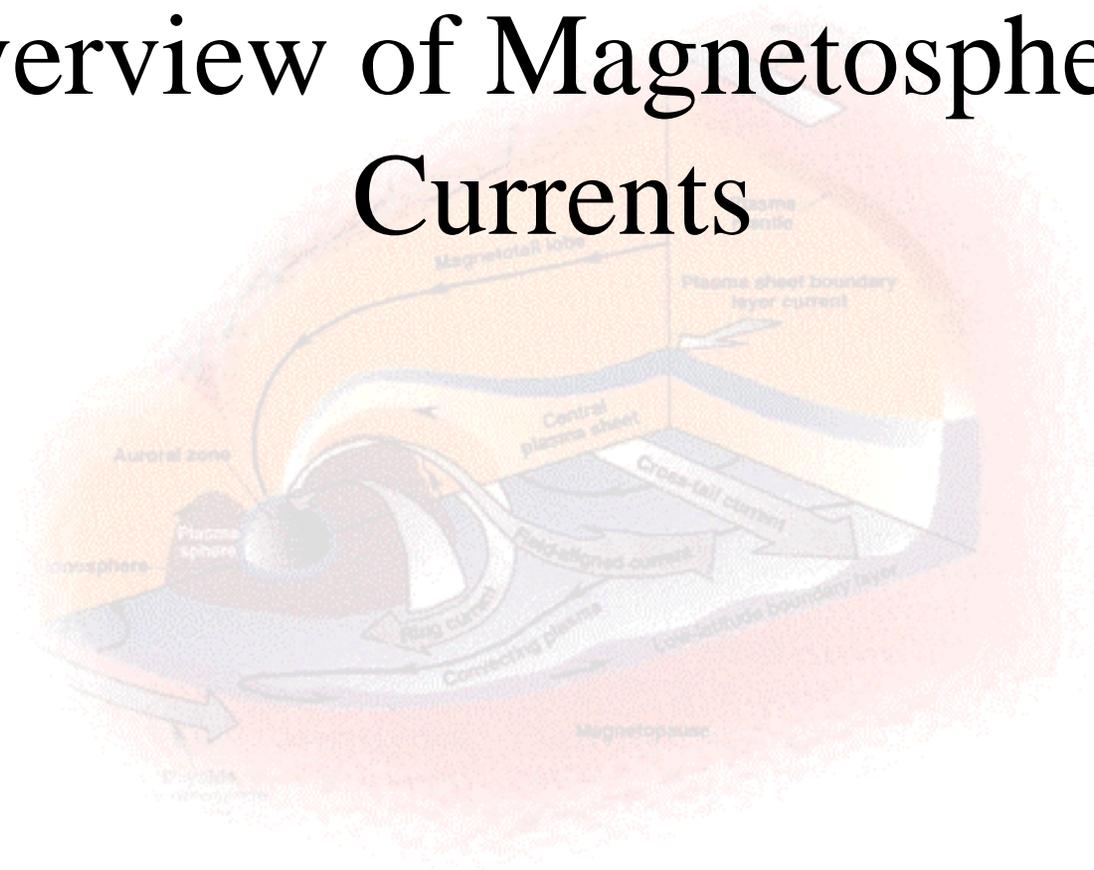


# Outline

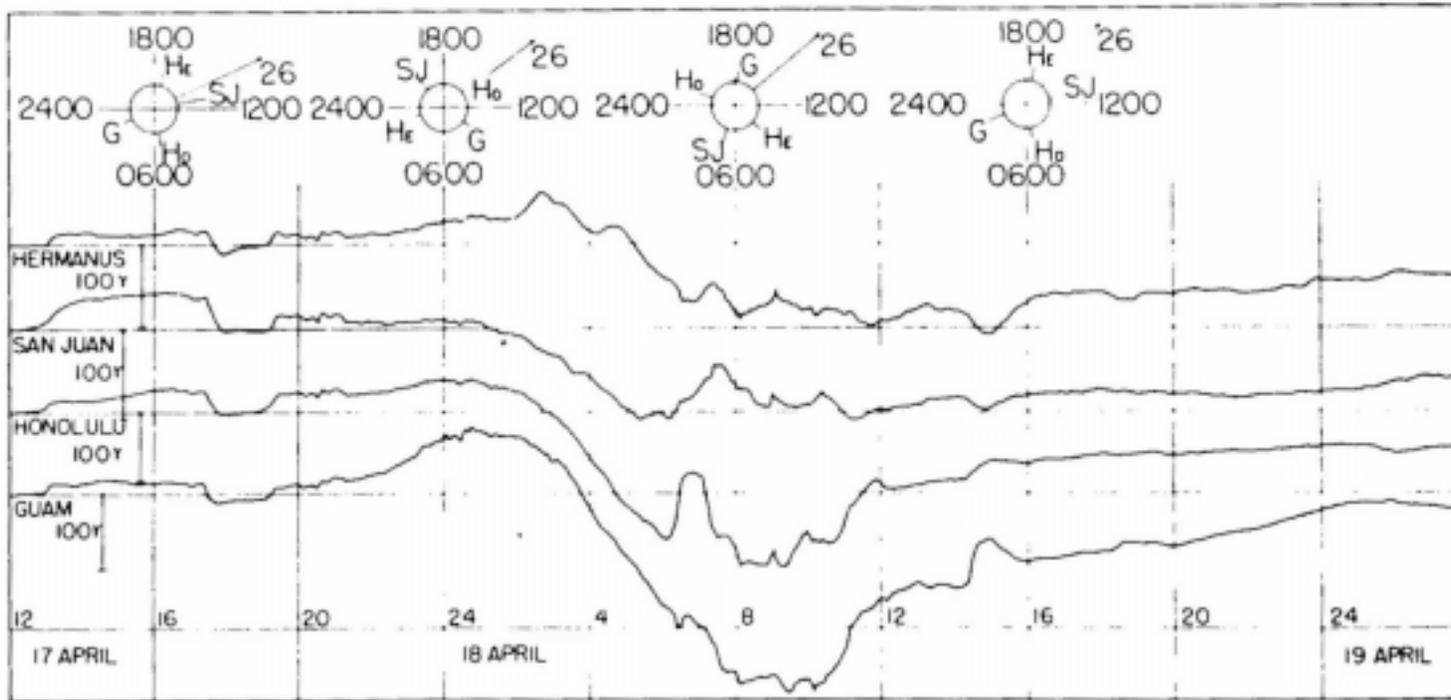
- Steady State Magnetosphere
  - Magnetospheric Current Systems
  - Plasma Populations
  - Magnetospheric Boundaries
- Dynamic Magnetosphere
  - Storms and Substorms
  - Ionospheric Outflows
  - Aurora/Auroral Acceleration



# Overview of Magnetospheric Currents



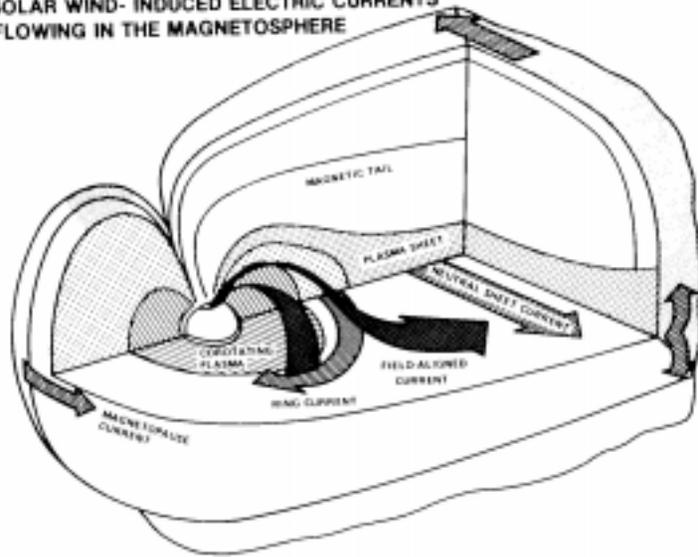
# Magnetometer Measurements: External Current Systems Discovered



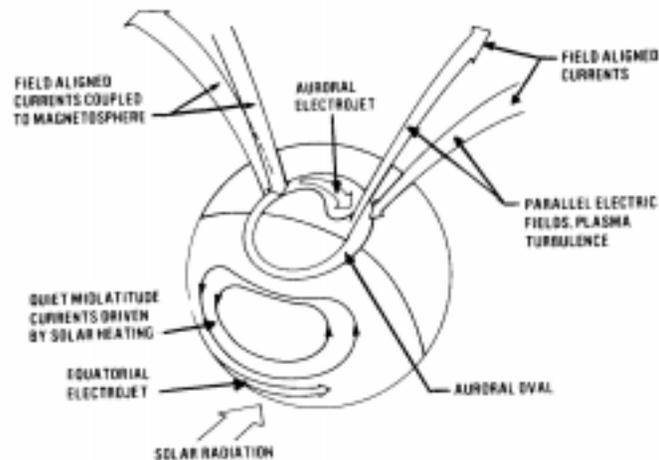
- Horizontal Component of Earth's Magnetogram--Note Large Fluctuations
- $50 \gamma = 50 \text{ nT} \sim B(10R_E)$

# Magnetospheric Currents

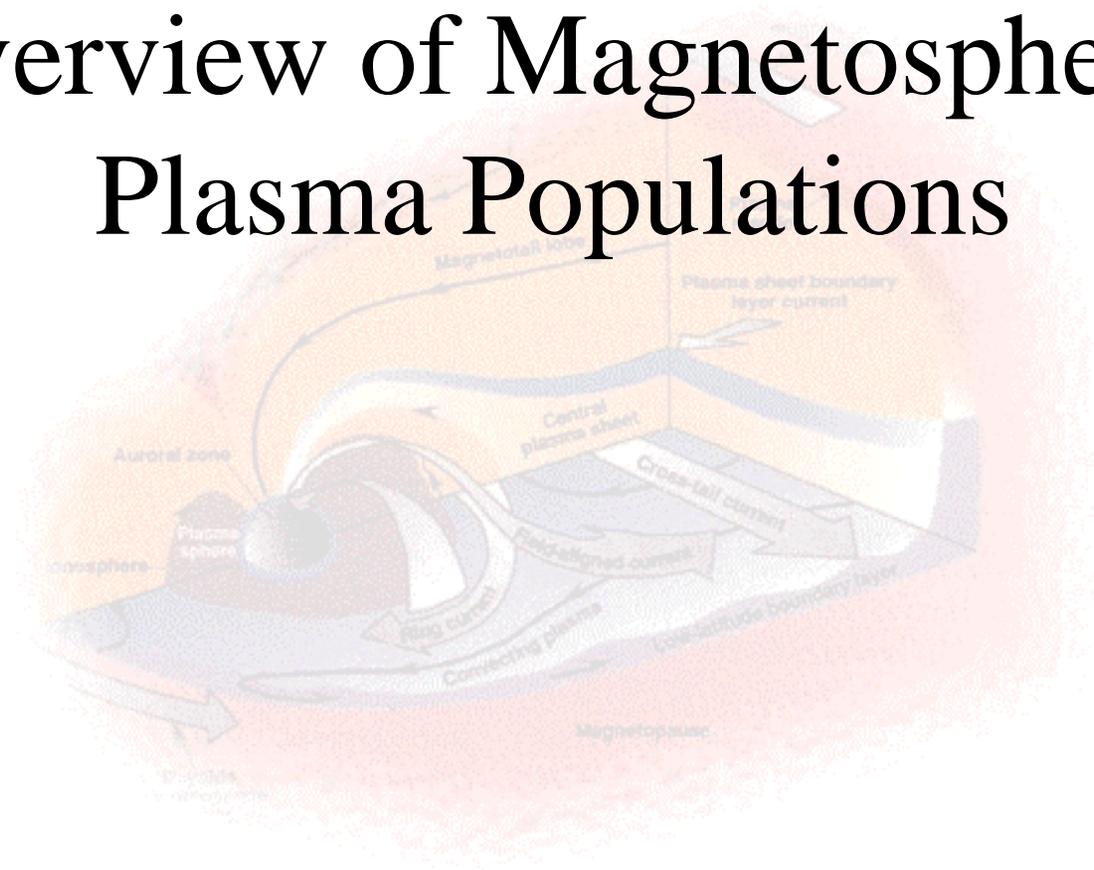
SOLAR WIND- INDUCED ELECTRIC CURRENTS  
FLOWING IN THE MAGNETOSPHERE



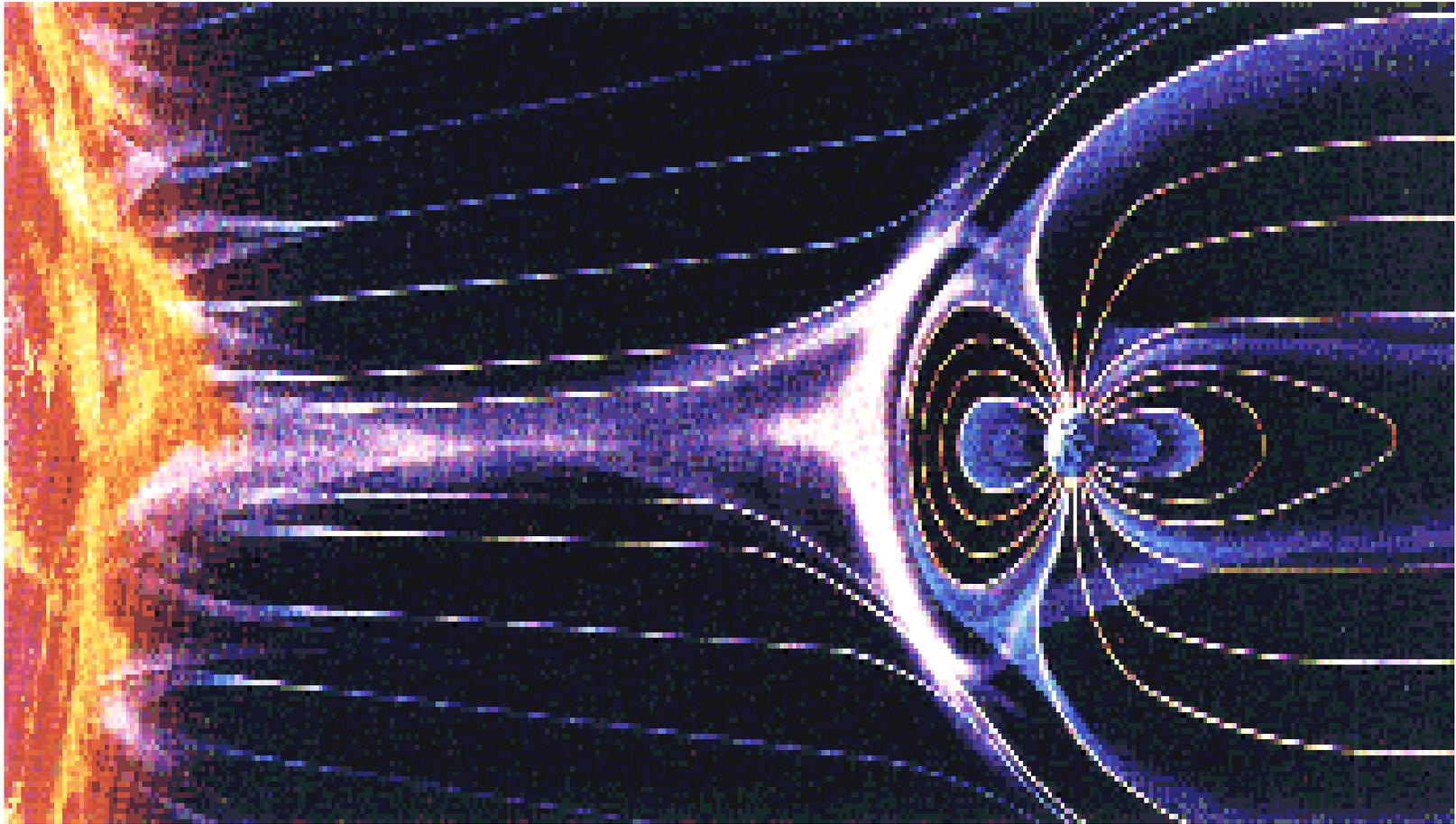
- Boundary Current
- Ring Current
- Tail Current
- Birkeland Current
- Ionospheric Current



# Overview of Magnetospheric Plasma Populations

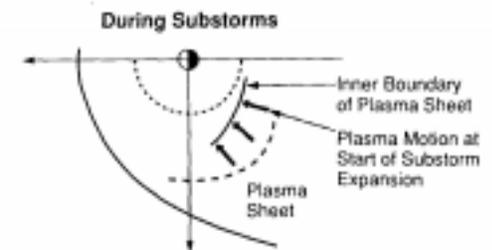
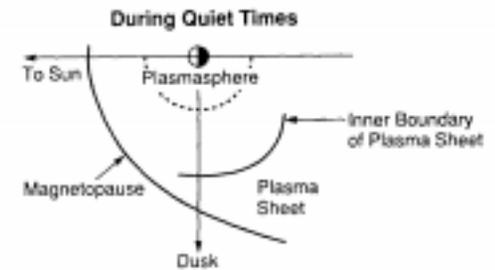
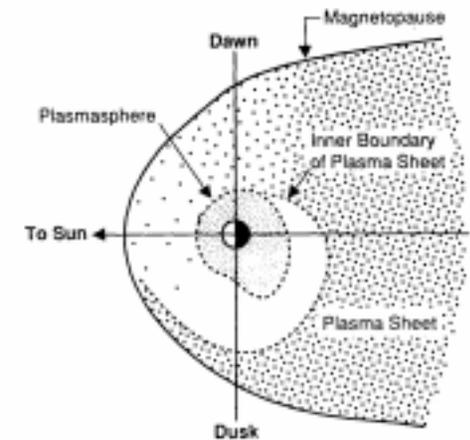
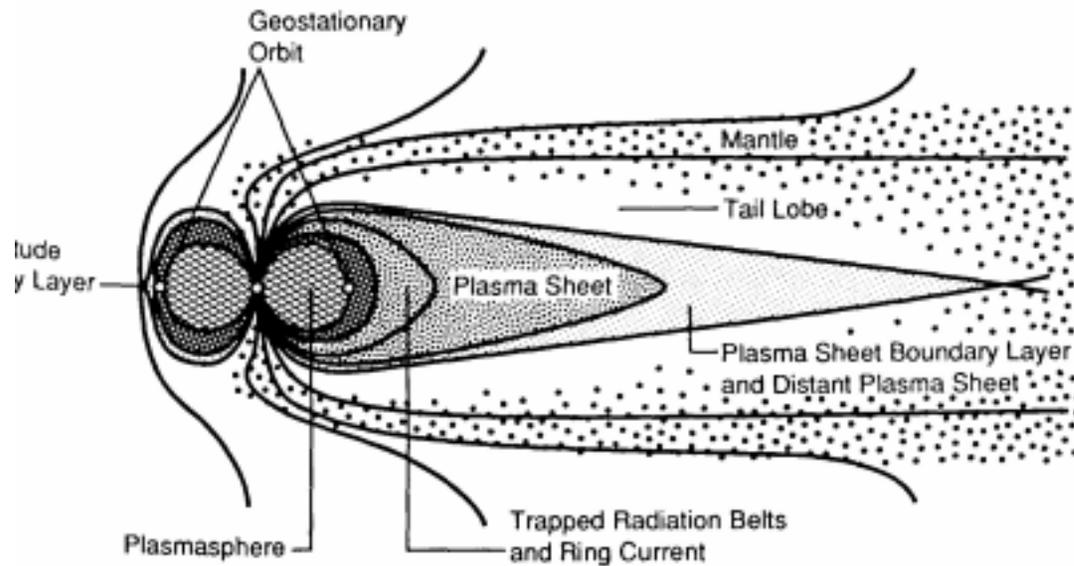


# Magnetospheric Populations

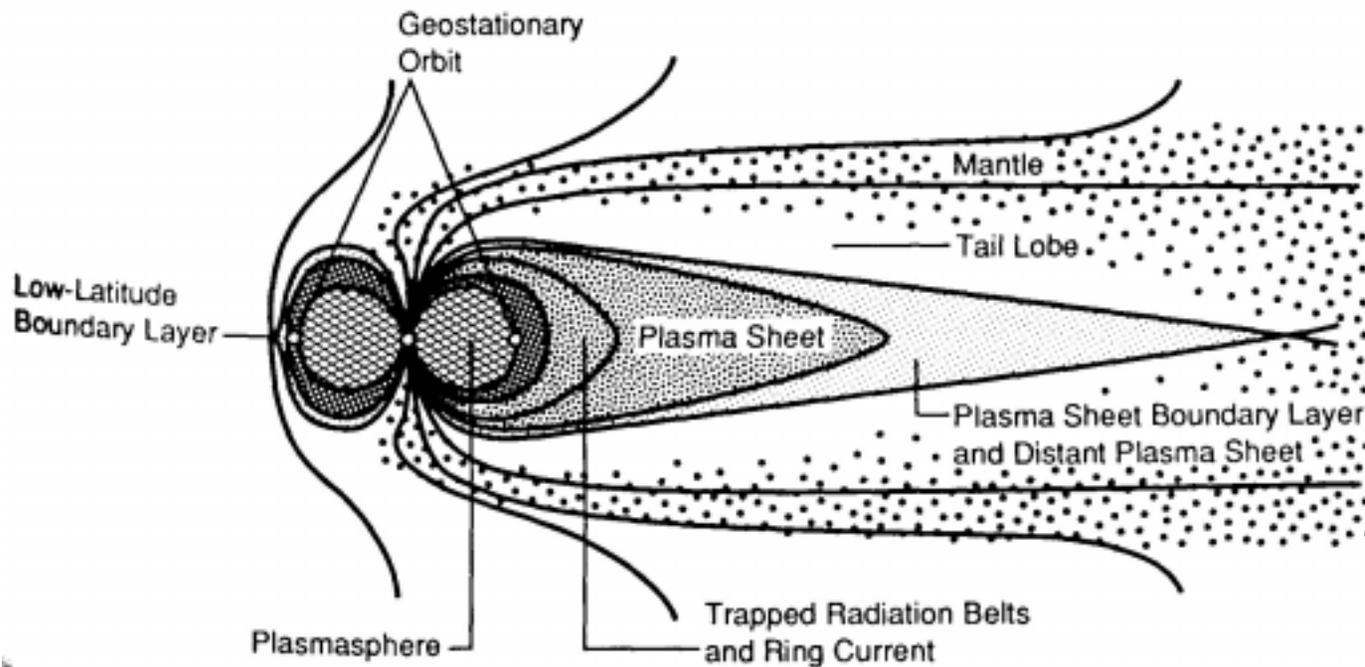


- Solar Wind:  $n \sim 10 \text{cm}^{-3}$ ,  $V \sim 400 \text{km/s}$ ,  $T \sim 10 \text{eV}$

