

# Inner Magnetospheric Physics



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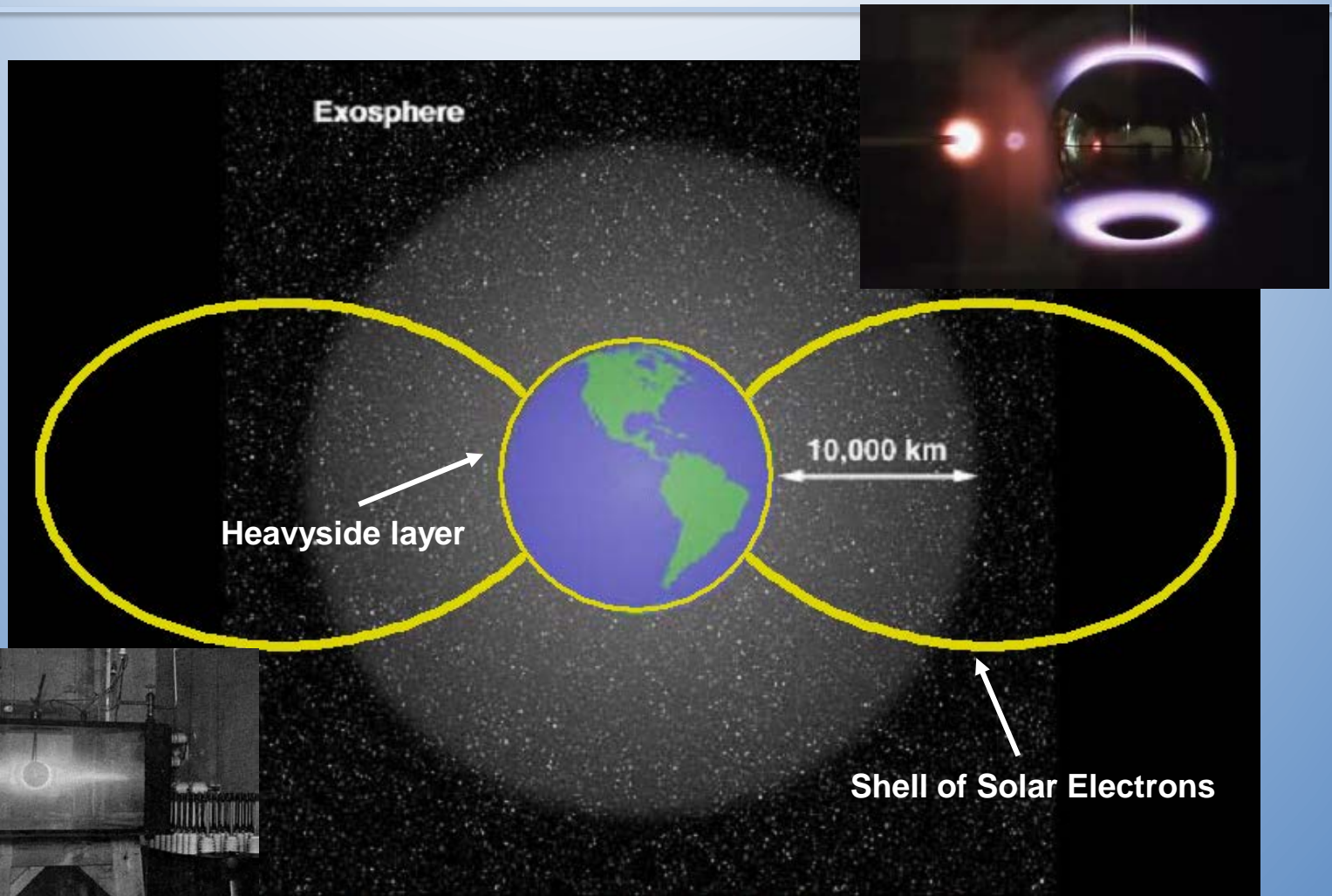
# Inner Magnetosphere Effects

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- Historical Background
- Main regions and transport processes
  - Ionosphere
  - Plasmasphere
  - Plasma sheet
  - Ring current
  - Radiation belt
- Geomagnetic Activity
  - Storms
  - Substorm
- Models

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# Historical Background: Space in 1950