# Magnetospheric Plasma Populations

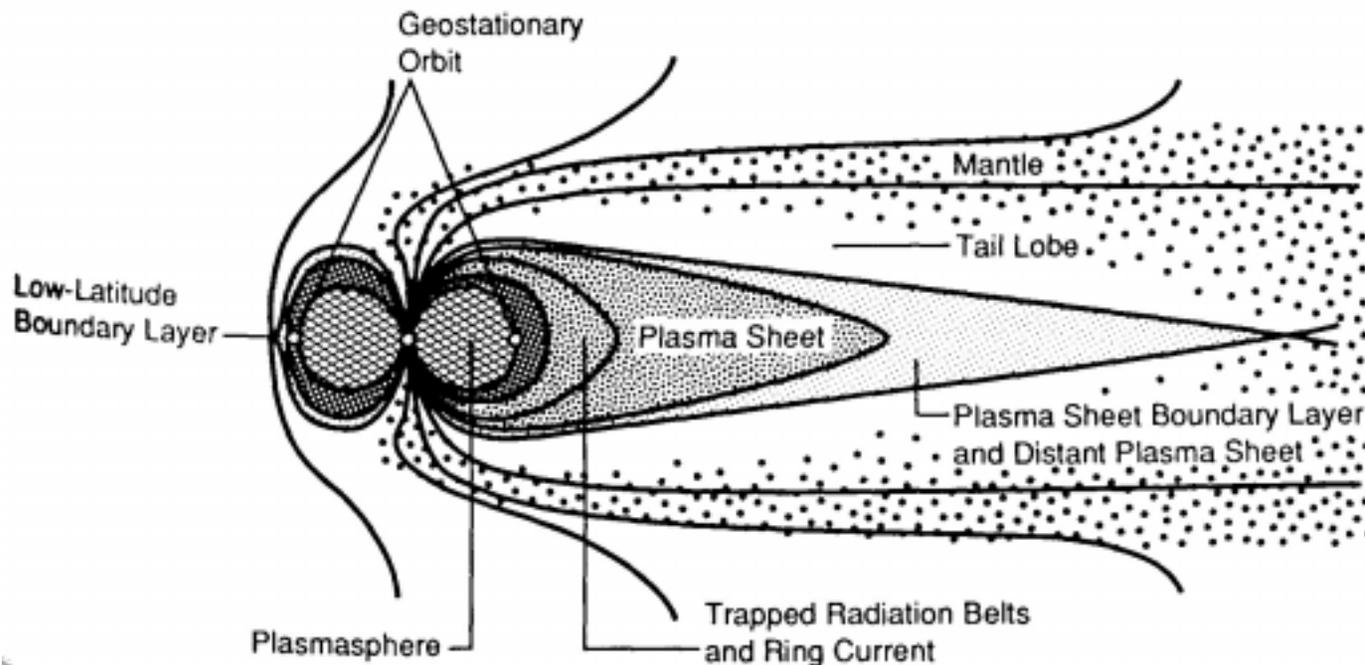


# Magnetospheric Plasma Populations



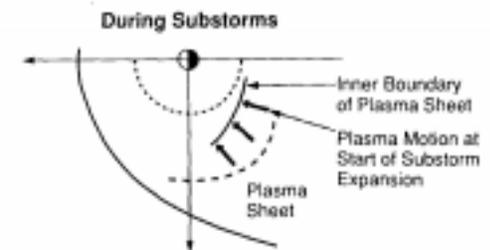
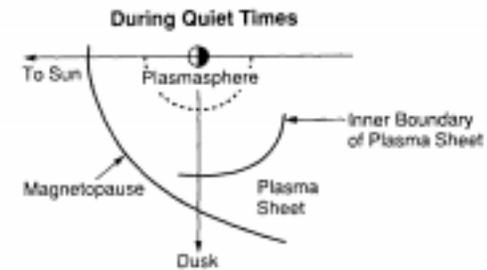
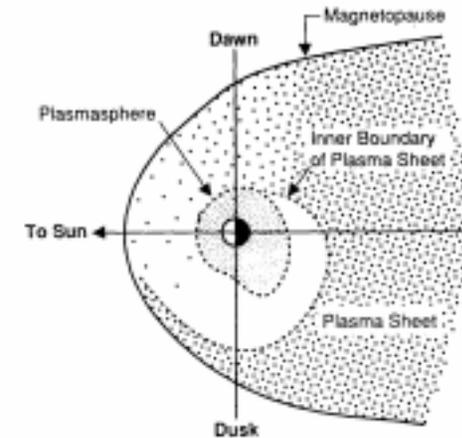
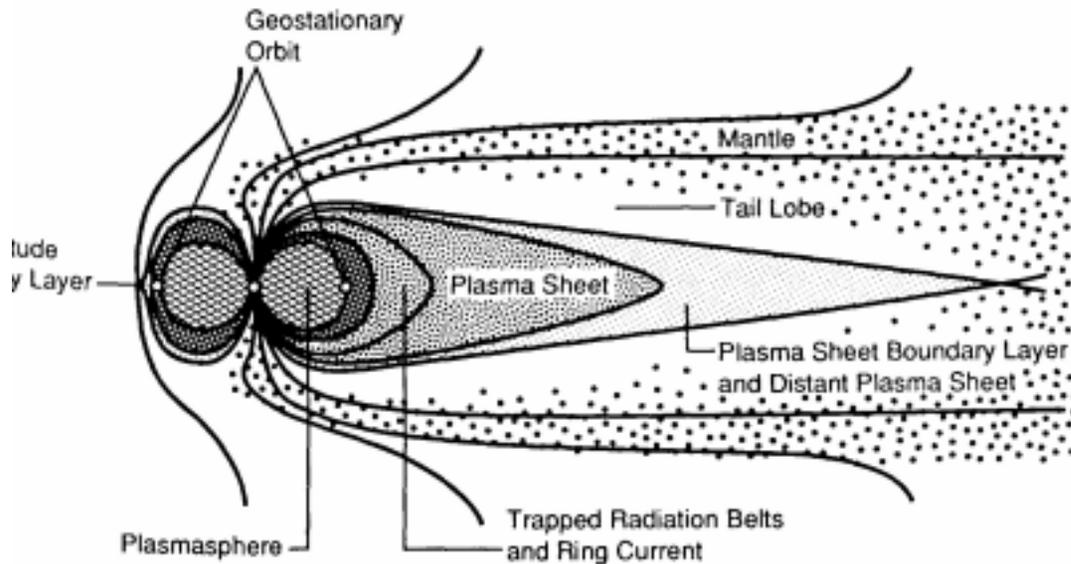
- Boundary Layer:  $n \sim 0.1-1 \text{ cm}^{-3}$ ,  $V \sim 200 \text{ km/s}$

# Magnetospheric Plasma Populations



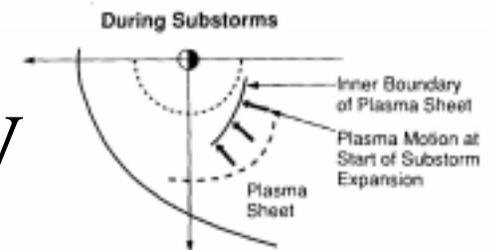
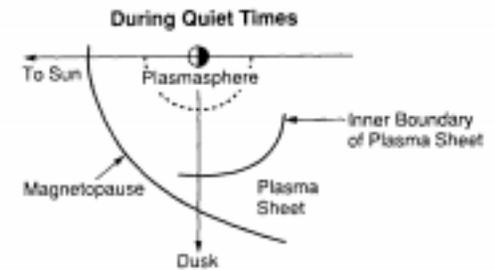
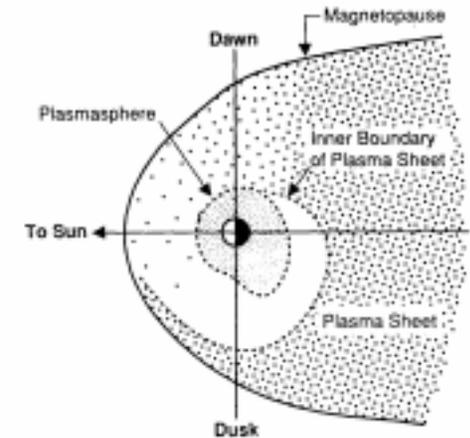
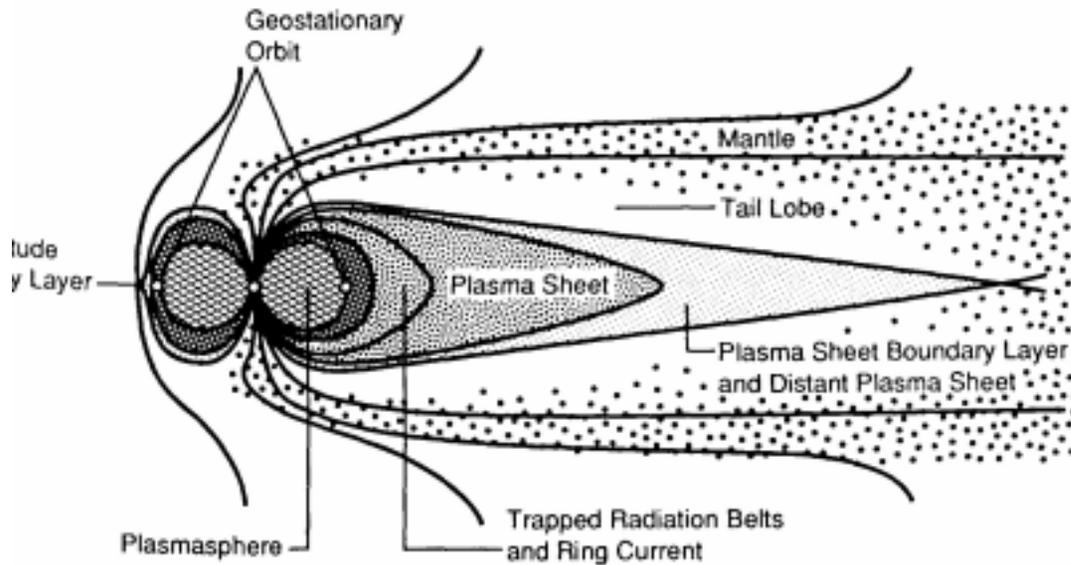
- Tail Lobes:  $n \sim 0.1 \text{ cm}^{-3}$ ,  $T \sim 5-50 \text{ keV}$

# Magnetospheric Plasma Populations



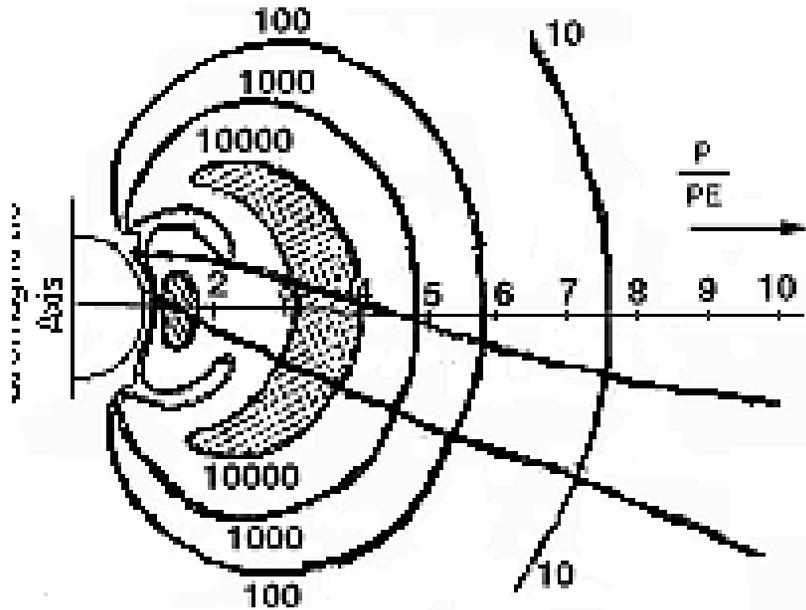
Plasma Sheet:  $n \sim 0.1-1 \text{ cm}^{-3}$ ,  
 $T \sim 1-10 \text{ keV}$  ,  $T_i/T_e \sim 1/7$

# Magnetospheric Plasma Populations



Plasmasphere:  $n \sim 10^3 \text{ cm}^{-3}$ ,  $E \sim 1 \text{ eV}$

# Plasma Populations: Radiation Belts (1958)

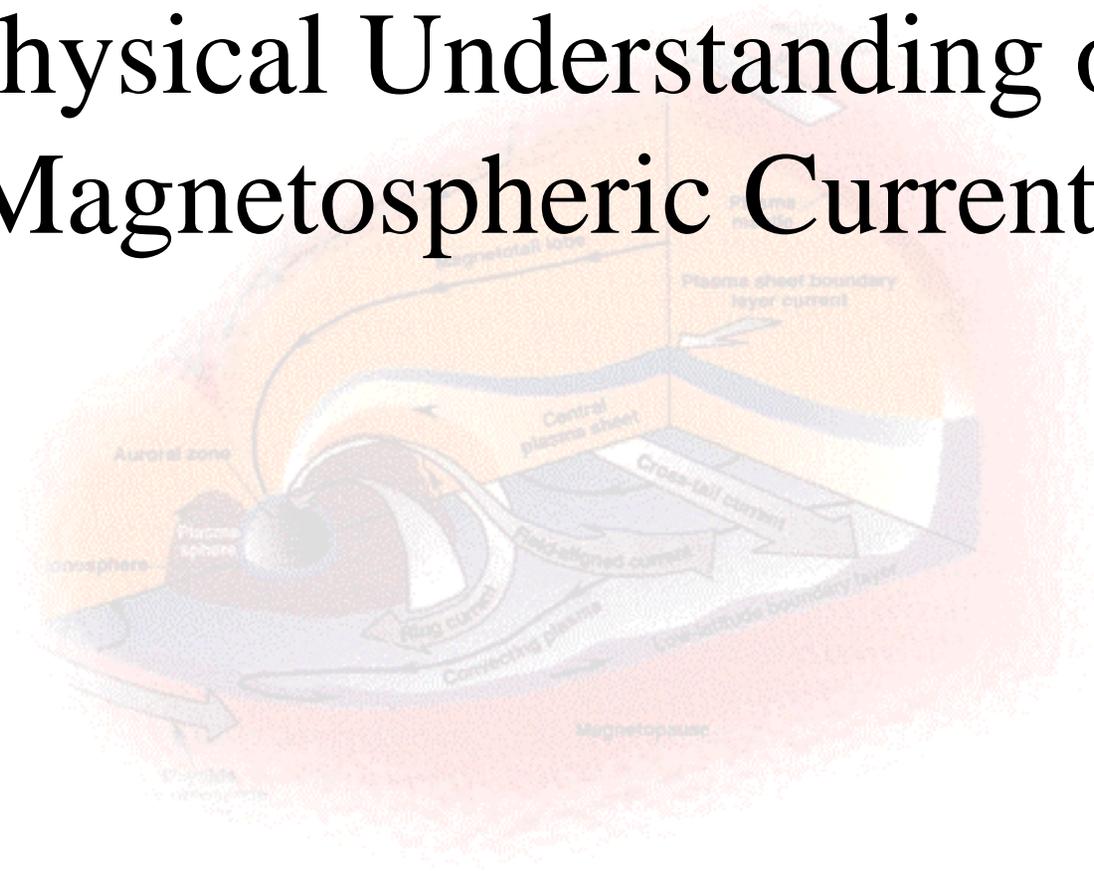


- Explorer IV
- Van Allen
- $n \sim 1 \text{ cm}^{-3}$ ,
- $T \sim 1 \text{ keV} - 100 \text{ MeV}$

# Plasma Parameters

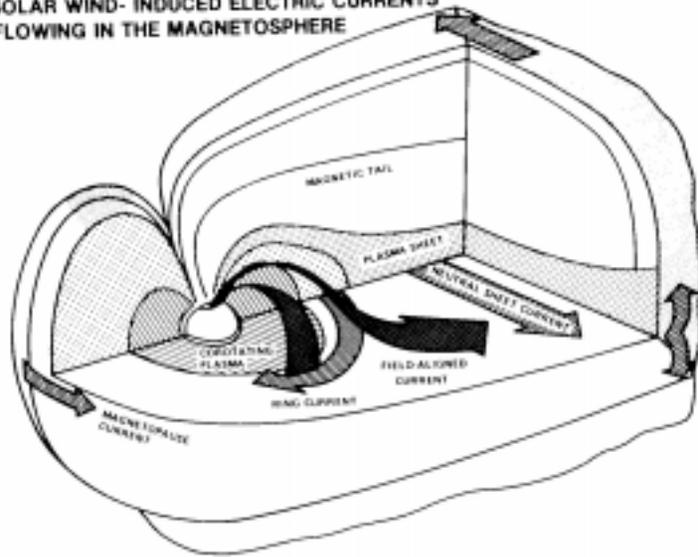
- $V_A \sim 200 \text{ km/s}$  at Magnetopause
- At High Latitude  $V_A / c \sim 1$  in Topside Ionosphere
- $V_A \sim 1000 \text{ km/s}$  in Plasmasphere near Earth
- Solar Wind  $\beta \gg 1$ ; Ram Pressure Dominates
- in Magnetosheath  $\beta \sim 1-10$ ,  $\rho_i \sim 50 \text{ km}$
- in Plasma Sheet  $1 > \beta > m_e/m_i$ , ,
- $\rho_i \sim 50 \text{ km}$  at Ionosphere  $\beta \ll m_e/m_i$

# Physical Understanding of Magnetospheric Currents

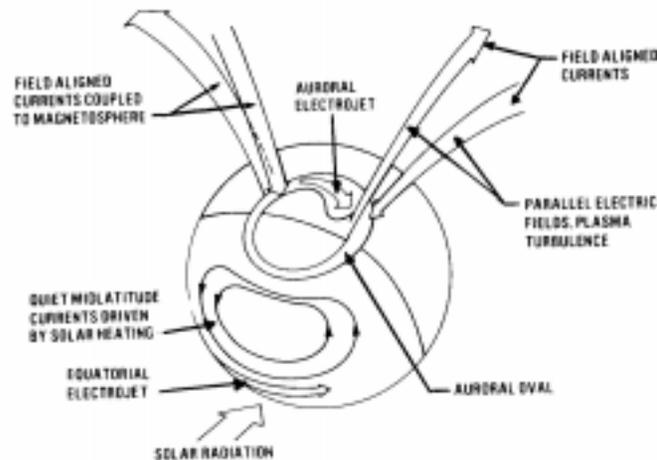


# Magnetospheric Currents

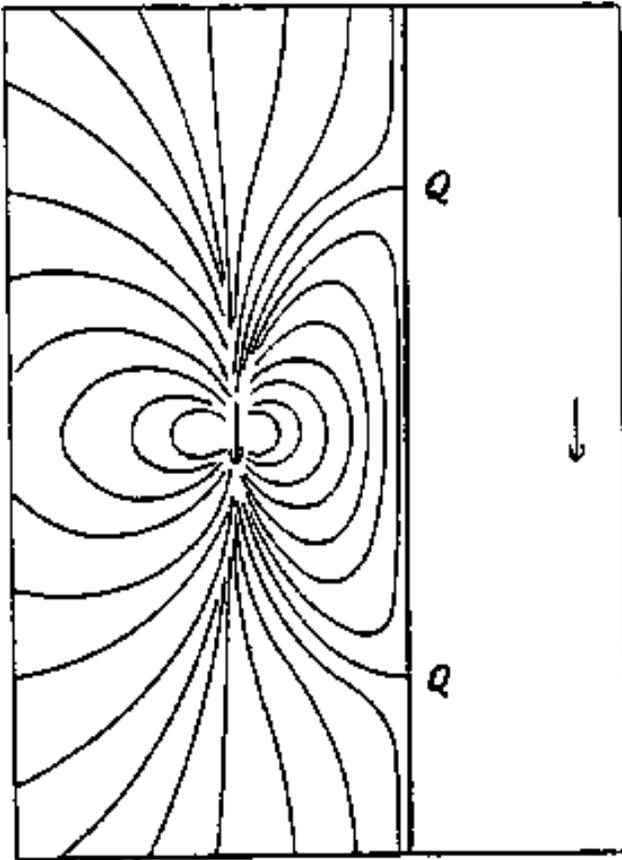
SOLAR WIND- INDUCED ELECTRIC CURRENTS FLOWING IN THE MAGNETOSPHERE



- Boundary Current
- Ring Current
- Tail Current
- Birkeland Current
- Ionospheric Current

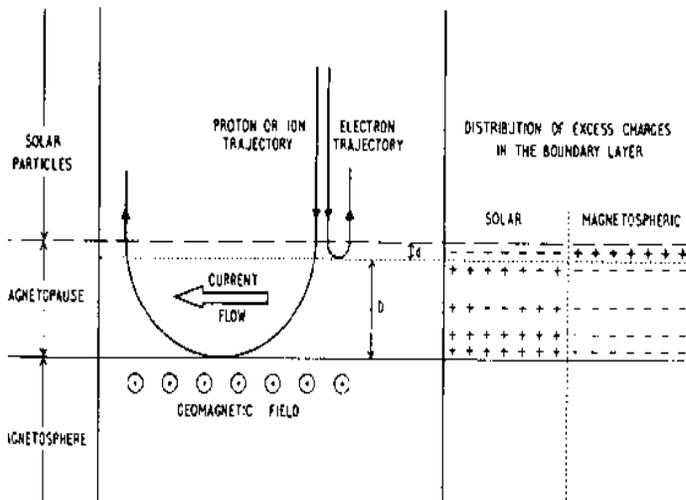
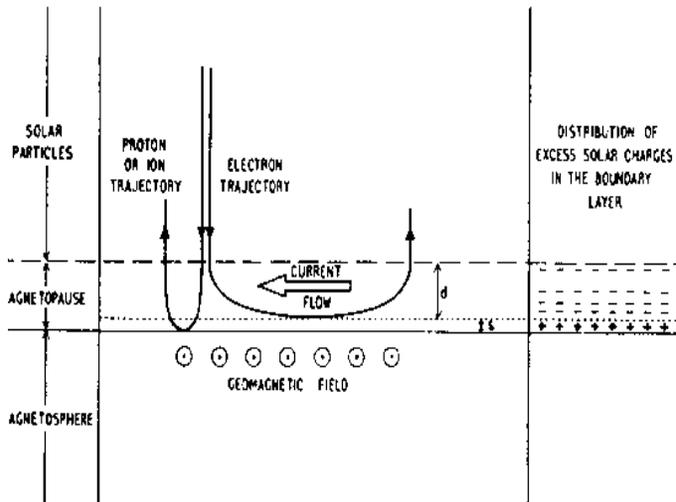


# Chapman Ferraro Model



- Solar Particles
- Planetary Dipole Field
- Image Dipole ( $B_n=0$ )
- Compression of Planetary Field
- Cusps (Q)
- Boundary Current

# Chapman-Ferraro Current



- Current Results from Particle Motion

- Charge Separation

$$L^2 = \rho_i \rho_e$$

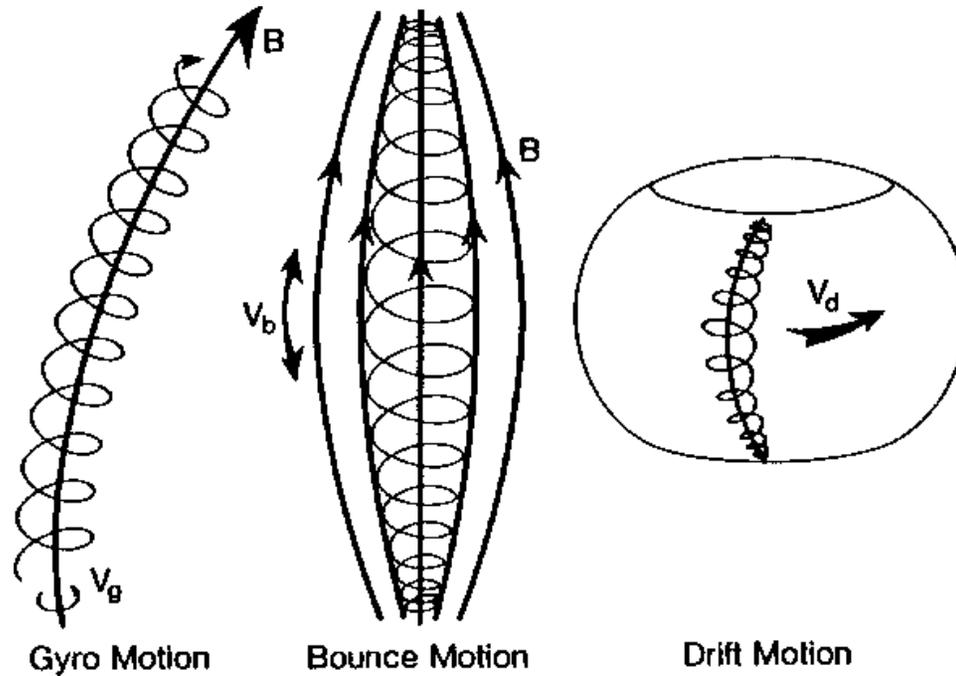
- Neutralizing Ionospheric Electrons

$$L = \rho_i \quad (\rho_{sw} v^2 = B^2/2)$$

- Right Answer

$$L = 10\rho_i$$

# Adiabatic Invariants



$$\tau_c = (0.66s) \left( \frac{100\text{nT}}{B} \right) \left( \frac{m}{m_p} \right)$$

$$\tau_B \sim (5\text{min}) \left( \frac{l_b}{10R_E} \right) \left( \frac{m}{m_p} \right)^{1/2} \left( \frac{1\text{keV}}{W_{\parallel}} \right)$$

$$\tau_D = (56\text{hr}) \left( \frac{r}{5R_E} \right)^2 \left( \frac{B}{100\text{nT}} \right) \left( \frac{1\text{keV}}{W} \right)$$

# Ring Current

- Energy

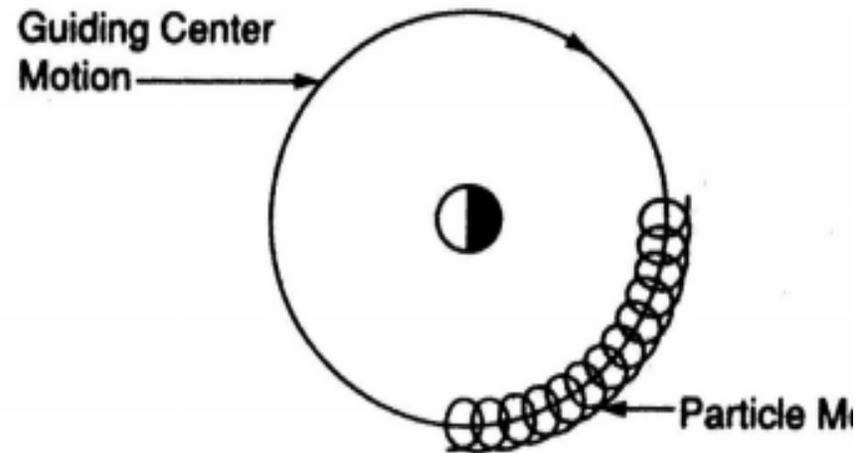
$$W(\mu, J, \mathbf{x})$$

- Curvature/Gradient Drift/Current

$$V_{GCD} = \frac{B \times \nabla W}{qB^2}$$

- Magnetization Current
- Change in Magnetic Field

$$\frac{\Delta B}{B_0} \sim -\frac{2}{3} \frac{W_{particles}}{W_{mag}}$$



During Storms

$$\Delta B = 100nT \Rightarrow W_{part} \sim 10^{15} \text{ J}$$

# Ring Current

- Energy

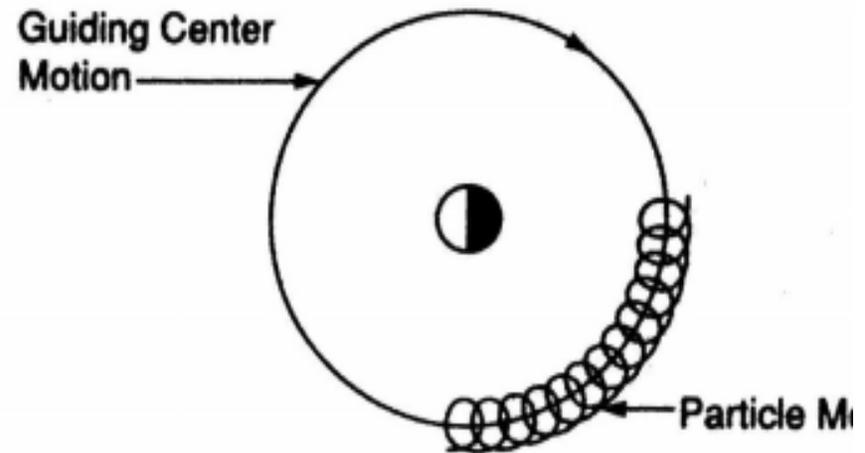
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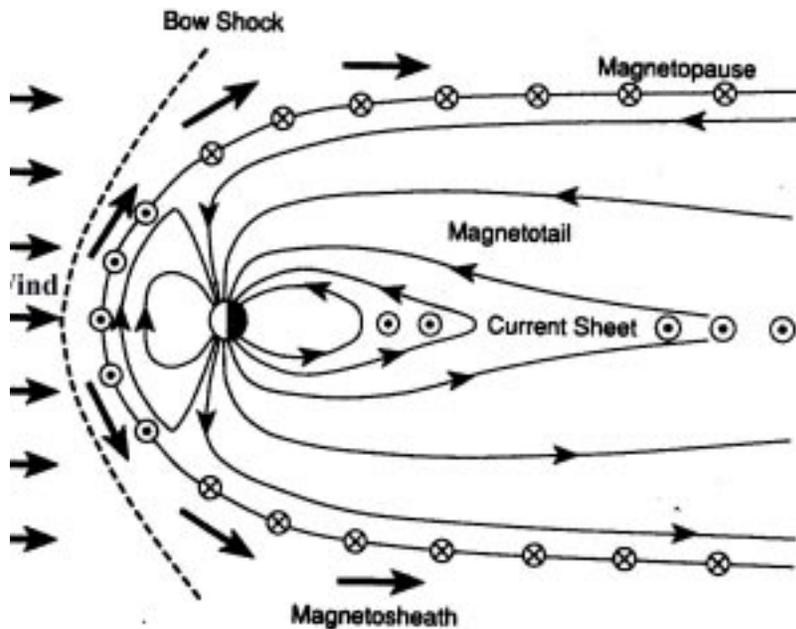
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$$\frac{\Delta B}{B_0} \sim -\frac{2}{3} \frac{W_{particles}}{W_{mag}}$$



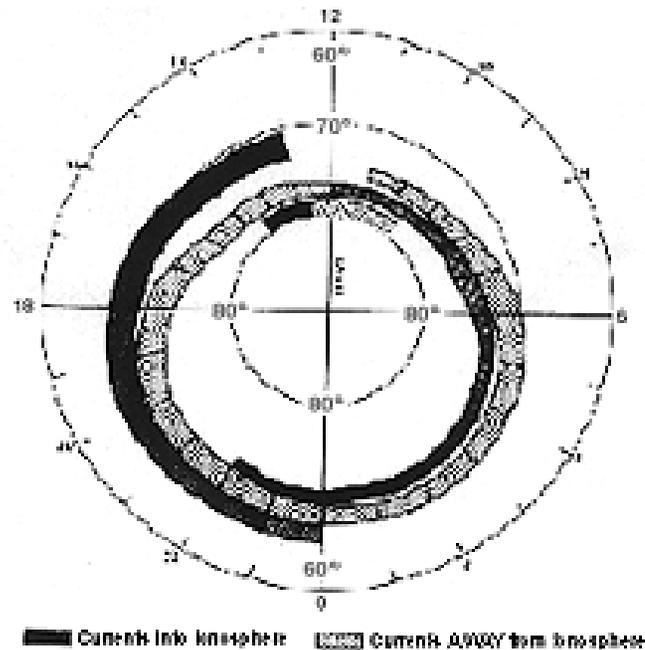
100 Early Atomic Bombs!

# Cross Tail Current



- Tail Serves as a Reservoir of Energy
- Magnetic Pressure  $\gg$  Particle Pressure in Lobes
- Particle Pressure in Plasma Sheet  $\gg$  Magnetic Pressure
- $10^6$  A/ $5R_E$  in Tail
- Flux Added to Tail Increases Lobe Pressure and Intensifies Current in Current Sheet

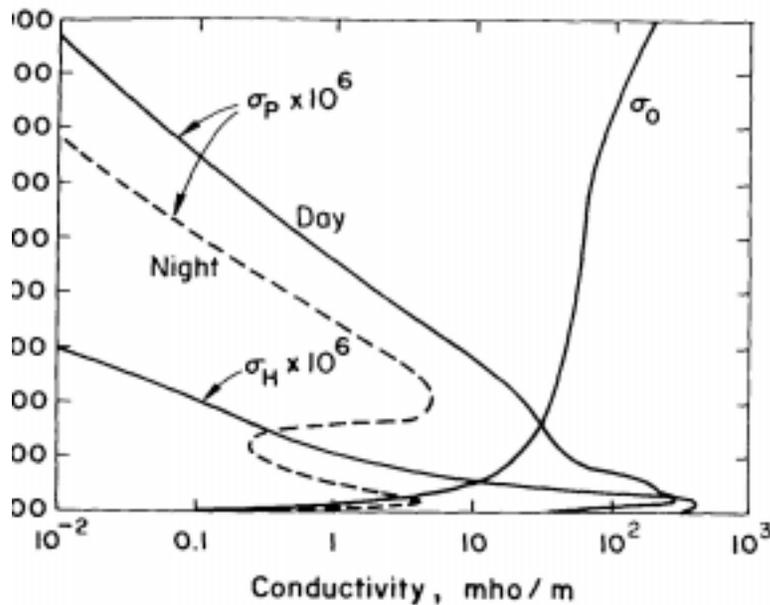
# Birkeland (Field Aligned) Currents



- Iijima and Potemra
- Region 1: Connect to Boundary Layers
- Region 2: Plasma Sheet Pressure Gradient
- Due to Geodesic Curvature of B

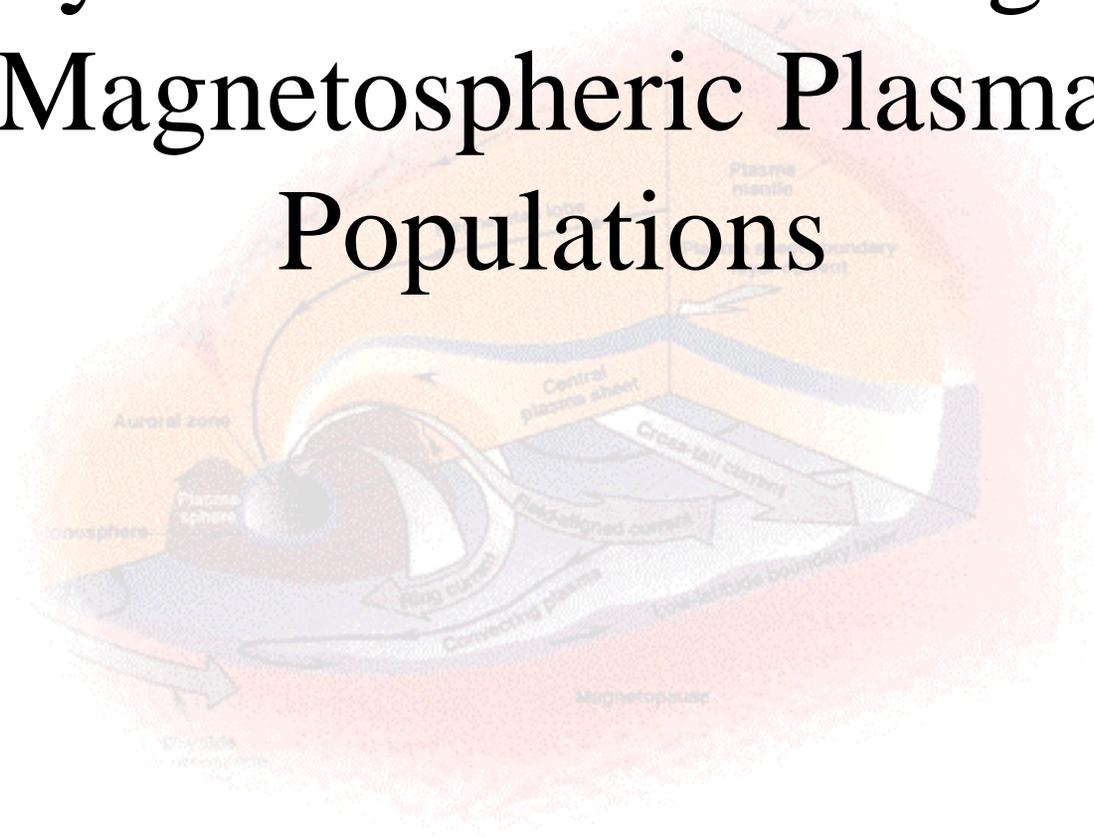
$$\nabla_{\parallel} J_{\parallel} = 2 \frac{\mathbf{B} \times \nabla P}{B^2} \cdot [(\mathbf{b} \cdot \nabla) \mathbf{b}]$$

# Ionospheric Currents $J=\sigma E$

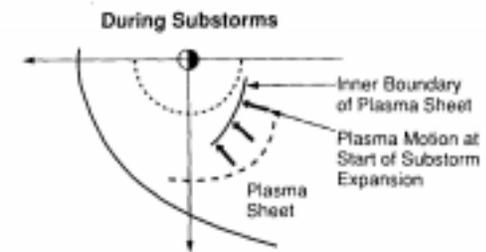
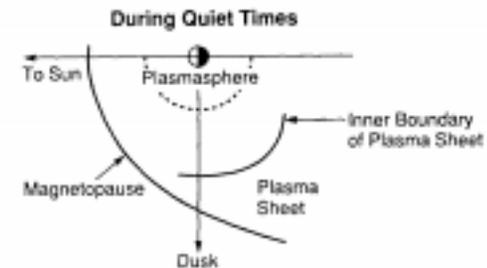
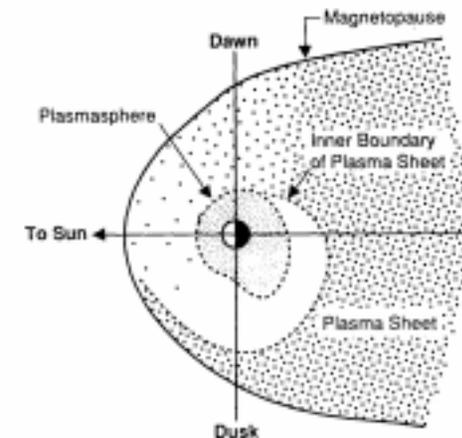
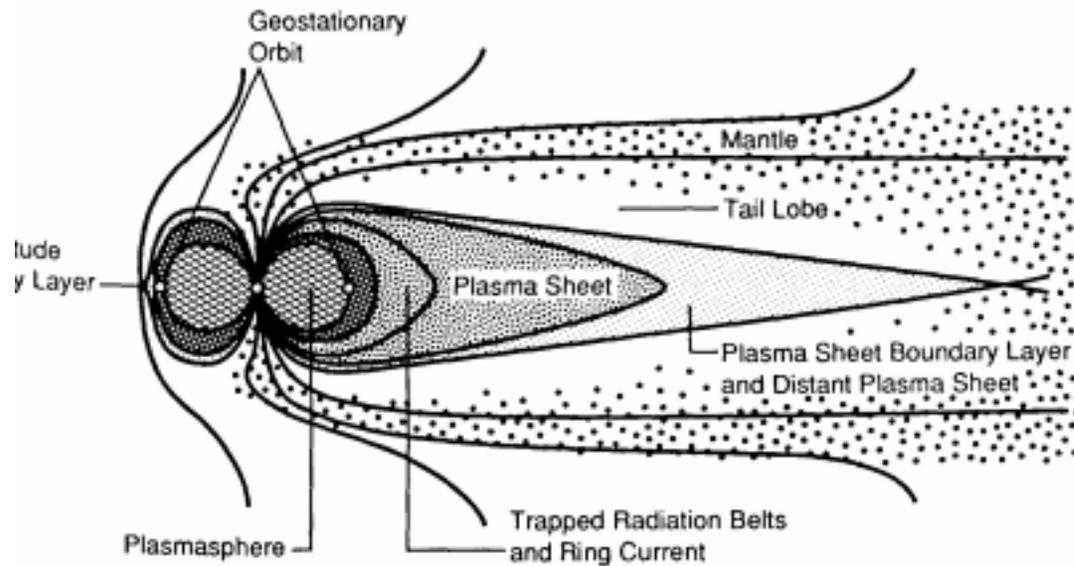


- $\sigma_p$  in direction of E due mostly to ion neutral collisions
- $\sigma_H$  in direction of  $E \times B$  The  $E \times B$  drift is impeded for ions leading to current
 
$$\frac{\sigma_P}{\sigma_H} \sim \frac{\Omega_i}{V_{in}}$$
- $\sigma_0$  along b is large due to high electron mobility
- (ve-n =ve-i ~200-280km)