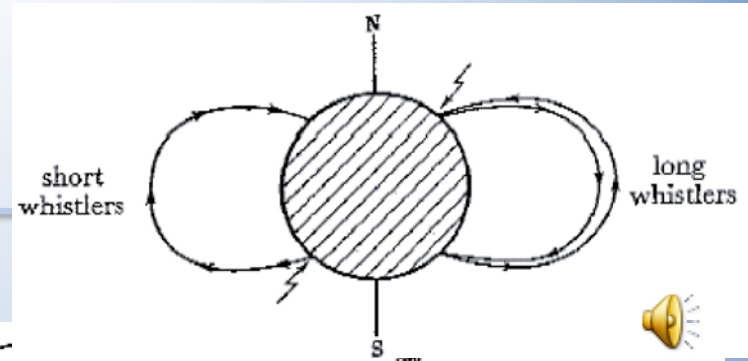
# Historical Background

Whistlers revealed unexpected plasma



**1952**

**L. R. Owen Storey  
Cavendish Laboratory  
University of Cambridge**



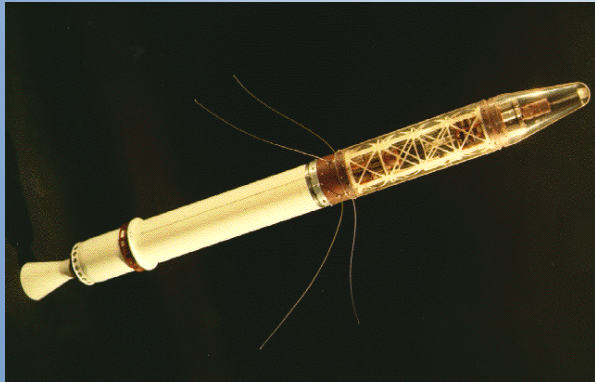
**Whistlers**



*Historical Background*

# Historical Background

Explorer 1  
January 31, 1958

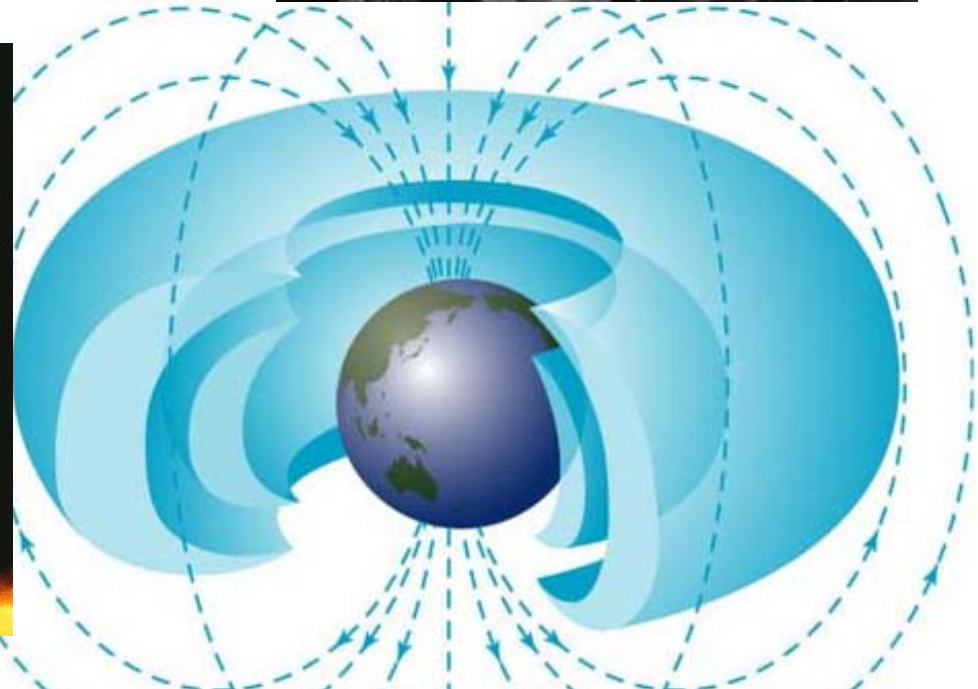
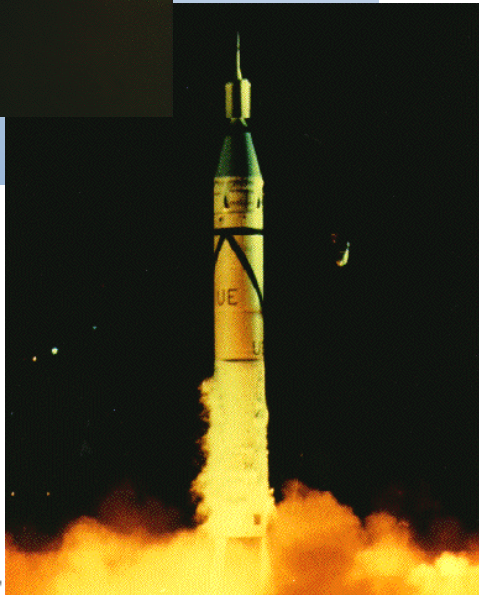
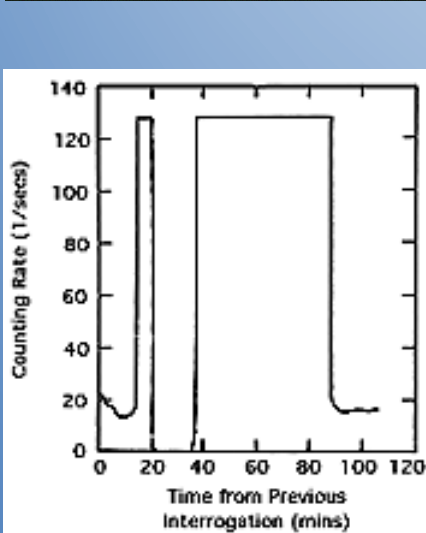