# Physical Understanding of Magnetospheric Plasma Populations

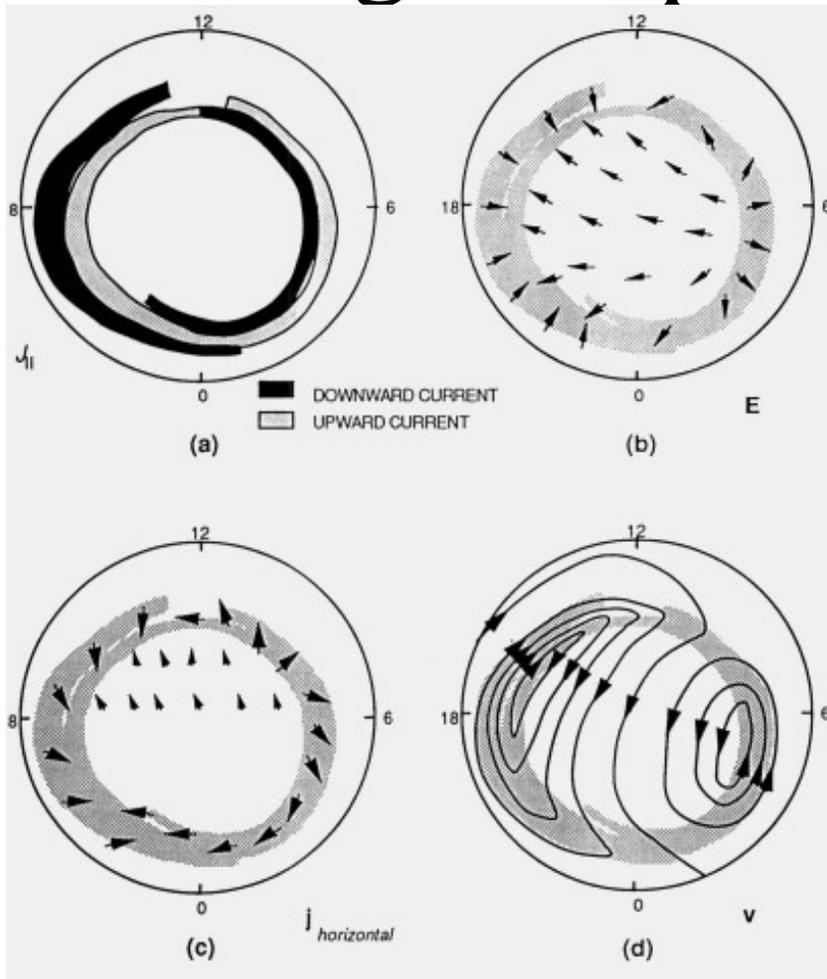


# Magnetospheric Plasma Populations





# Electric Fields and Magnetospheric Convection



- Birkeland Current
- Electric Field
- Ionospheric Current
- Plasma Velocity
- Potential Drop = Transport of Mag Flux

# Flux Transfer and Polar Cap Convection

- Radar Measure of Plasma Velocity in Ionosphere ( $\sim 300$  m/s)

$$E = \frac{\phi}{2R_{PC}} = v_{PC} B_{PC}$$

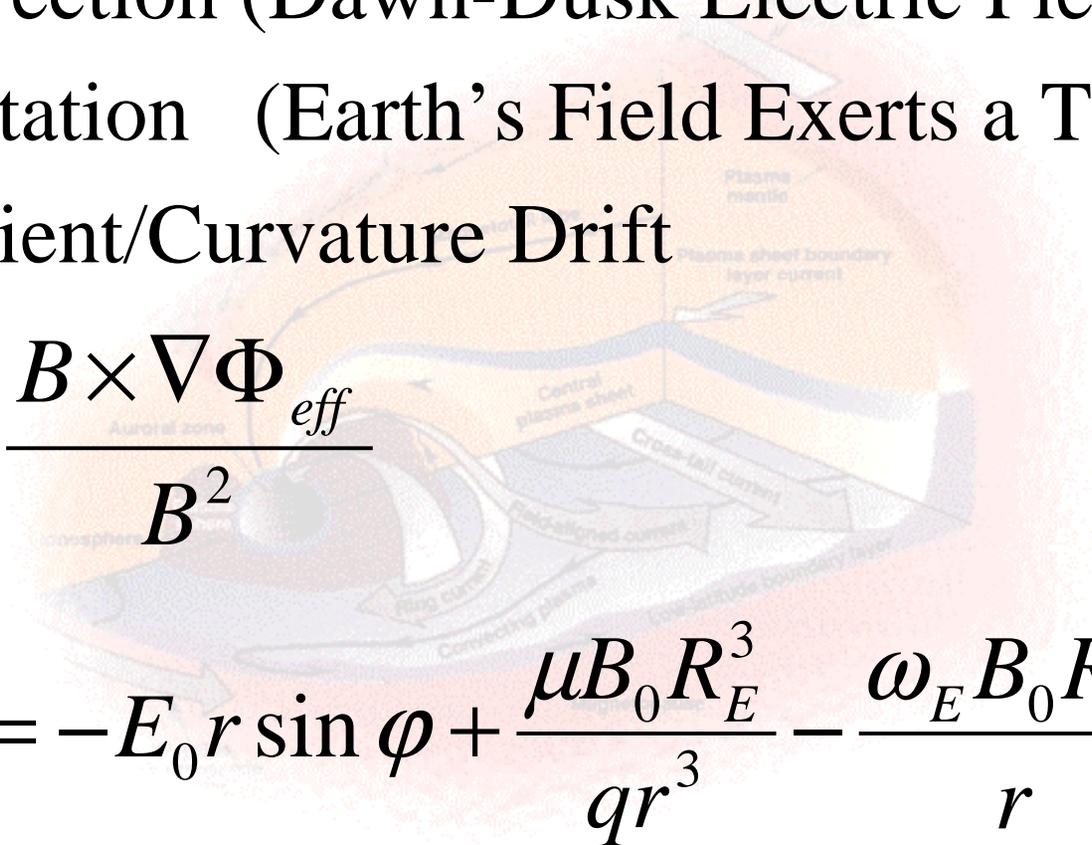
- $\phi \sim 50$  kV across Polar Cap
- At tail  $V_{sw} \sim 400$  km/s,  $B \sim 5$  nT,  $R_{tail} \sim 50$  km
- $\phi \sim 600$  kV across tail
- About 1/10 of Solar Wind Flux Reconnects

# Plasma Convection

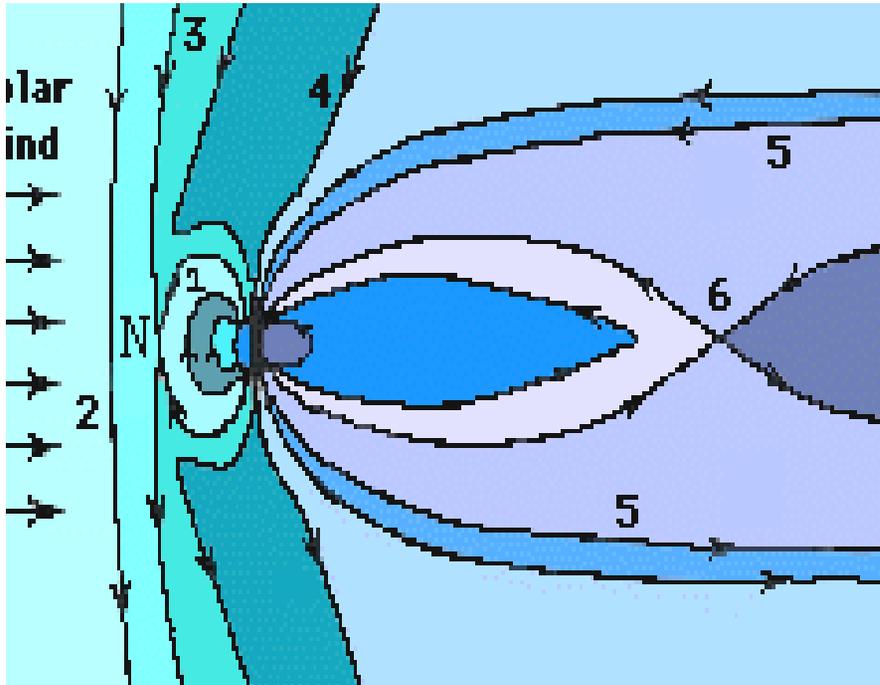
- Convection (Dawn-Dusk Electric Field)
- Corotation (Earth's Field Exerts a Torque)
- Gradient/Curvature Drift

$$V_D = \frac{B \times \nabla \Phi_{eff}}{B^2}$$

$$\Phi_{eff} = -E_0 r \sin \varphi + \frac{\mu B_0 R_E^3}{qr^3} - \frac{\omega_E B_0 R_E^3}{r}$$

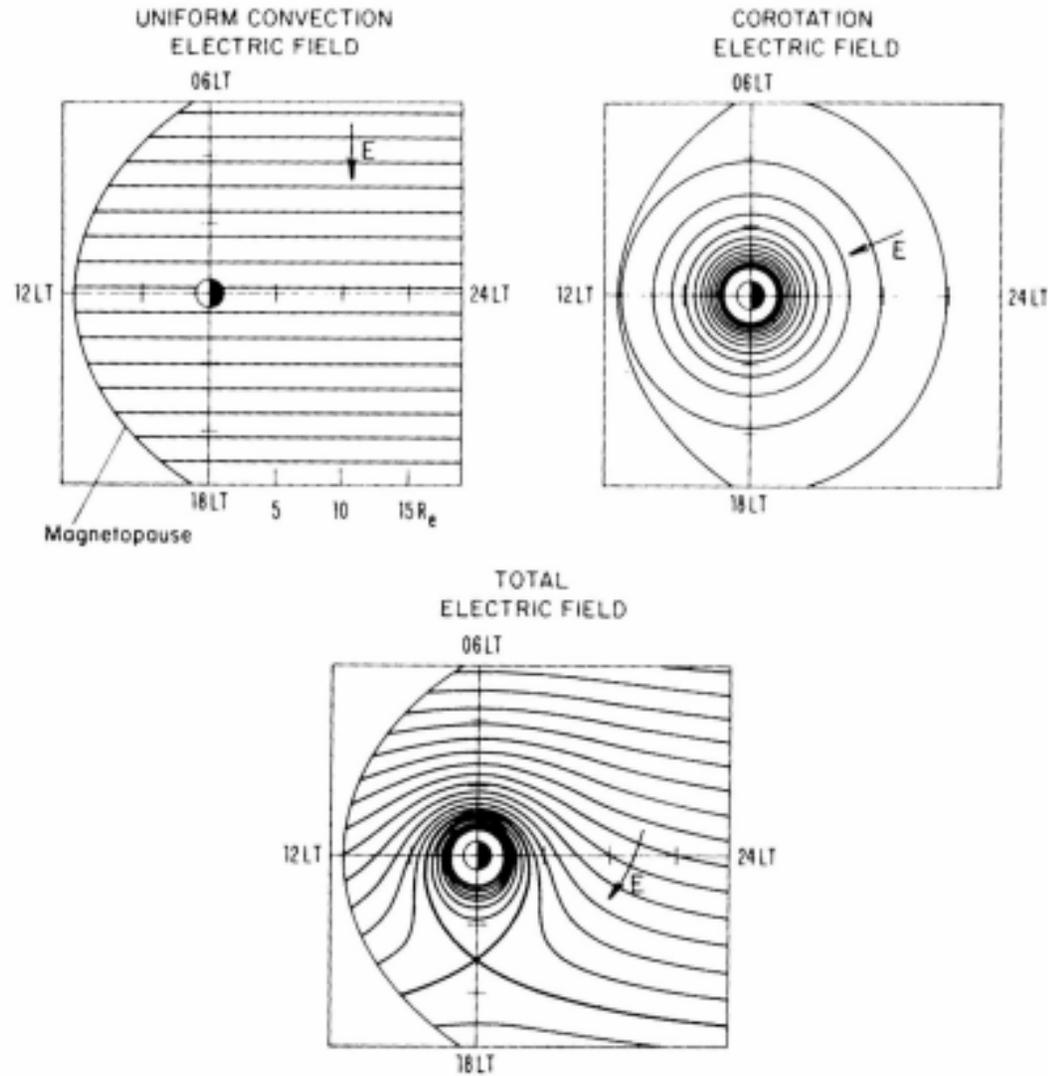


# Convection Model

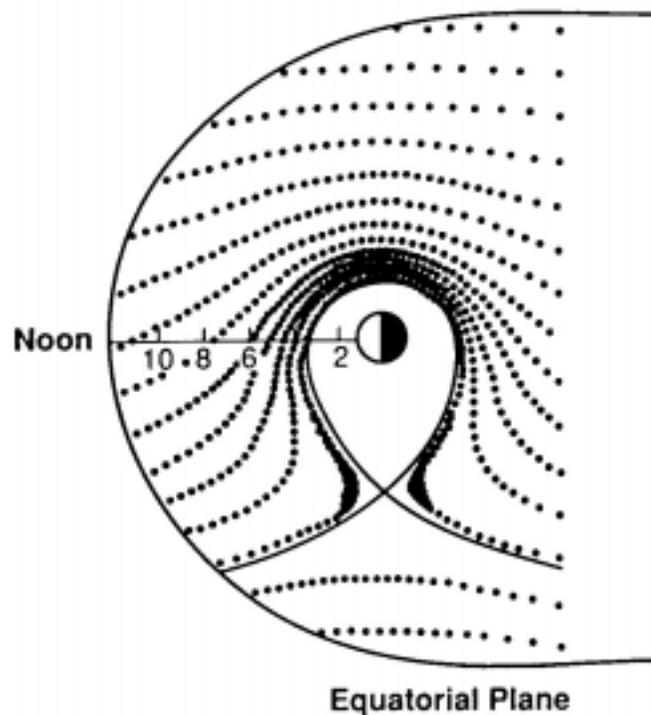


- Ionospheric Flows Major to Magnetospheric Convection
- Dungey (1961) Reconnection
- Antisunward Flow in Polar Cap
- Return Flow at Lower Latitudes
- Electric Field ( $V \times B$ )

# Convection and Corotation



# Origin of Plasmasphere

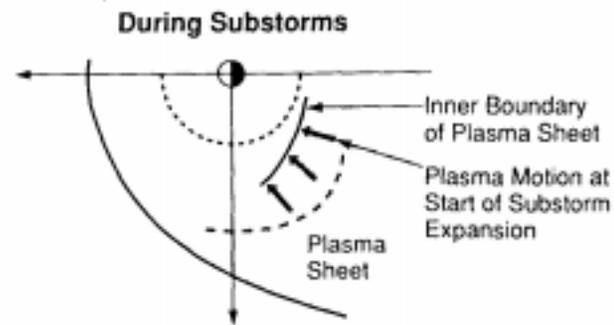
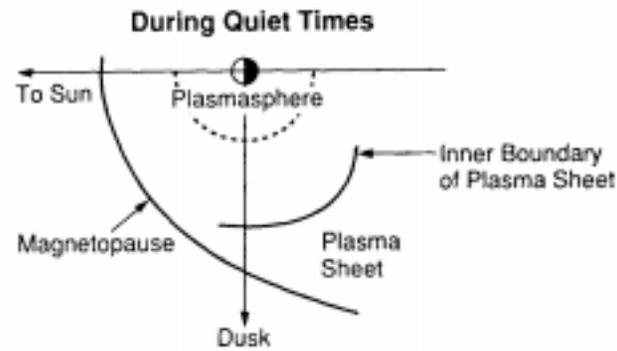
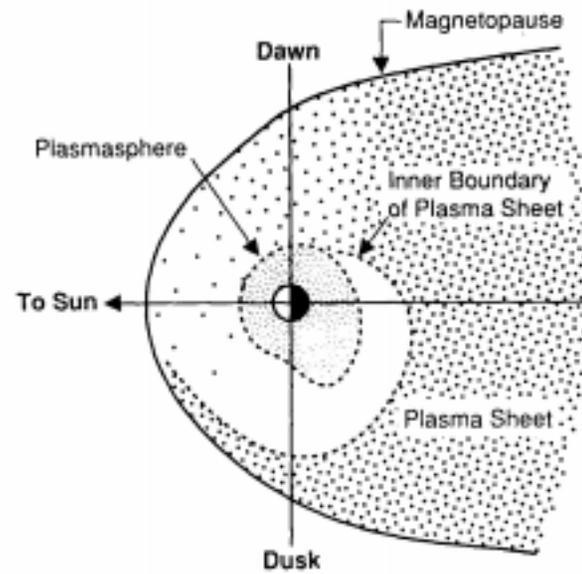


- Cold Particles

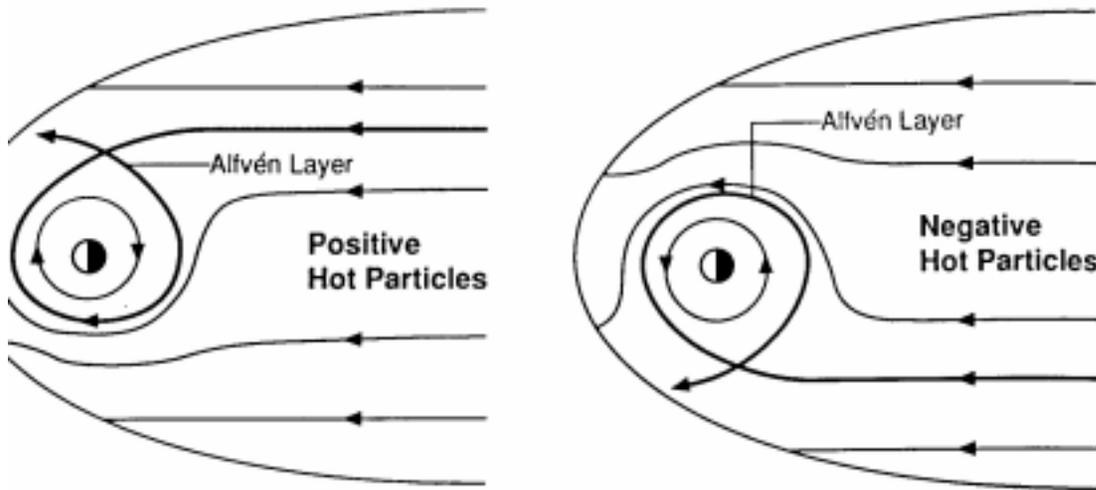
$$r_0^2 = \frac{\omega_E B_0 R_E^3}{E_0}$$

- $r > r_0$  Convected to Magnetopause
- $r < r_0$  Trapped
- Bulge is Observed
- Plasmasphere Shrinks when Magnetosphere Active

# Plasmasphere Observed



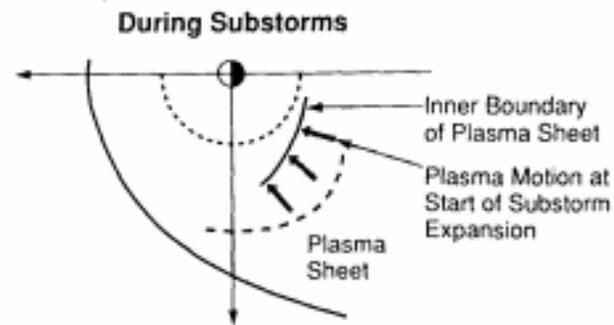
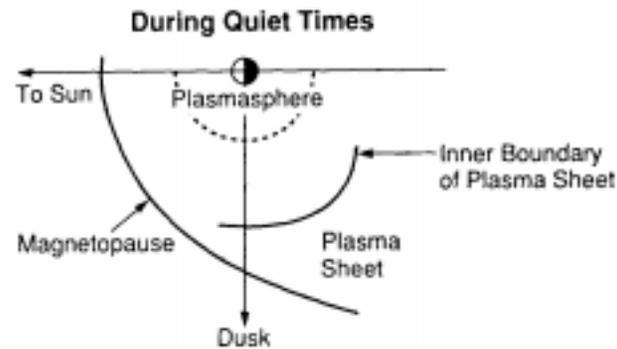
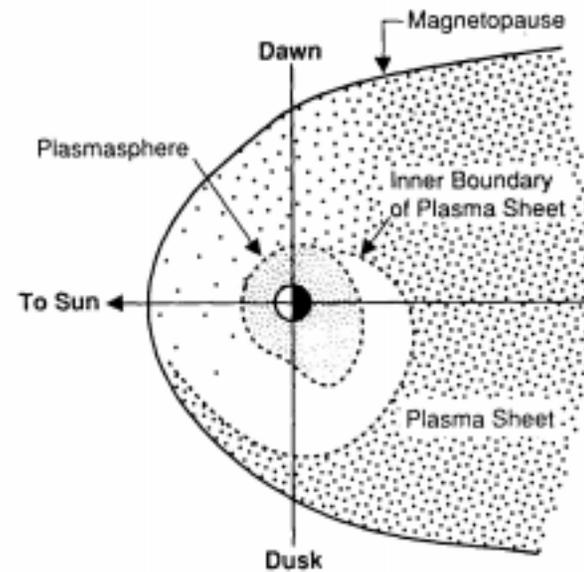
# Alfvén Layers