William Pickering

James van Allen

Wernher von Braun

Pick



**Radiation Belts Discovered**

Van Allen, James A., Observation of high intensity radiation by satellites 1958 alpha and 1958 gamma, IOWA Univ. preprint SUI 60-13, reprinted in p. 58-75, Space Science Comes of Age, P.A. Hanle and V.D. Chamberlain, editors, Smithsonian Inst. Press, Washington, DC 1981

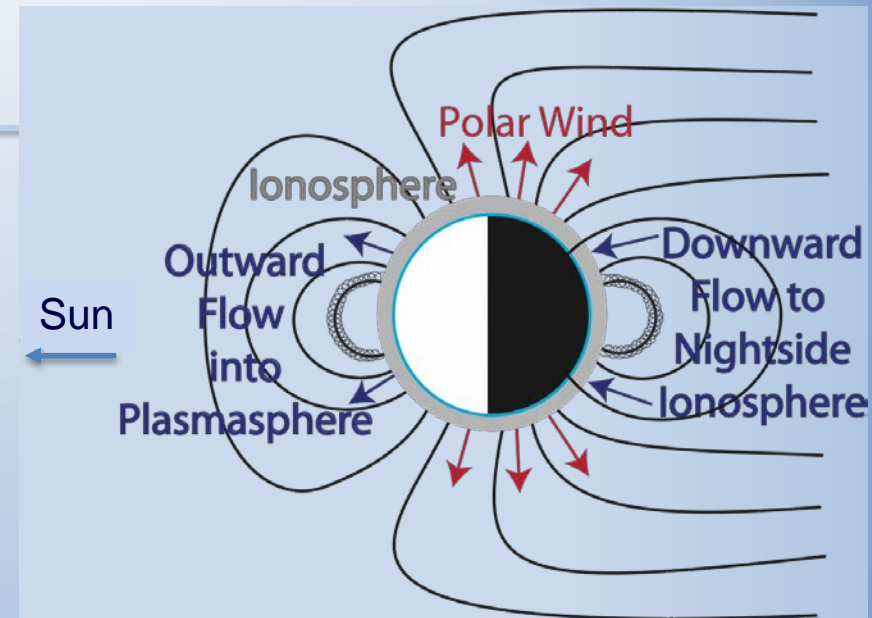
# Ionosphere

Reactions			Common Constituents
$X+\gamma \rightarrow X^++e^-$	$XY+\gamma \rightarrow X+Y$	$X^++e^- \rightarrow X$	X-rays, EUV, O, N, O <sub>2</sub> , N <sub>2</sub> , NO, H, O <sub>3</sub>
$X^-+Y \rightarrow XY+e^-$	$X^++YZ \rightarrow YX^++Z$	$X^++e^- \rightarrow X+\gamma$	
		$XY+e^- \rightarrow Y+X$	
		$X+e^- \rightarrow X^-$	