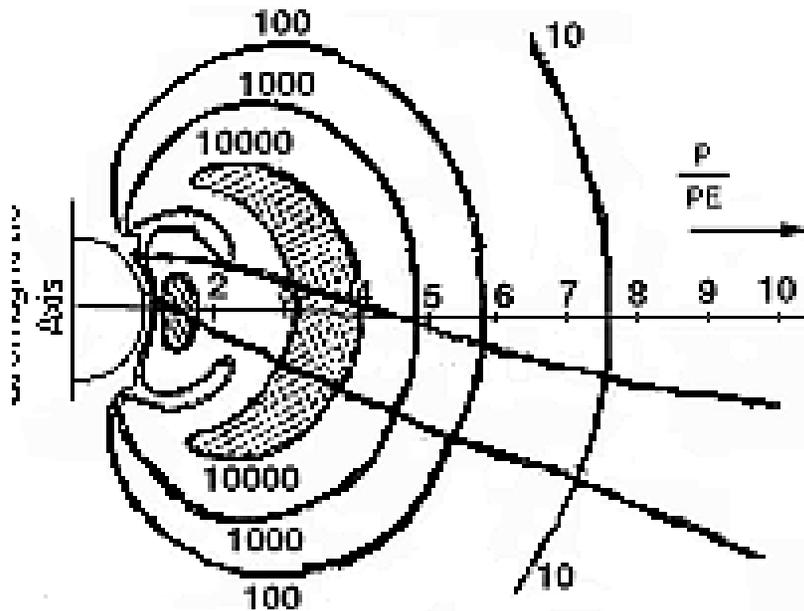
$$r_0 = \left[ \frac{3\mu B_0 R_E^3}{|q|E_0} \right]^{1/4}$$

- Hot Particles
- More Energetic Particles drift to MP
- Increased Convection can Inject Energetic Particles where they can be Trapped
- Electron Edge Closer at Dawn, Ions at Dusk

# Inner Edge of Plasma Sheet Electrons



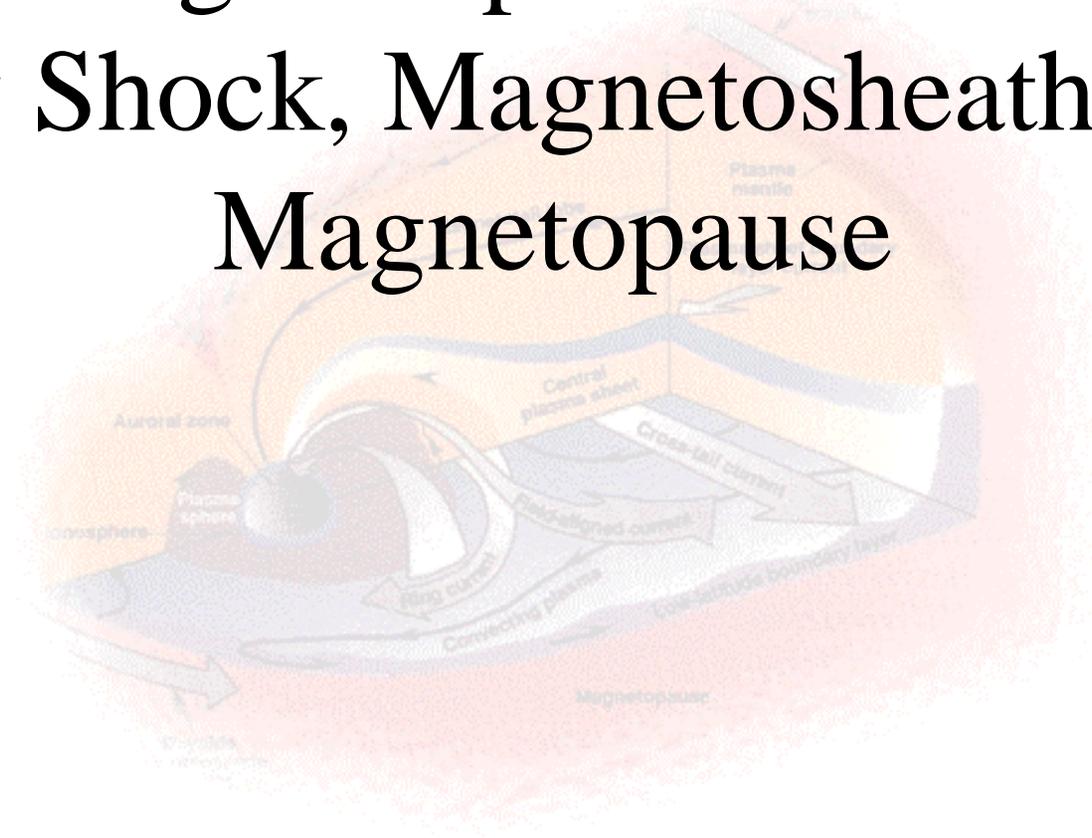
# Radiation Belts (1958)



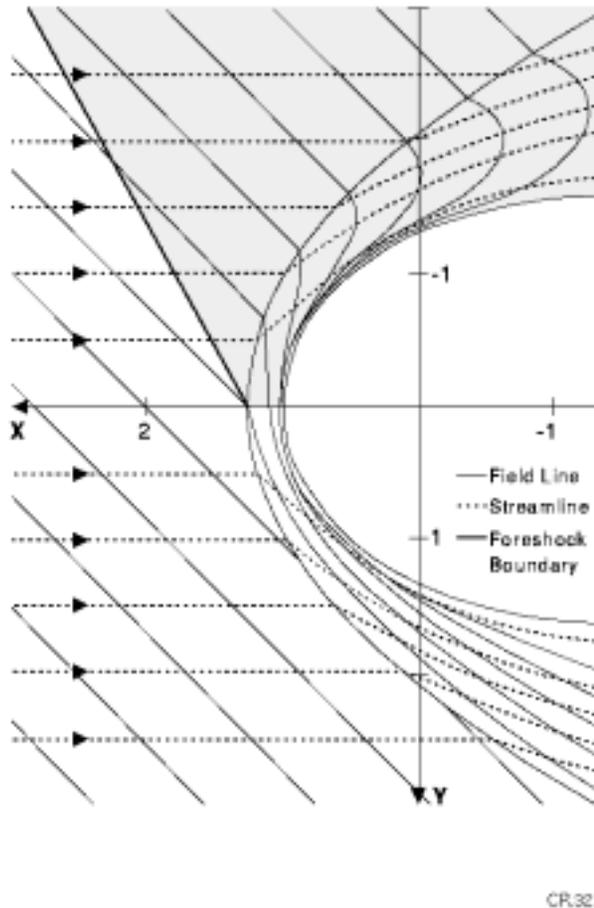
Van Allen  
Explorer IV

- Inner Radiation Belt  
Ionosphere --  $2 R_E$   
10 MeV Protons  
Origin: Cosmic Rays
- Outer Radiation belt  
between  $3-4 R_E$   
100keV electrons  
Origin: Geomagnetic  
Storms

# The Magnetospheric Boundary: Bow Shock, Magnetosheath, and Magnetopause

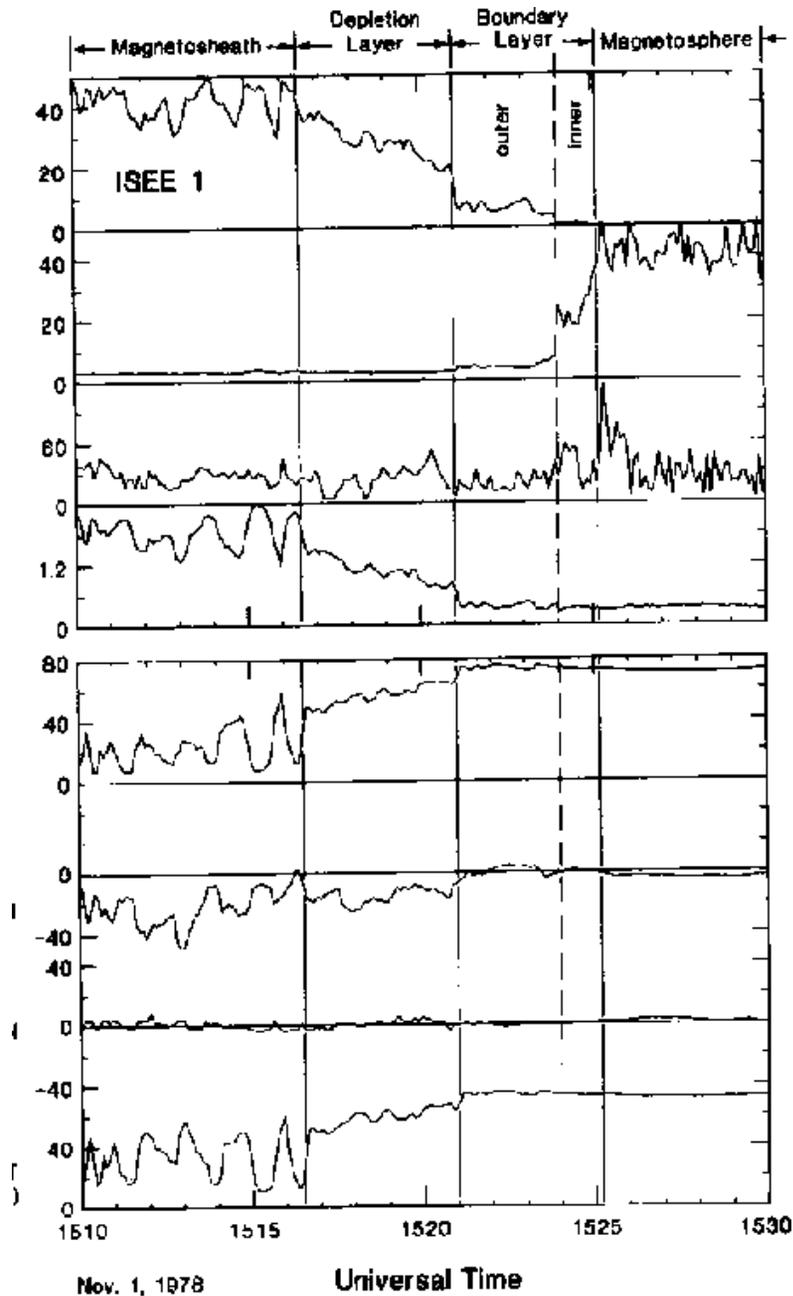


# Magnetosheath/Magnetopause



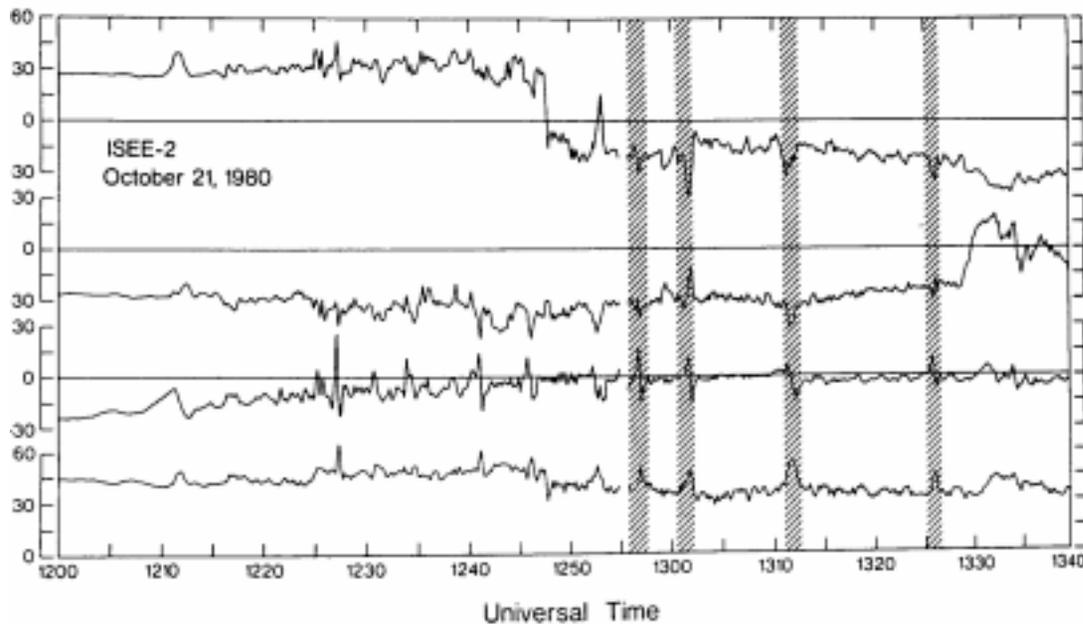
- Bow Shock  $V_A = V_{sw}$
- Collisionless (Heating due to Wave Particle Interaction)
- Foreshock Due to Reflection/Plasma Waves
- Magnetosheath (Anisotropy, SubAlfvenic Flow, high  $\beta$ )
- Magnetopause (Current Layer, Transition to Lower  $\beta$ ) — Mirror Waves

# Magnetopause Crossing (Northward IMF)



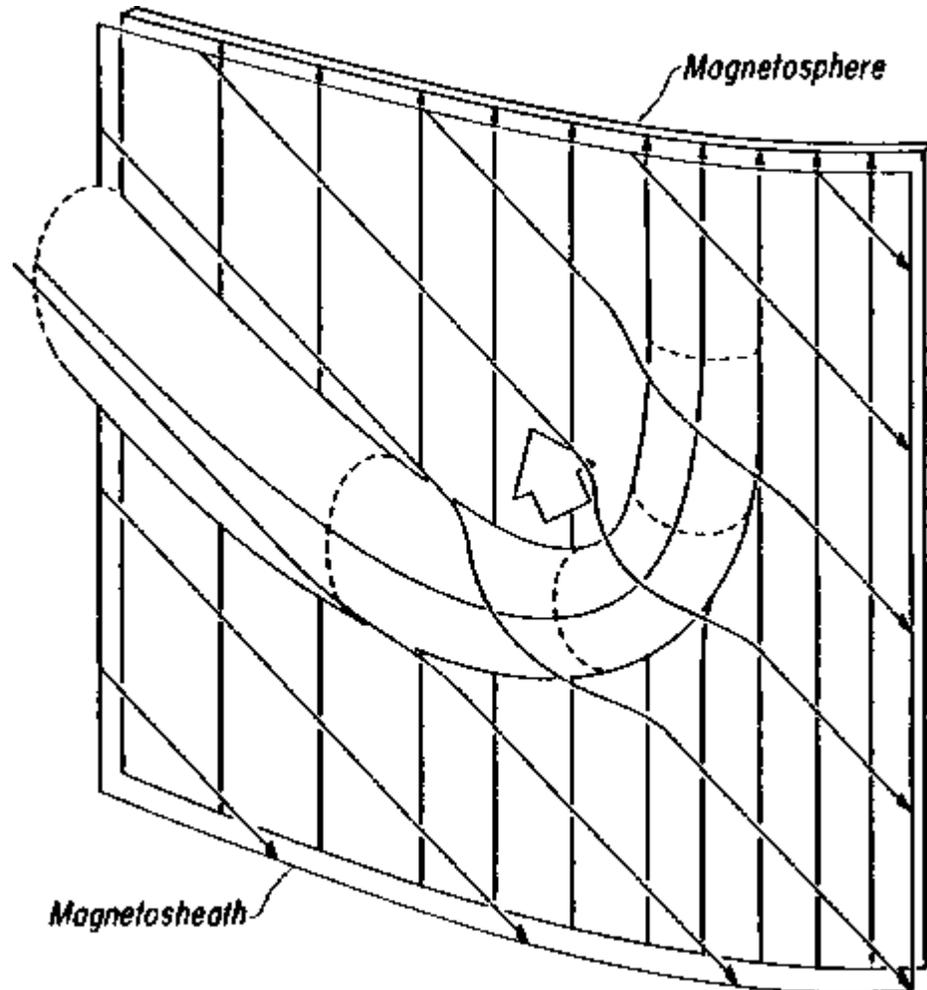
- Mirror Modes in Sheath
- Depletion Layer
- Low Latitude Boundary Layer
- Increase of B, Decrease of Density

# Flux Transfer Events



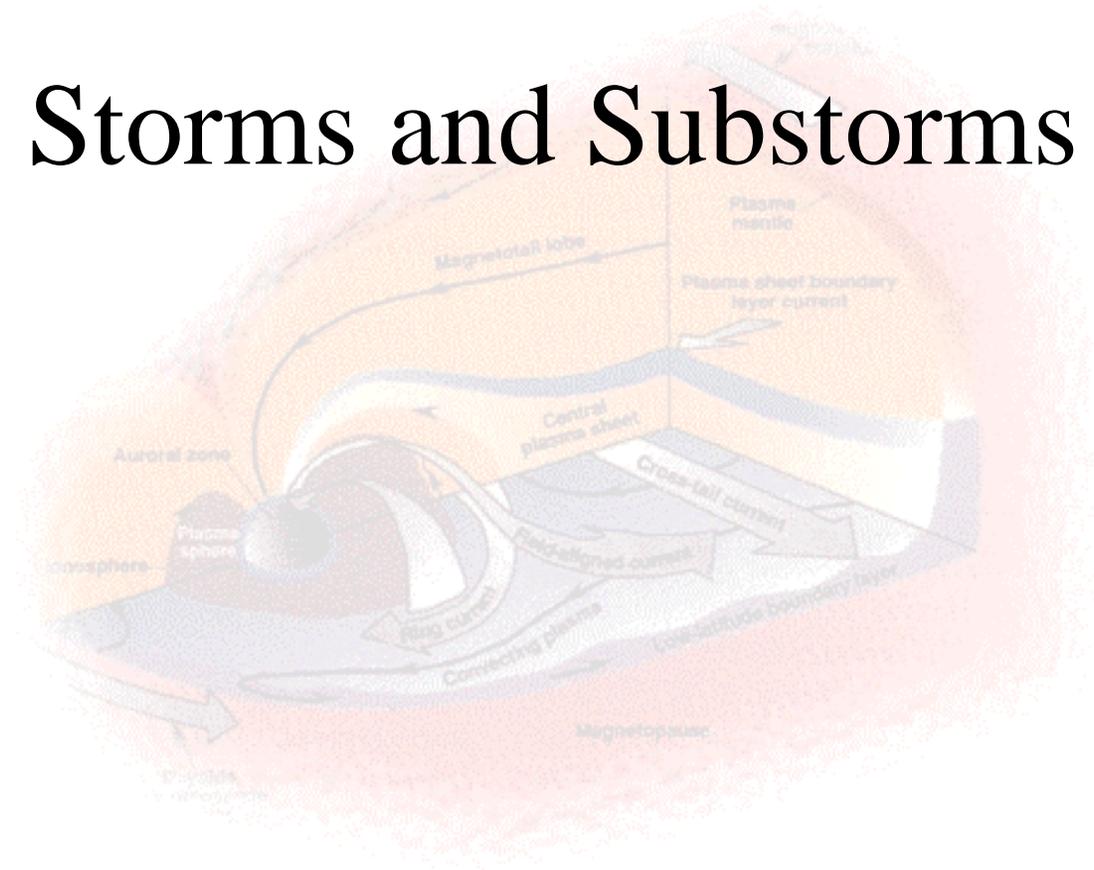
- At Magnetopause
- Bipolar  $B_n$  Signature
- $B_{tot}$  increases
- Mix of Magnetosphere/Magnetosheath Particles

# Flux Transfer Events



- At Magnetopause
- Bipolar  $B_n$  Signature
- $B_{tot}$  increases
- Mix of Magnetosphere/Magnetosheath Particles

# Storms and Substorms



# Magnetospheric Dynamics

## Storms (1-5 days) (Dst)

- Associated with Intense Solar Disturbances
- Initial Phase (increase of B)
  - Compression
  - 0-25 hours
- Main Phase (decrease of B)
  - Growth of Ring Current
  - 1 day
- Recovery Phase (gradual increase of B)
  - Dipolarize
  - many days

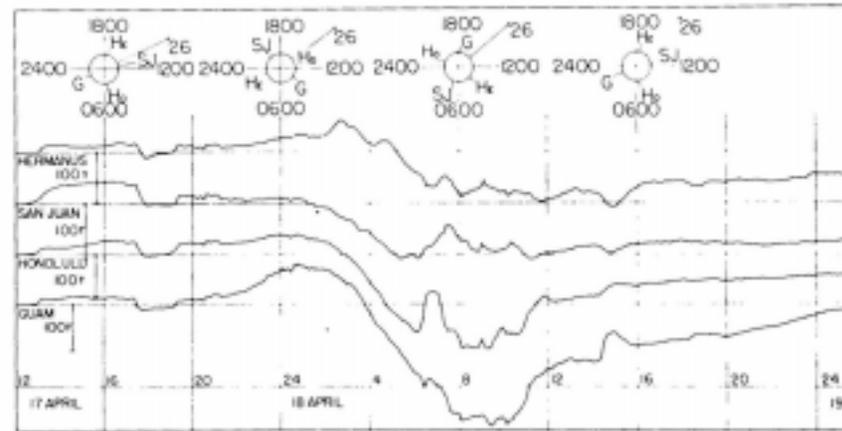
## • Substorms (AU,AL)

- Associated with Earth's Response to Local Conditions
- Growth Phase (30 min)
  - Storage of Solar Wind Energy
- Expansion Phase (20 min)
  - Sudden Release of Magnetic Energy
  - Current Disruption
- Recovery Phase (hours)
  - Return of Magnetosphere to Original Condition

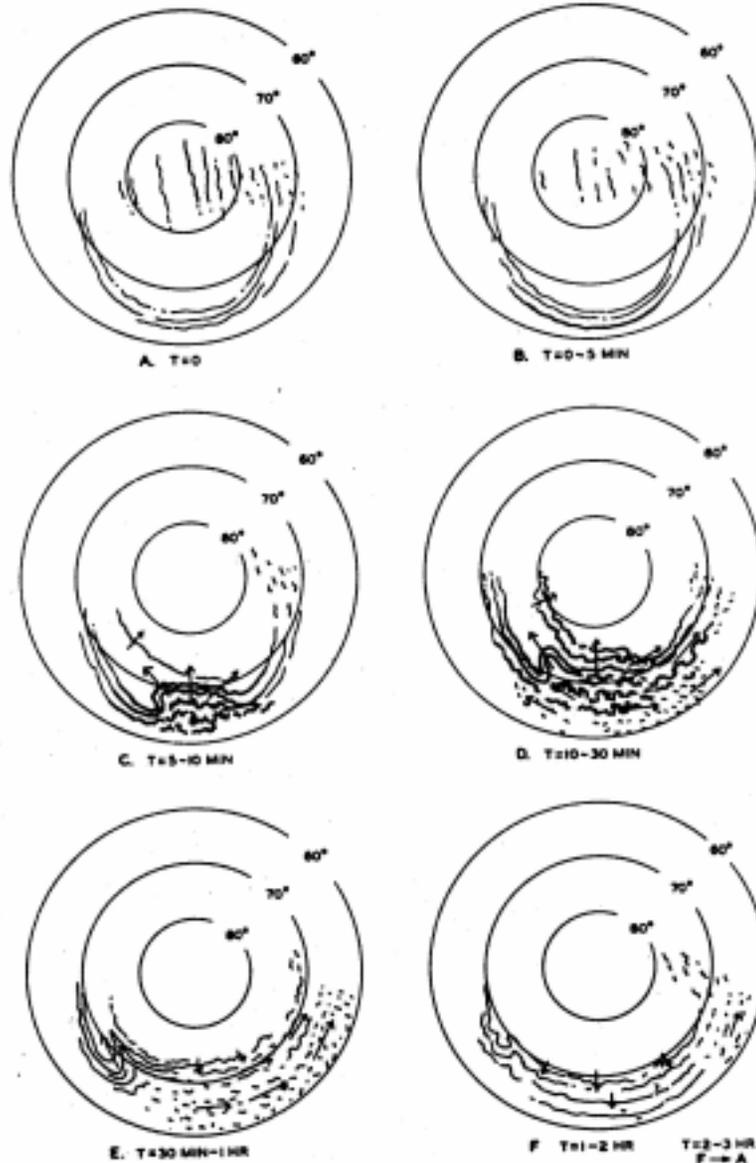
# Magnetospheric Dynamics

## Storms (1-5 days) (Dst)

- Associated with Intense Solar Disturbances
- Initial Phase (increase of B)
  - Compression
  - 0-25 hours
- Main Phase (decrease of B)
  - Growth of Ring Current
  - 1 day
- Recovery Phase (gradual increase of B)
  - Dipolarize
  - many days

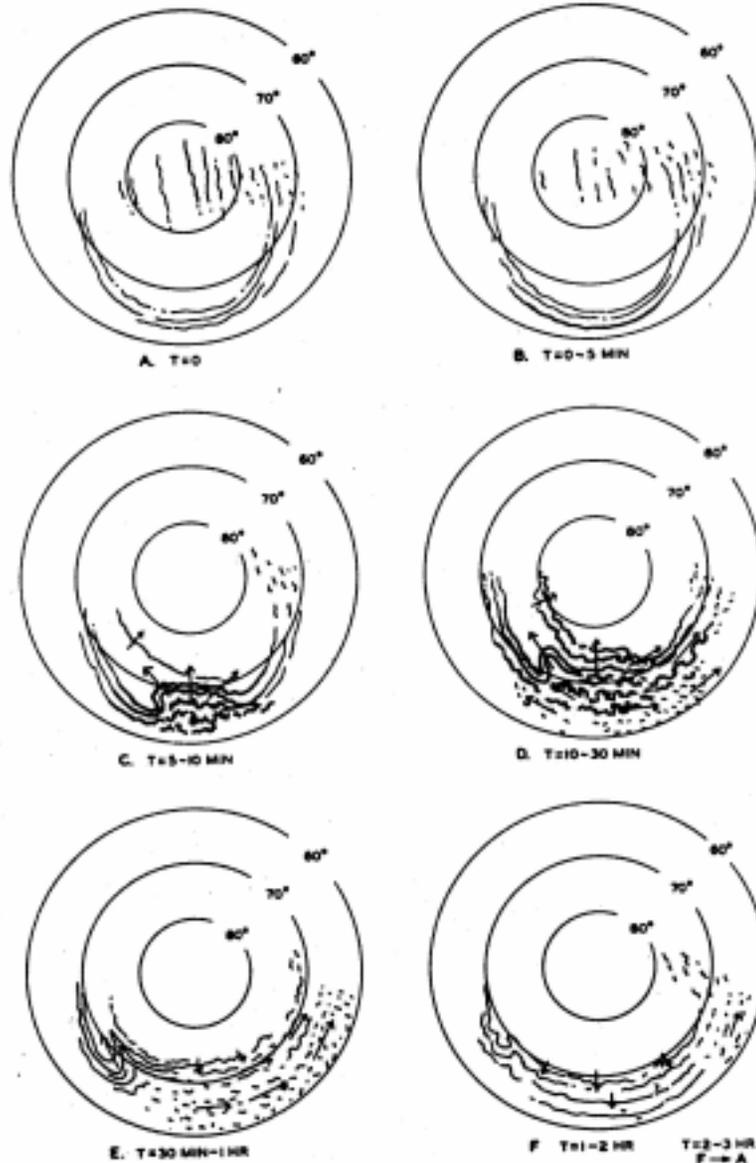


# Magnetospheric Dynamics



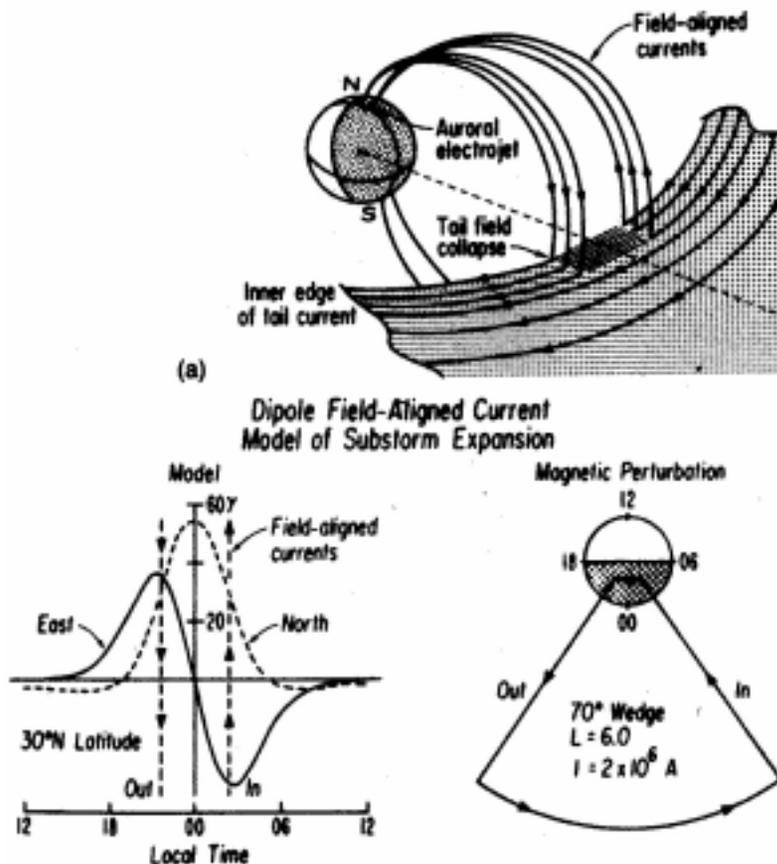
- Substorms (AU,AL)
  - Associated with Earth's Response to Local Conditions
  - Growth Phase (30 min)
    - Storage of Solar Wind Energy
  - Expansion Phase (20 min)
    - Sudden Release of Magnetic Energy
    - Current Disruption
  - Recovery Phase (hours)
    - Return of Magnetosphere to Original Condition

# Outstanding Substorm Issue



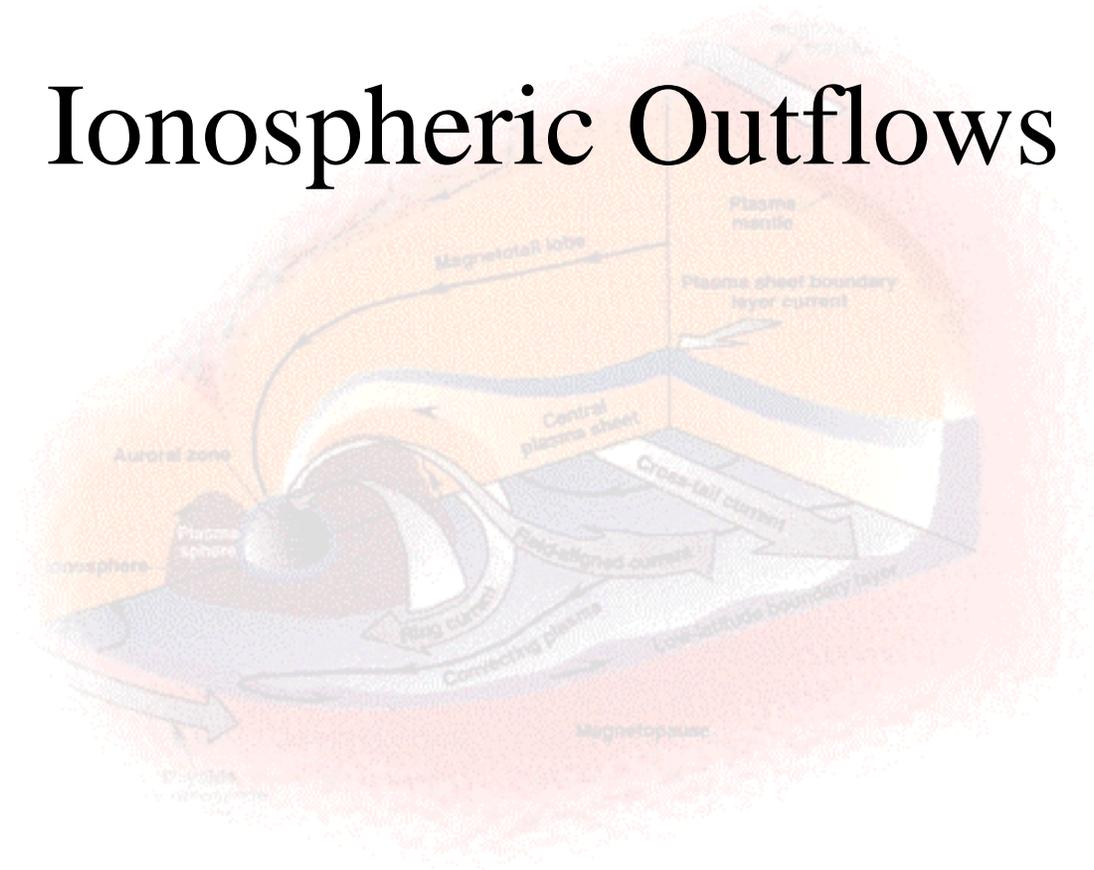
- Location of Substorm Onset
- Model 1: Near Earth (9R) Due to Instability Associated with Current Disruption
- Model 2: Far Tail Due to Reconnection

# Magnetospheric Dynamics

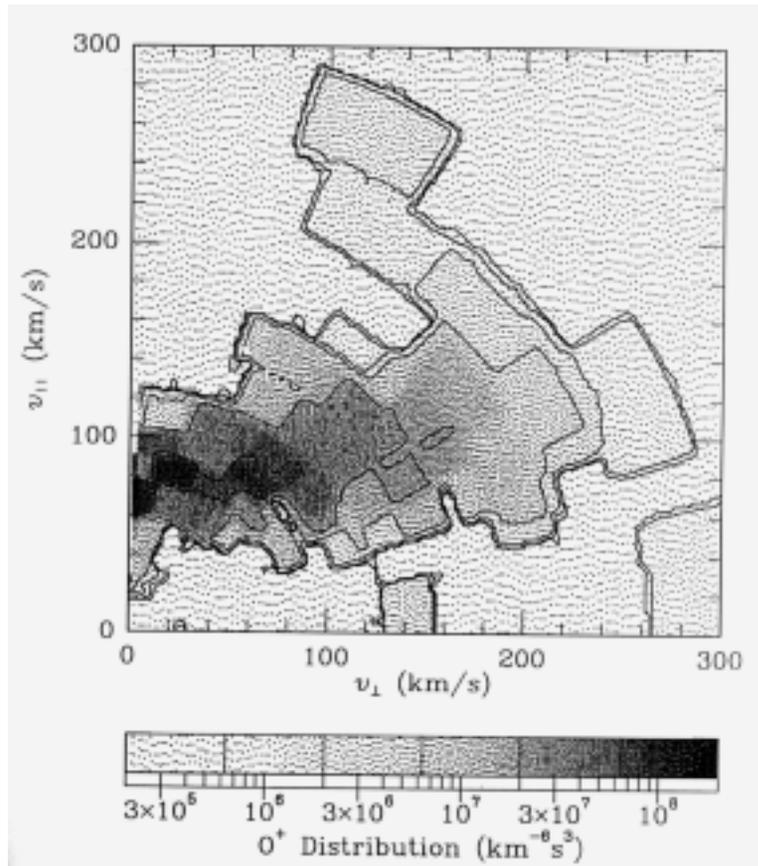


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# Ionospheric Outflows

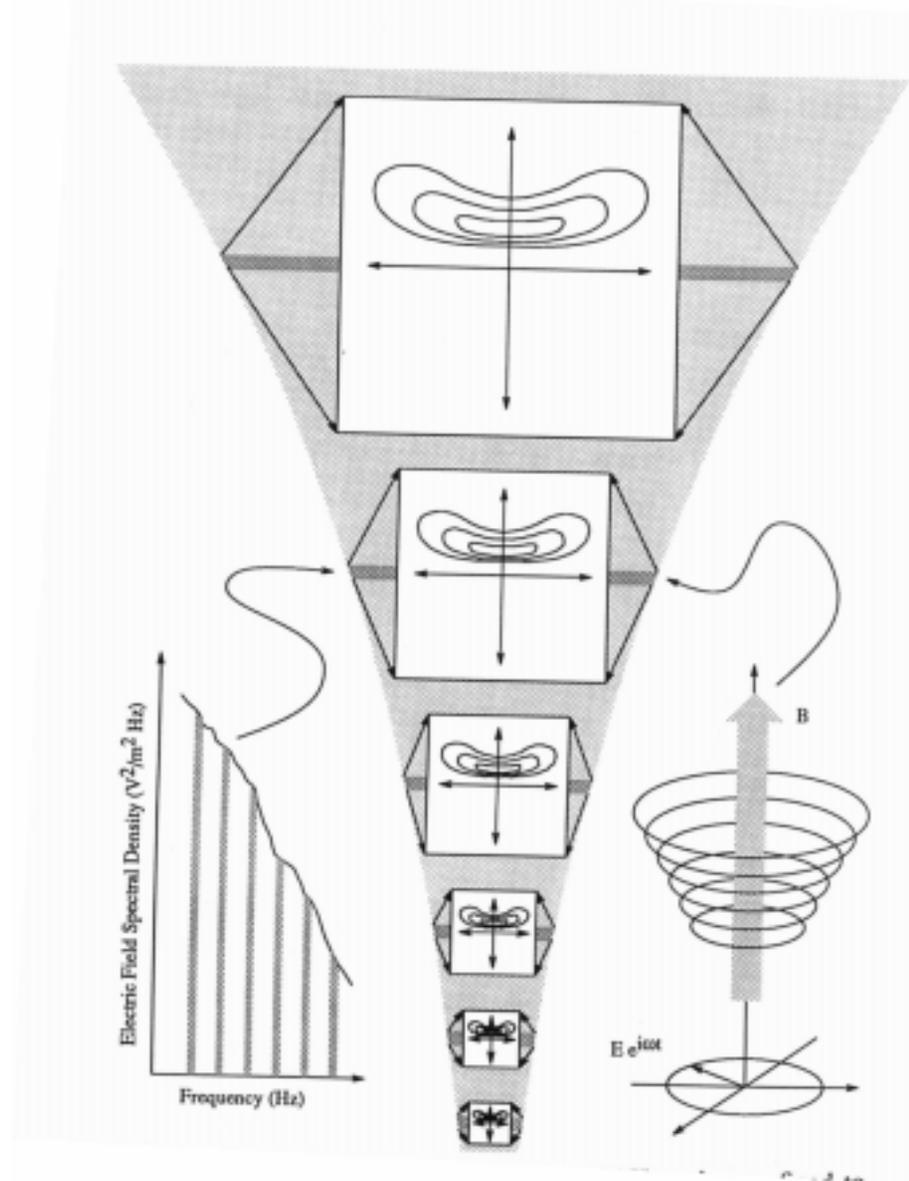
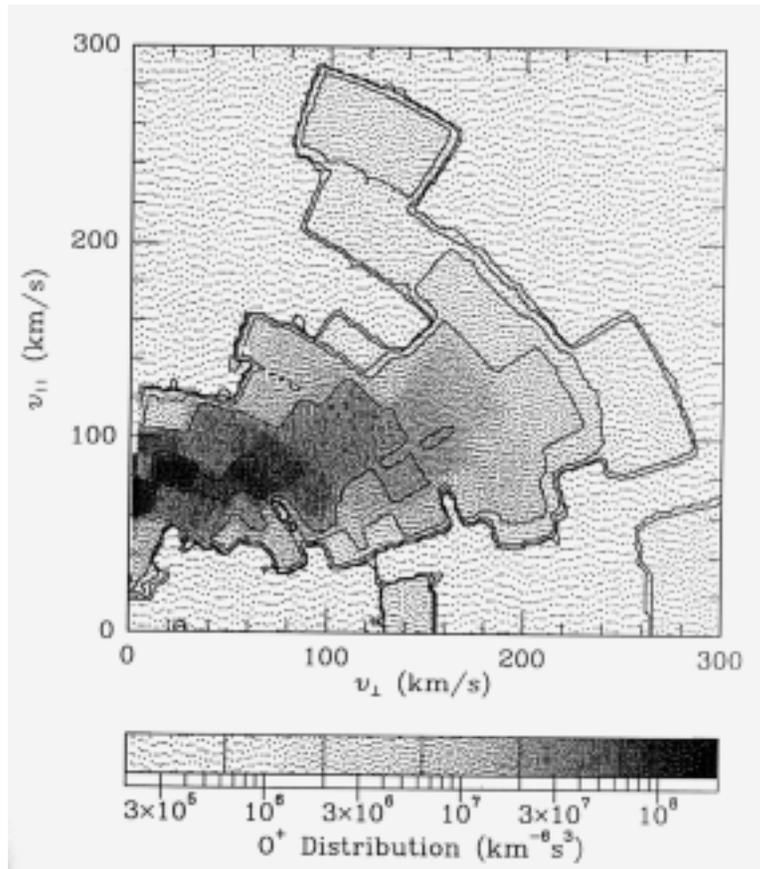


# Ion Conics

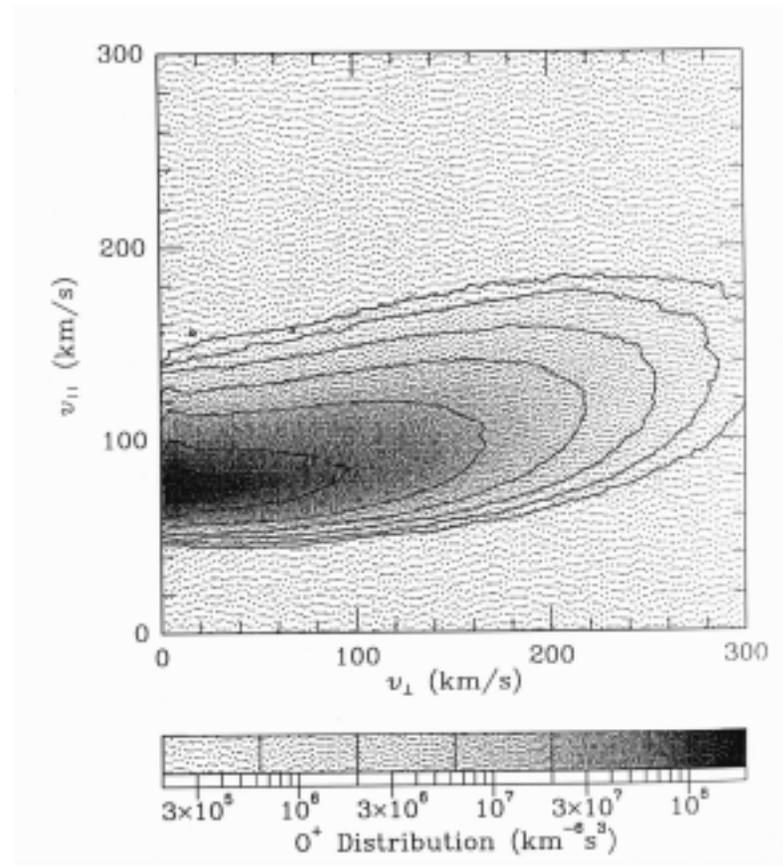
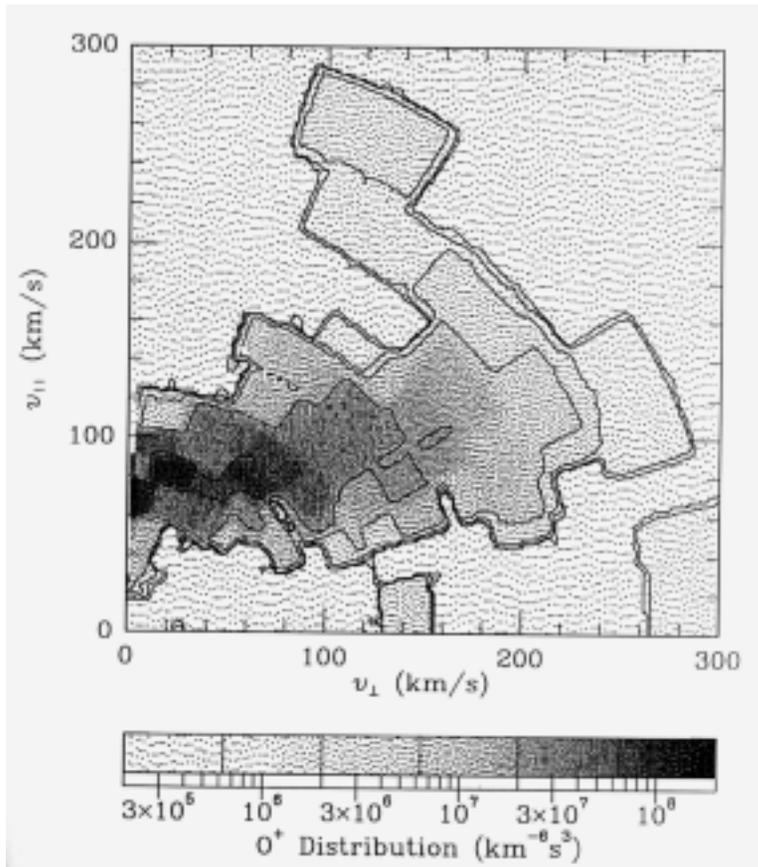