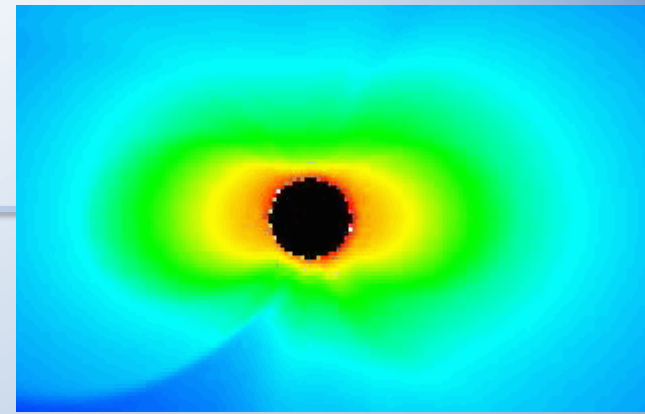
- Ionosphere: ionized portion of upper atmosphere
  - Extends from around 60 km to beyond 1000 km
  - Completely encircles the Earth
  - Main Source: photoionization of neutrals
    - ✦ Other production processes dominate in different ionospheric regions
  - Loss Mechanism: ionospheric outflow, recombination

# Ionosphere outflow

- Main cause
  - Ambipolar electric field
  - pressure gradients
  - Mirror force due to gyration of charged particles
- Polar wind: Ionospheric loss at polar latitude
  - Along essentially open geomagnetic field lines
- At mid-latitudes the plasma may bounce to the conjugate ionosphere or become the plasmasphere

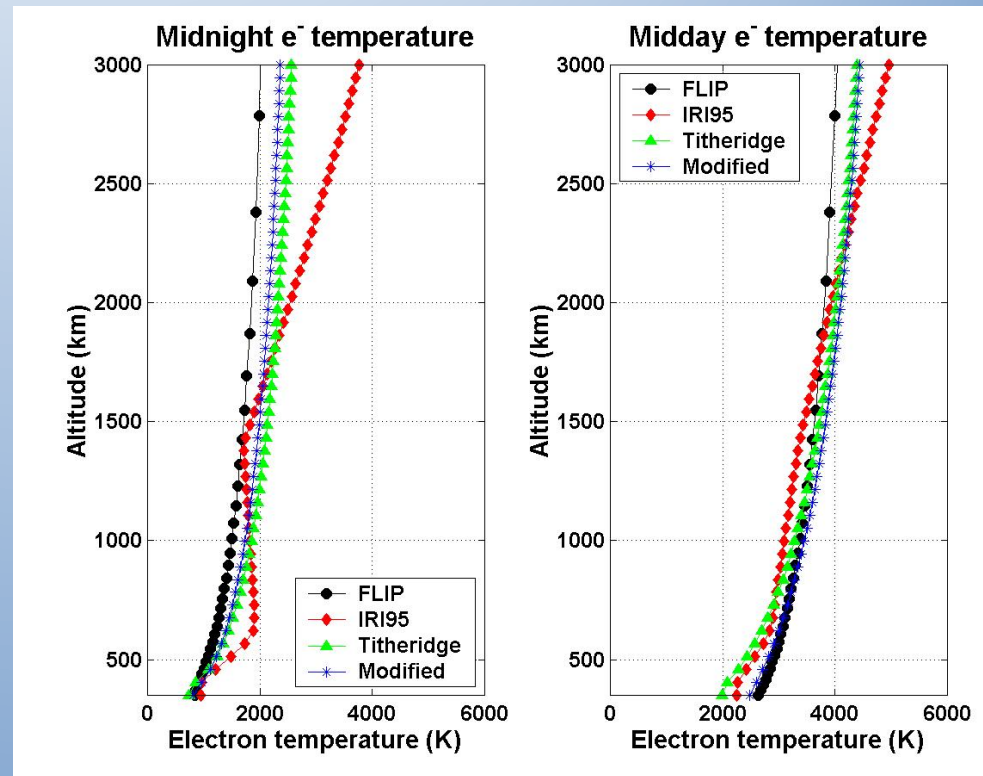


# Plasmasphere Formation: Diffusive Equilibrium



$$H_j = \left( \frac{kT_i}{m_j g} \right) \left( 1 - \frac{m_a T_e}{m_j T_t} \right)^{-1}$$