- During Storms 50 percent of Energetic Plasma Sheet Ions are Oxygen from the Ionosphere
- Heavy Ion Outflows Observed Along Auroral Field Lines
- Velocity Distribution Conical Shaped
- Broadband EMIC Waves

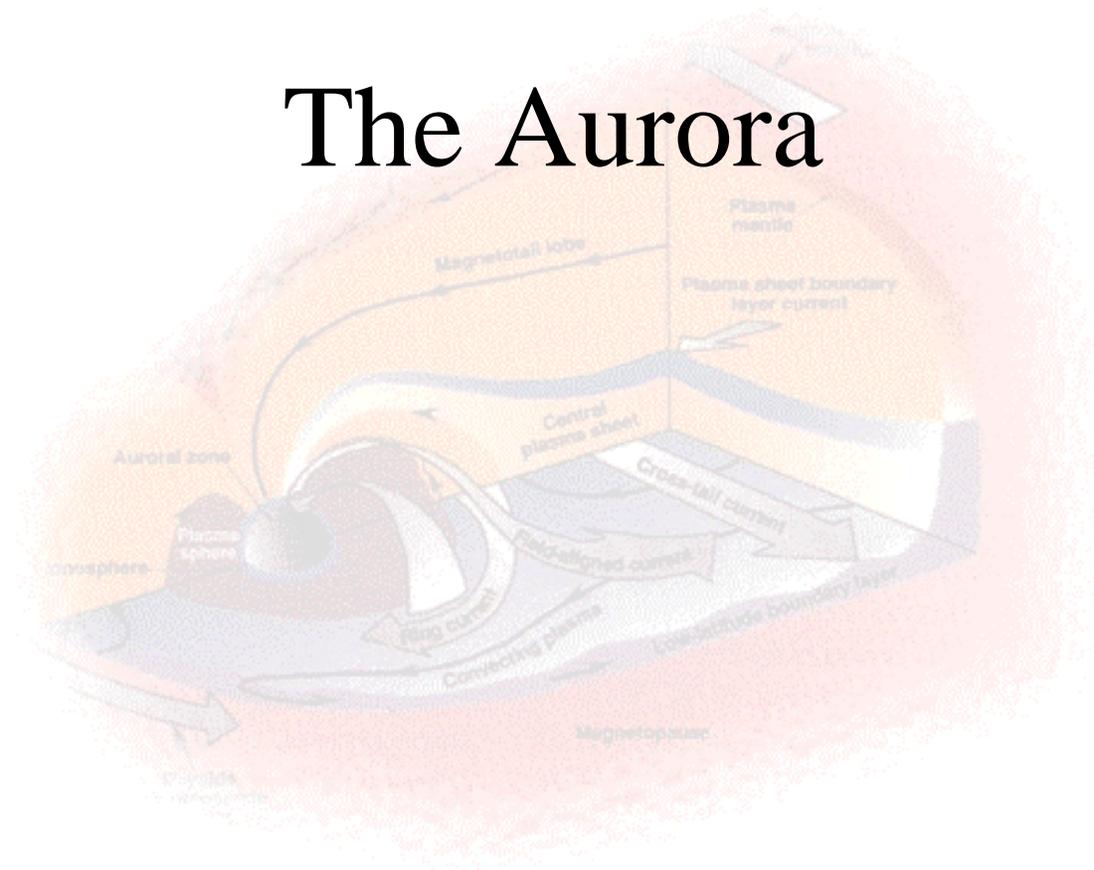
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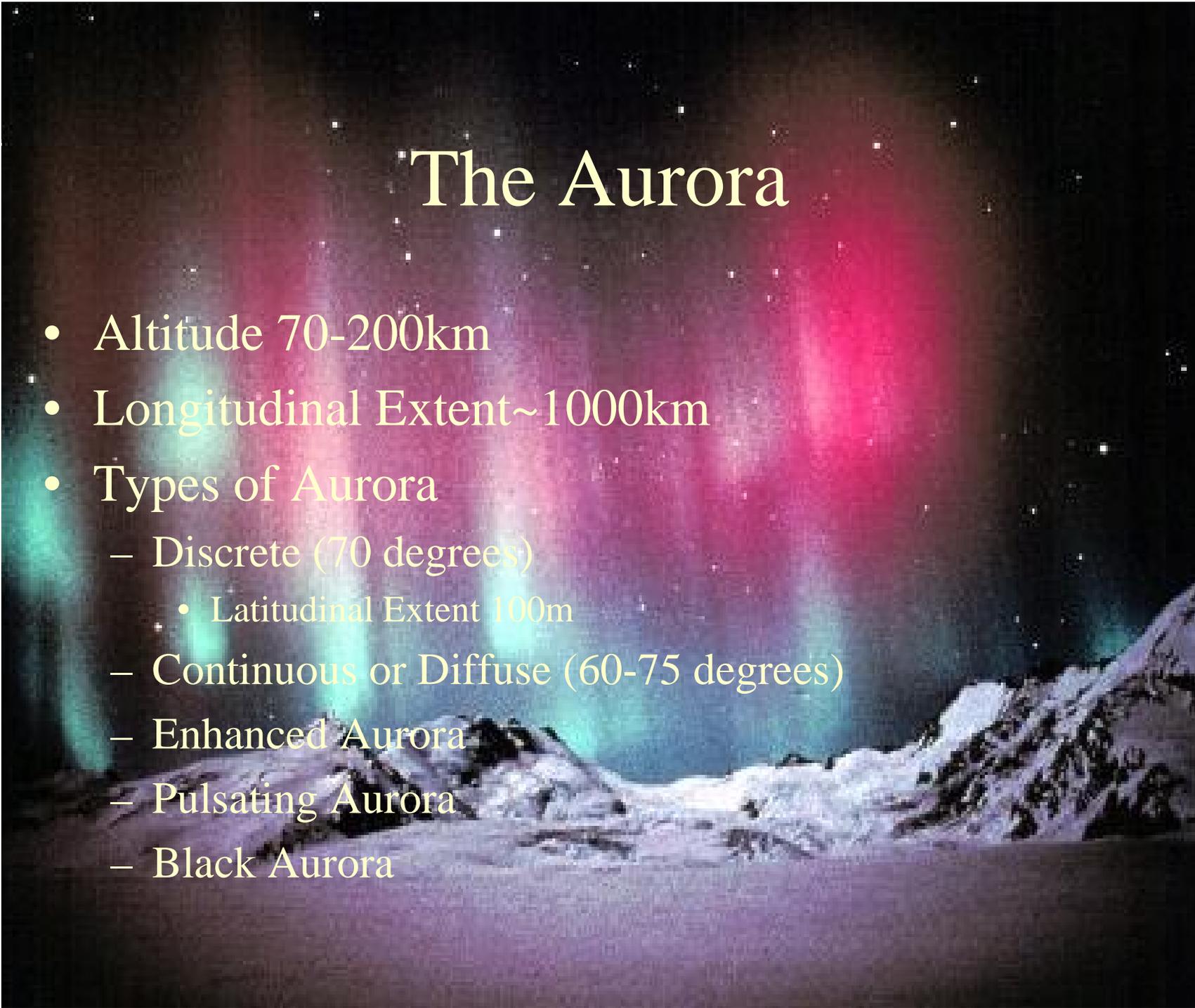
# Ion Conics



# The Aurora

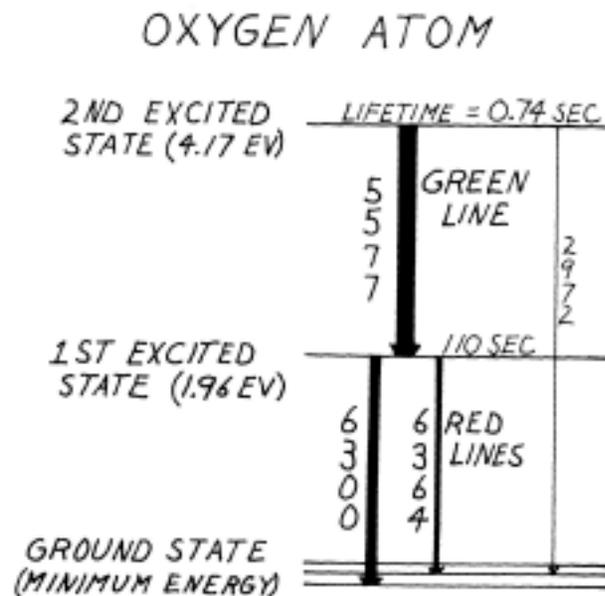


# The Aurora



- Altitude 70-200km
- Longitudinal Extent~1000km
- Types of Aurora
  - Discrete (70 degrees)
    - Latitudinal Extent 100m
  - Continuous or Diffuse (60-75 degrees)
  - Enhanced Aurora
  - Pulsating Aurora
  - Black Aurora

# Auroral Colors and Altitude



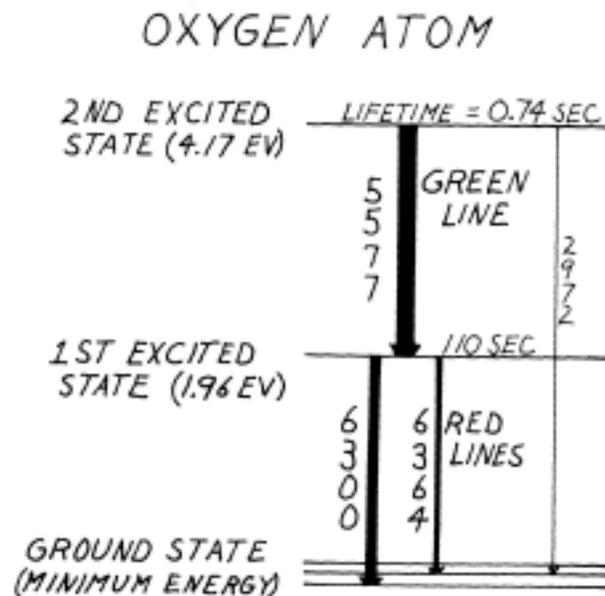
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- Blood Red Aurora Occurs when Electron Beam Energy < 500eV

# Auroral Colors and Altitude



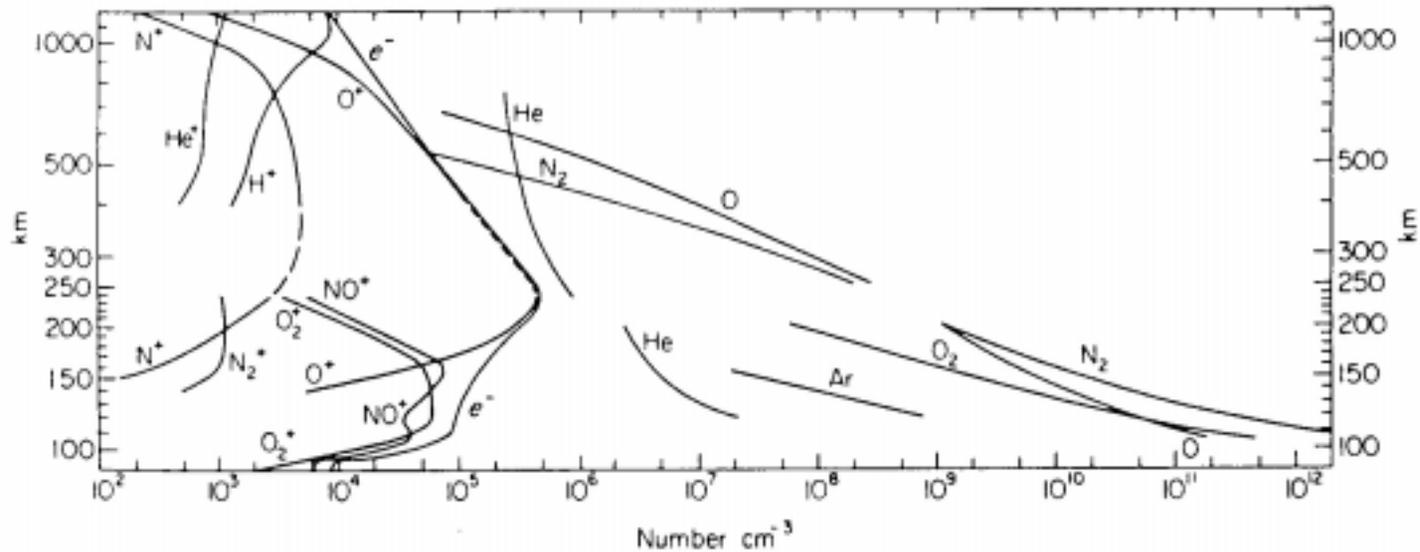
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# Auroral Colors and Altitude



- At 100-150 km collision rate too large so emission from metastable state quenched >> Green 5577
- Electrons about 10 keV

# Auroral Colors and Altitude



- Below 100 km N<sub>2</sub> can dominate O emission, so red emission seen at lower edge of arc

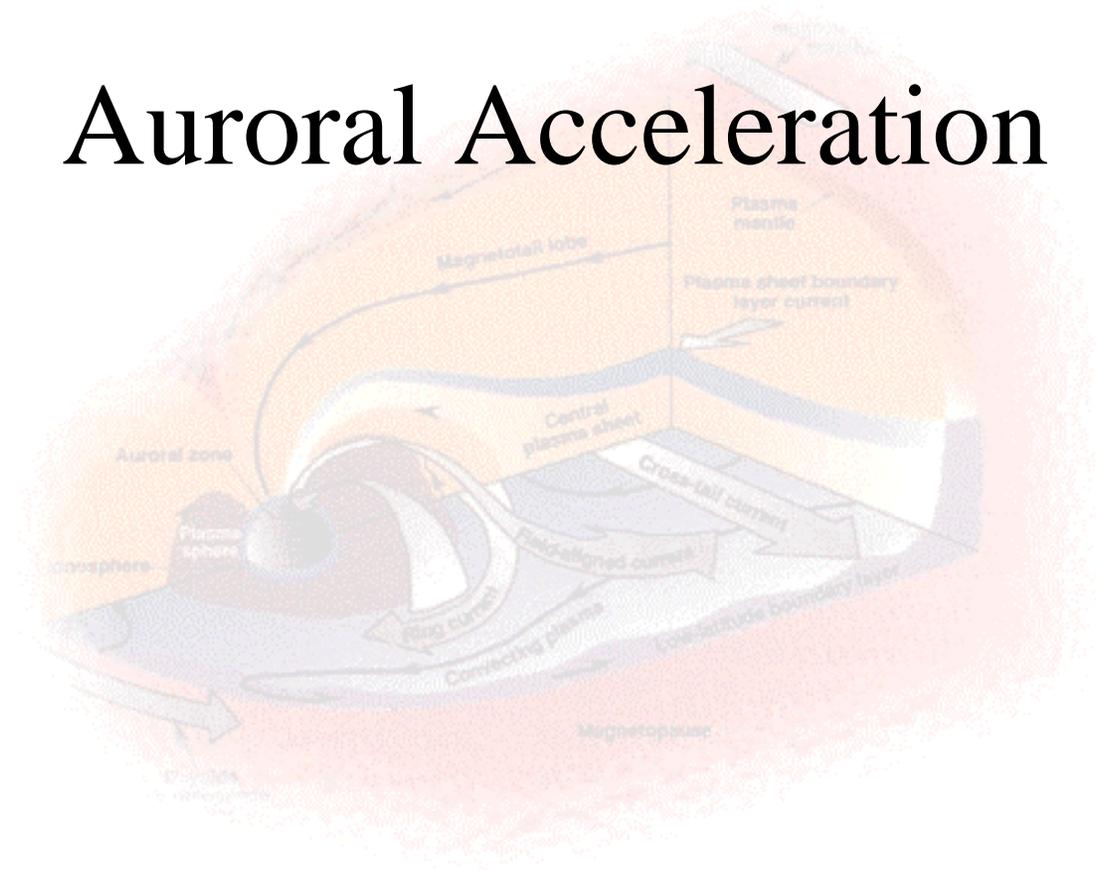


# Diffuse (Continuous) Aurora

- Diffuse Aurora from DE-1 and from the Ground
- Widespread in Latitude, Connects to Plasma Sheet
- Results From Wave Particle Scattering of Electrons and Ions into Loss Cone ( $< 3$  degrees)

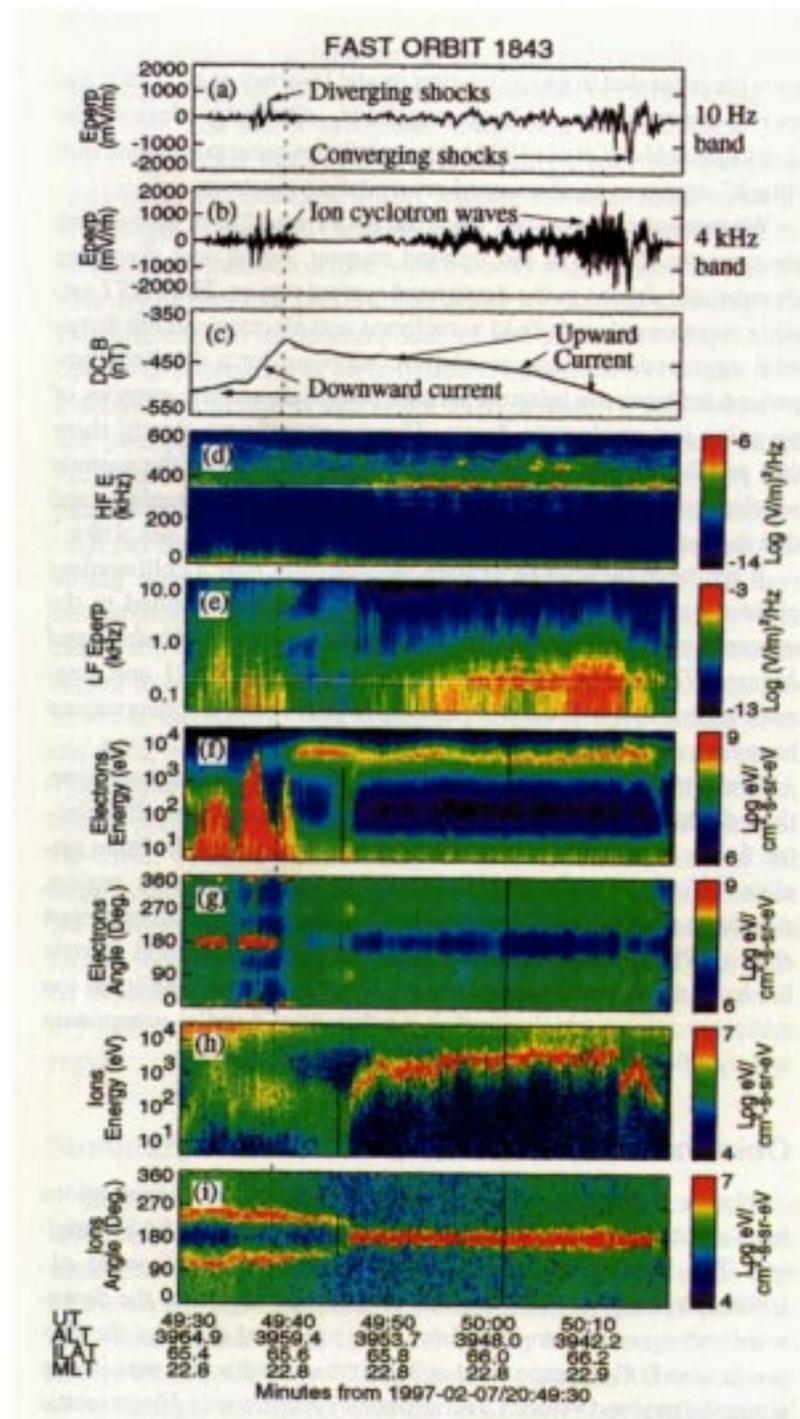


# Auroral Acceleration



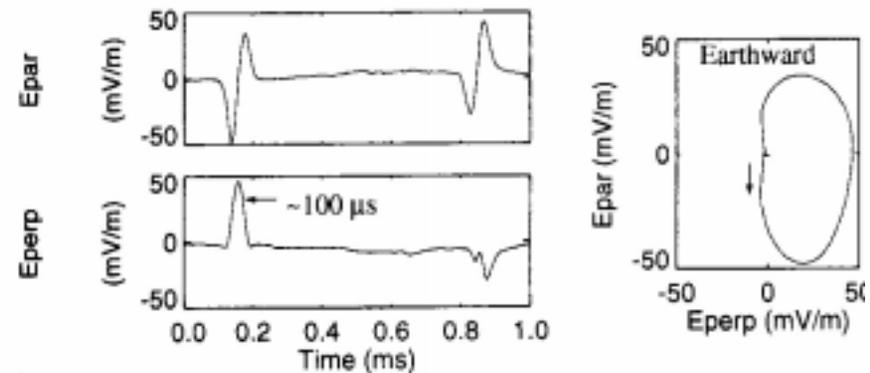
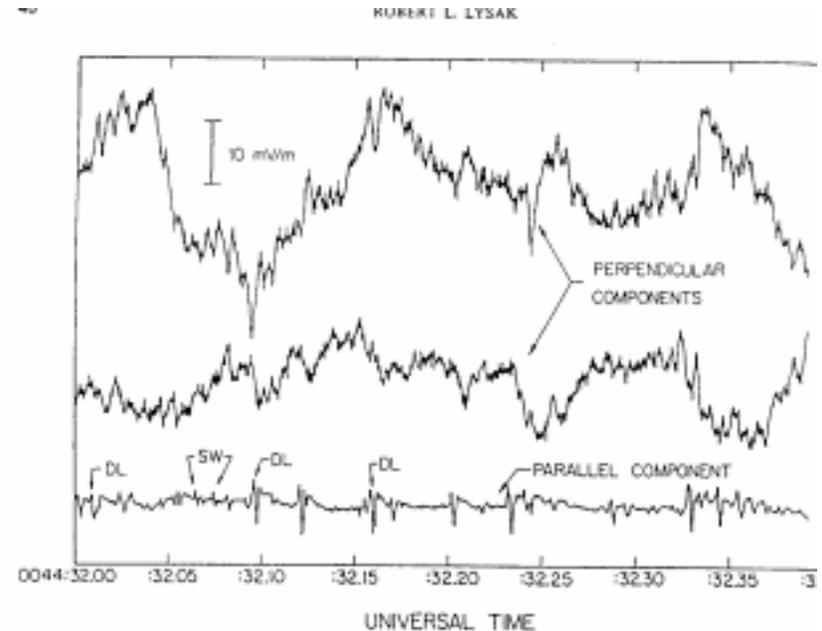
# Auroral Acceleration Mechanisms