$H_j$  = scale height  
 $k$  = Boltzmann constant  
 $m_j$  =  $j$ 'th ion mass  
 $g$  = gravitational constant  
 $m_a$  = mean ion mass  
 $T_e$  = electron temperature  
 $T_t = T_i + T_e$  total temperature



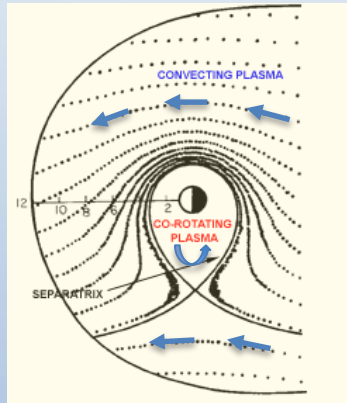
Titheridge, J.E., Planetary and Space Science, 20 (1972), pp. 353-369

Webb, P.A. and E.A. Essex, 2001, J. Atmos. Solar Terres. Phys., 63, 11, pgs 1249-1260, doi:10.1016/S1364-6826(00)00226-1

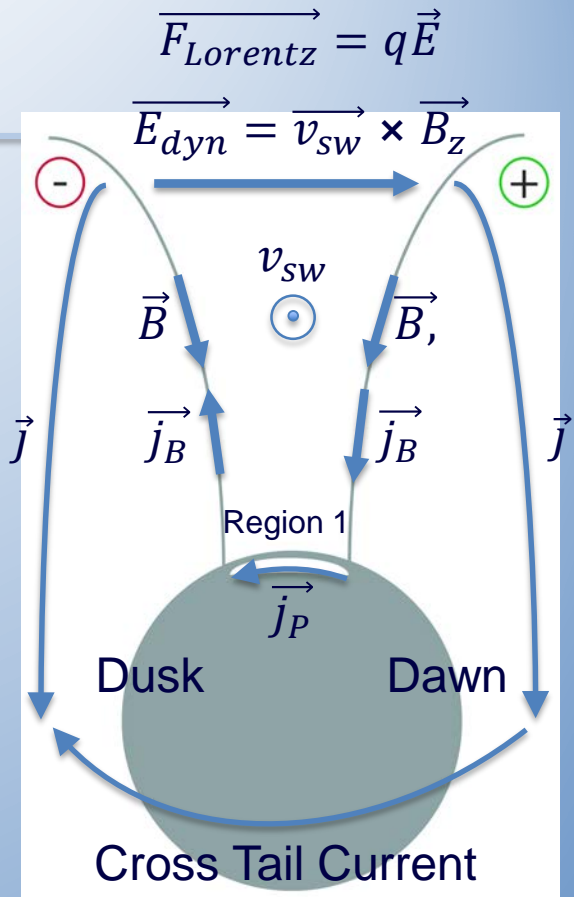
*Main regions and transport processes*

# Solar wind dynamo

- Highly conducting plasma in the solar wind flows across polar geomagnetic field lines