- Observations
  - Electron Energy 10keV
  - Parallel Electric Fields
  - Acceleration  $\sim 1-2R_E$
- Mechanisms
  - Double Layers
  - Generator Model
  - Kinetic/Inertial Alfvén Waves
  - Reconnection



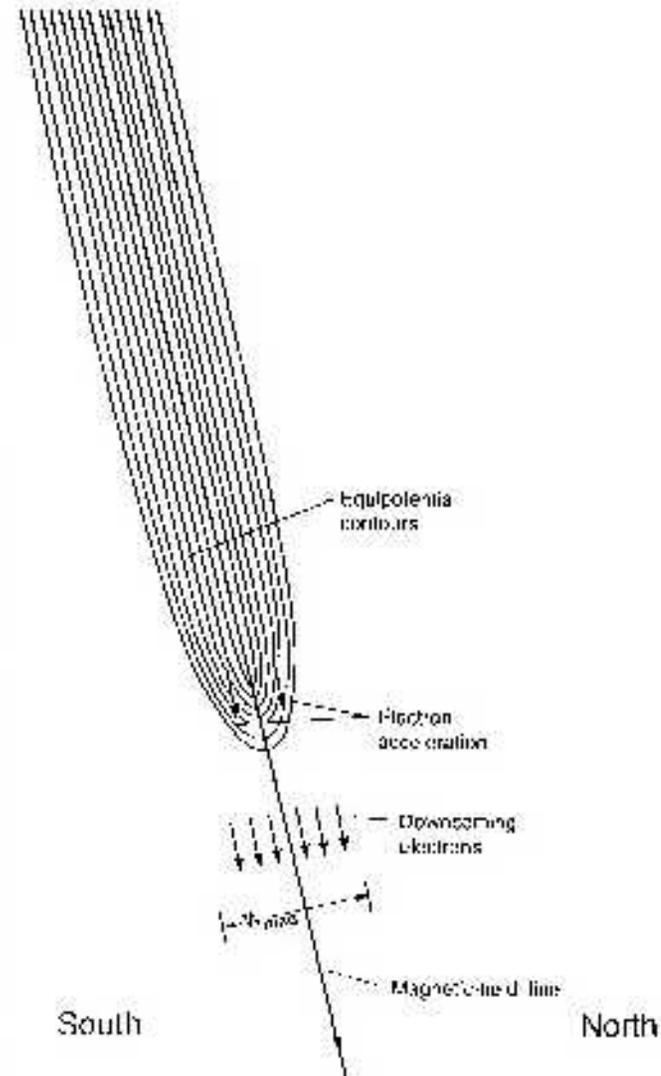
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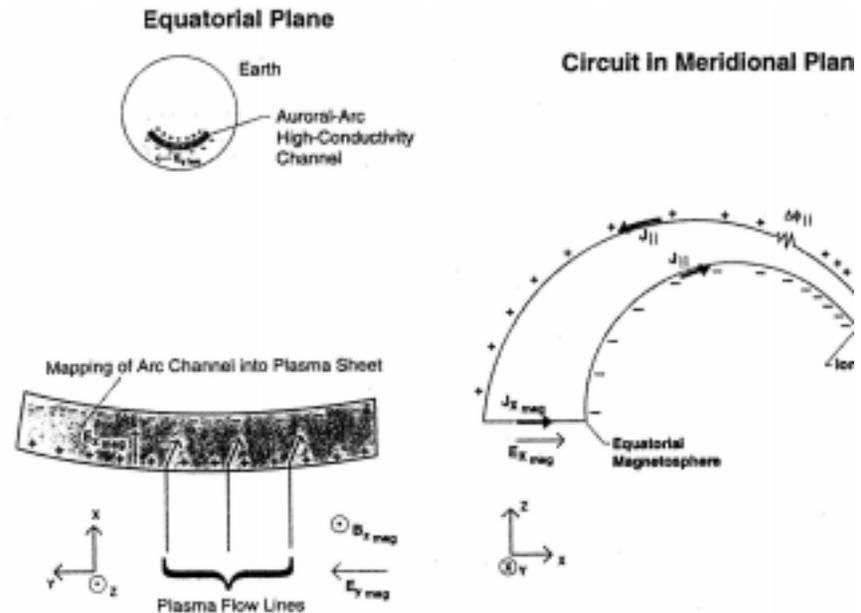
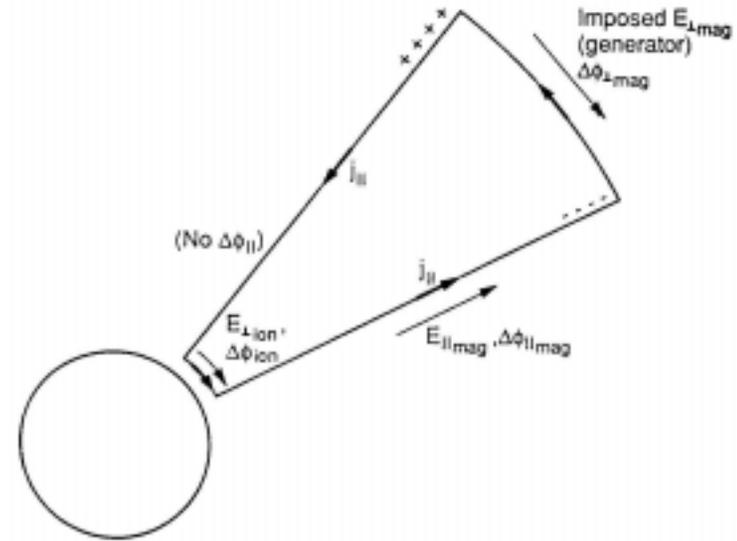
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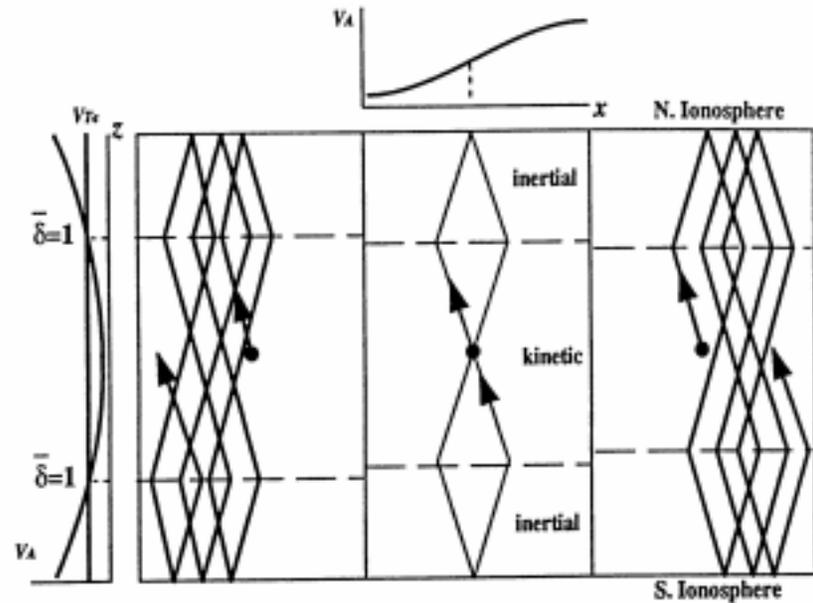
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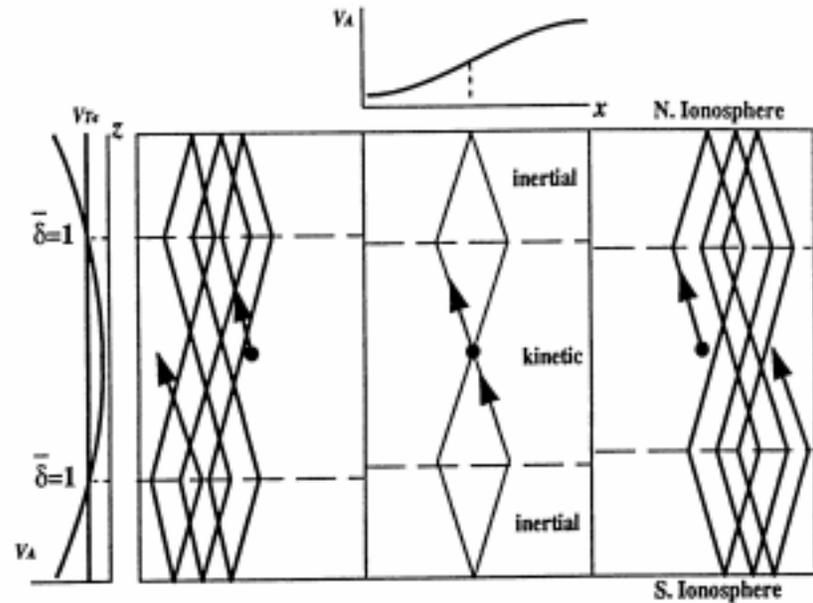


- Kinetic Regime

$$\omega^2 = k_{\parallel}^2 V_A^2 \left[ 1 + \left( 1 + \frac{T_e}{T_i} \right) k_{\perp}^2 \rho_i^2 \right]$$

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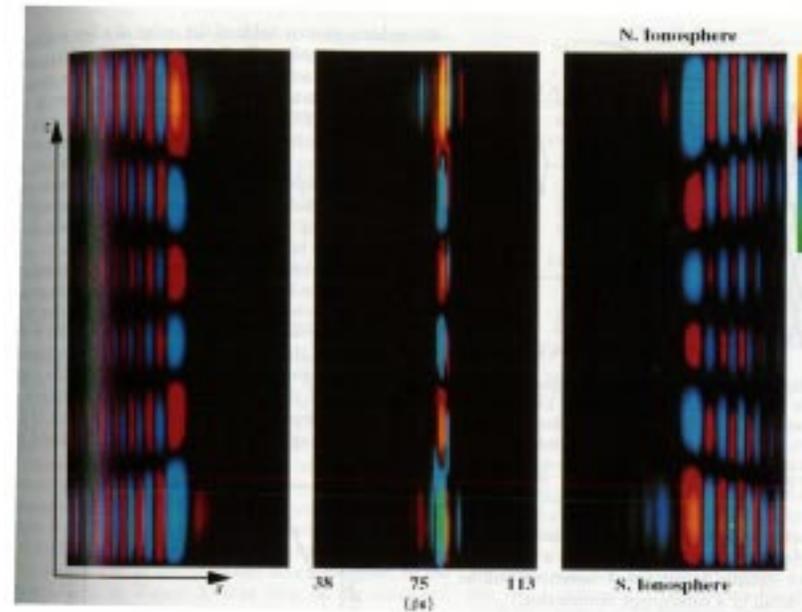
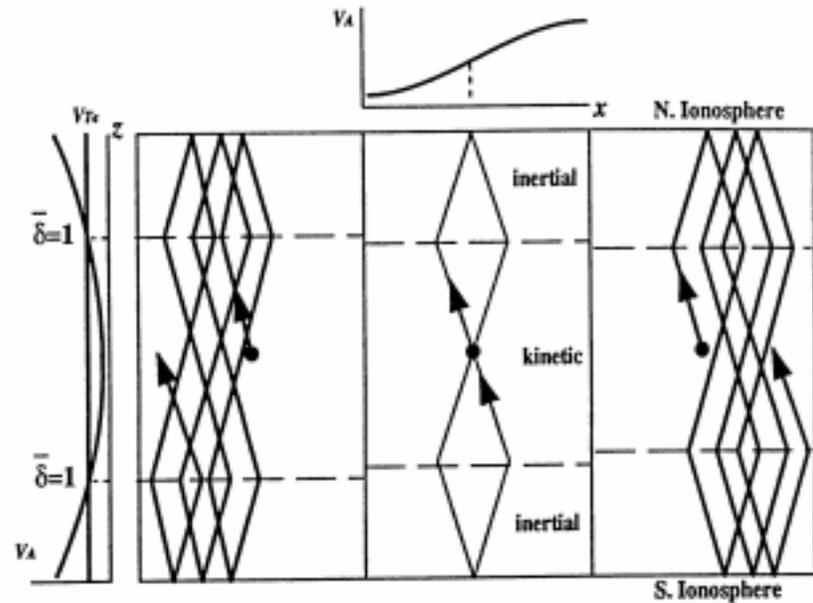


- Inertial Regime

$$\omega^2 = \frac{k_{\parallel}^2 V_A^2}{\left[ 1 + k_{\perp}^2 c^2 / \omega_{pi}^2 \right]}$$

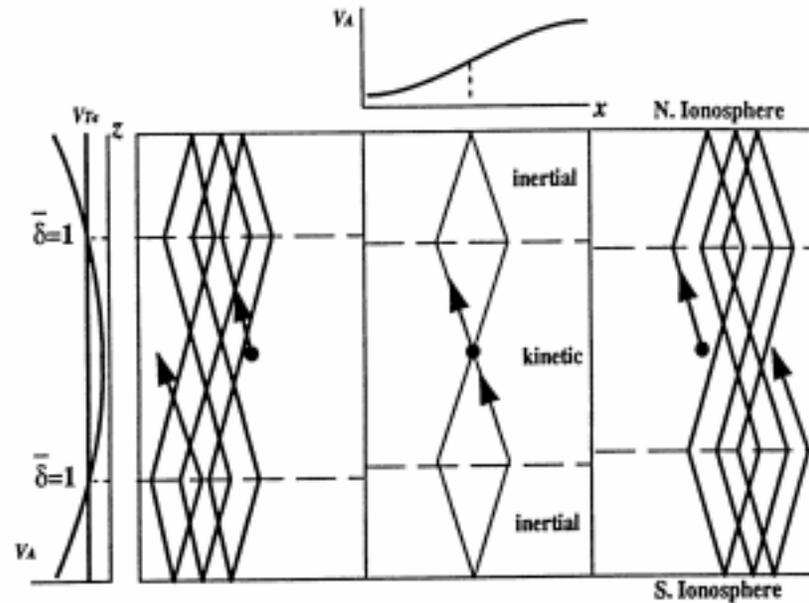
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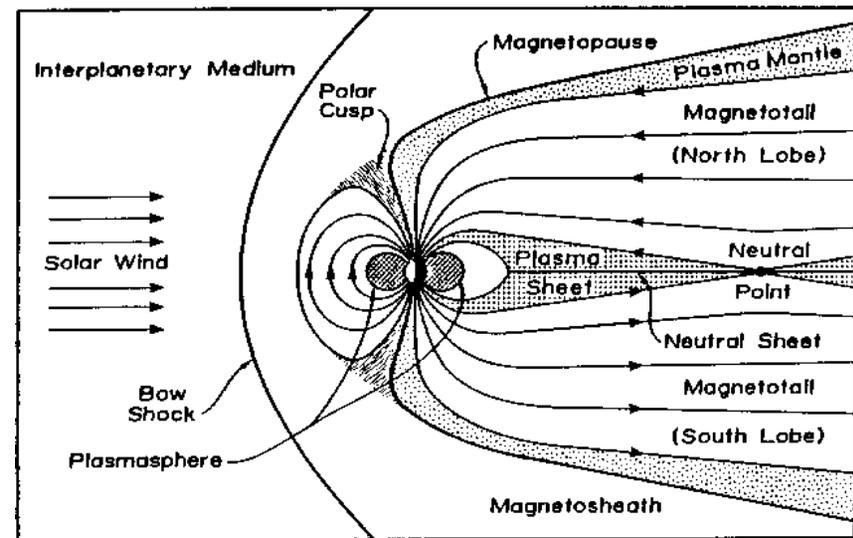
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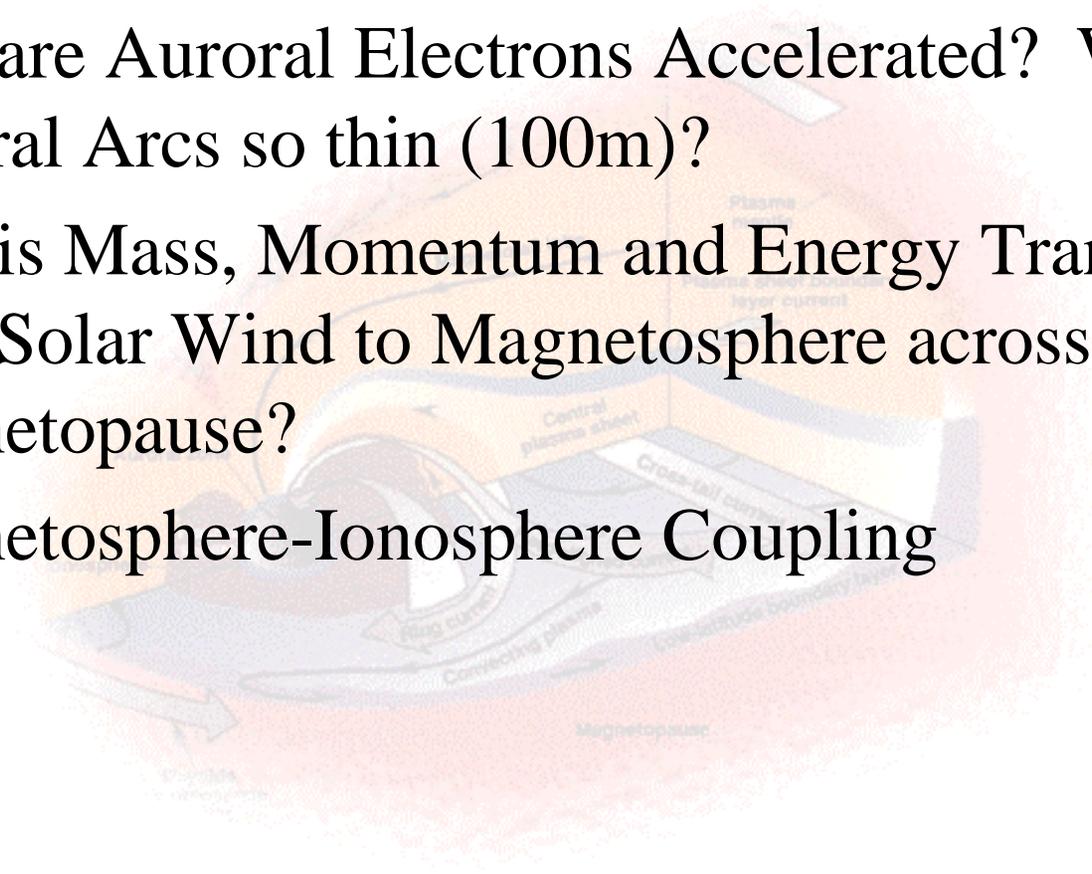
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# Outstanding Problems

- What is the Onset Mechanism For Substorms?
- How are Auroral Electrons Accelerated? Why are Auroral Arcs so thin (100m)?
- How is Mass, Momentum and Energy Transferred from Solar Wind to Magnetosphere across the Magnetopause?
- Magnetosphere-Ionosphere Coupling



# Sunlit Aurora