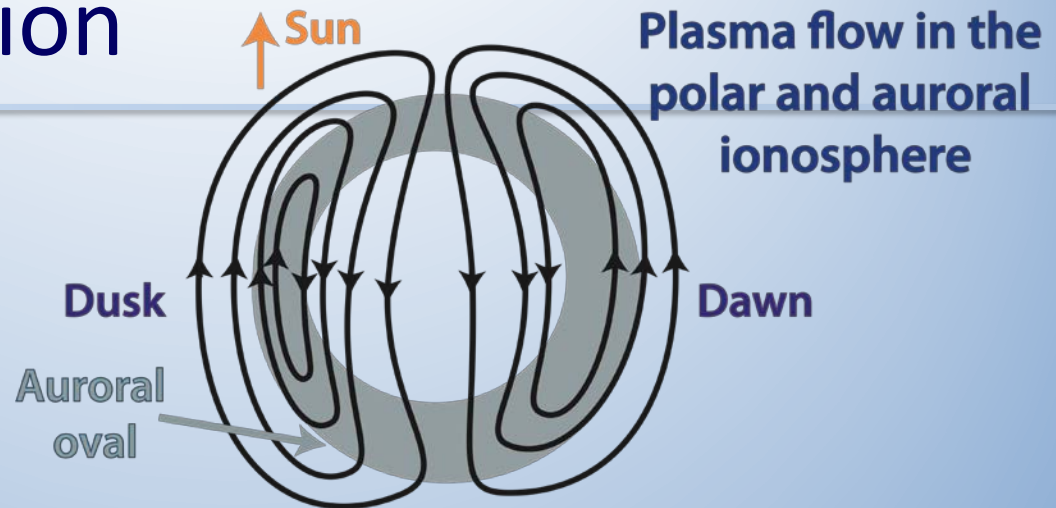


Flank of Tail  $\vec{j}$



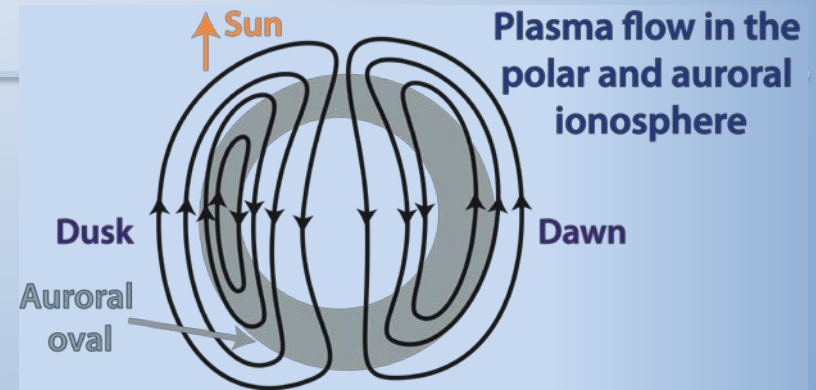
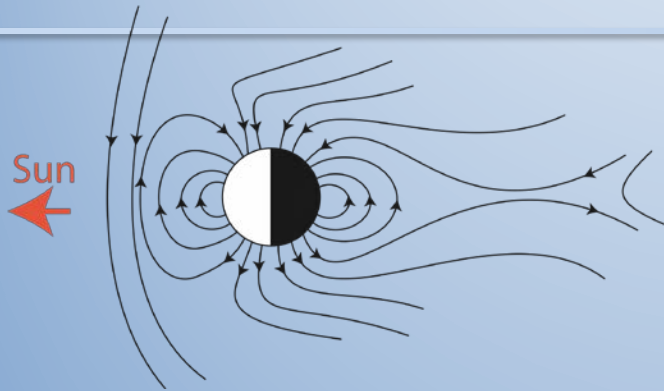
- Induces an electric dynamo field
- Plasma and B-field lines are transported: Frozen-in flux concept

# Global convection



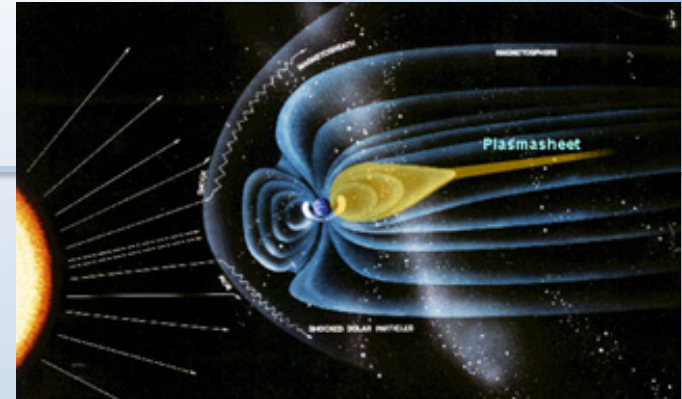
- In the Late 50s, ground-based measurements revealed the plasma flow pattern in the polar and auroral ionosphere
  - Anti-sunward flow over the polar cap and
  - Return flow equatorward of the auroral oval
- In 1959 Gold introduced the term convection
  - Resemblance to thermally driven flow cells

# Reconnection



- If the polar geomagnetic field lines are open
  - The electric field produces an anti-sunward  $E \times B$  drift of solar wind and magnetospheric plasma across the polar cap
  - Reconnection occurs down tail
  - Closed geomagnetic field lines flow back towards Earth at lower latitudes

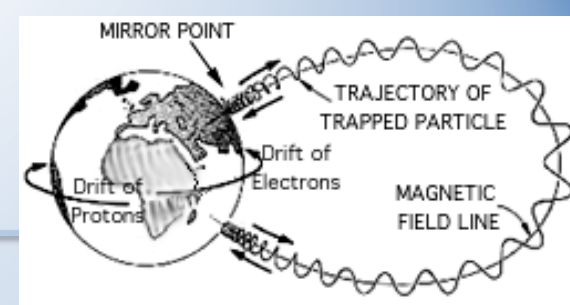
# Plasma sheet



- Plasma sheet: population of ionospheric and solar wind particles being accelerated Earthward
- Neutral current sheet: large-scale current flow from dawn to dusk across the plasma sheet
  - Separates the two regions of oppositely directed magnetic field in the magnetotail
  - Accelerates particles towards Earth
- Direct access to night side auroral oval
  - Can fall into the atmosphere producing aurora



# Adiabatic Invariants



Electrons and ions in a plasma follow paths driven by the changing ambient magnetic and electric fields. Three basic motions are described by the Adiabatic Invariants ( $\mu, J, \Phi$ ).

Gyration of a charged particle in a magnetic field results in it having a magnetic moment, the first Invariant:

$$\mu = \frac{mv_{\perp}^2}{2B}$$

A gyrating particle will bounce between regions of stronger magnetic field, the second Invariant:

$$J = \int_a^b v_{\parallel} ds$$

A bouncing particle on a planet's magnetic field drifts azimuthally, leading to the third Invariant:

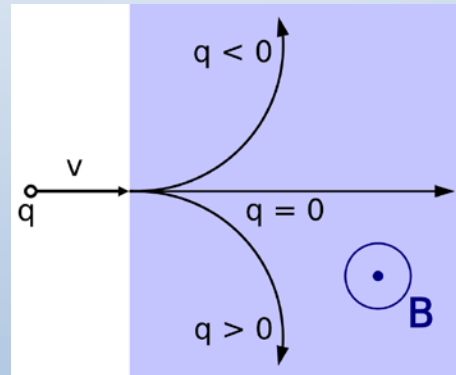
$\Phi$  = the total magnetic flux enclosed by a drift surface

# First Adiabatic Invariant

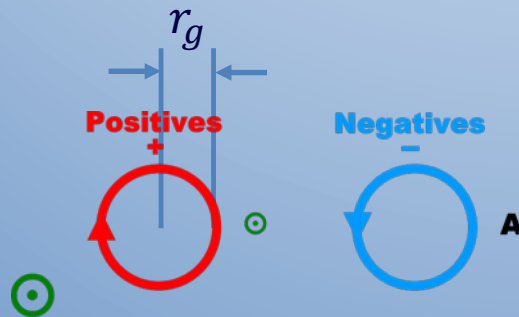
$$F = q\vec{E} = q\vec{v} \times \vec{B}$$

$$\mu = \frac{mv_{\perp}^2}{2B}$$

$$\mathcal{E} = \frac{1}{2}mv_{\parallel}^2 + \frac{1}{2}mv_{\perp}^2$$



$$r_g = \frac{mv_{\perp}}{2B}$$



For  $H^+$ ,  $T=1\text{eV}$ ,  $L=4$

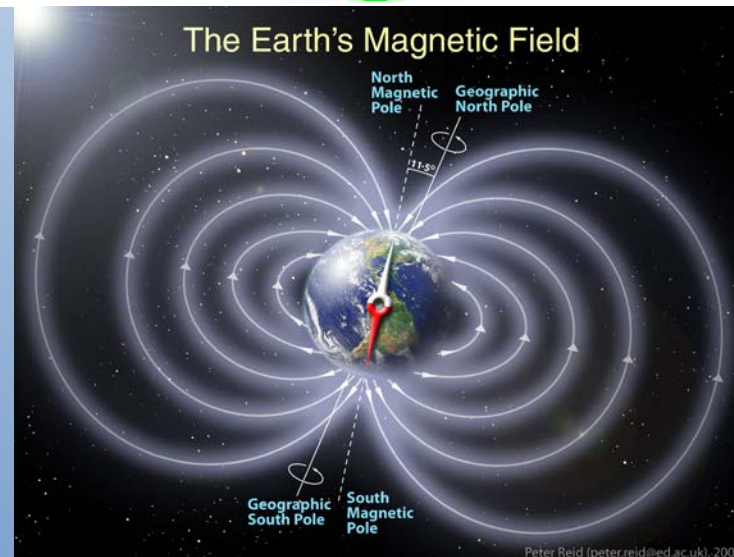
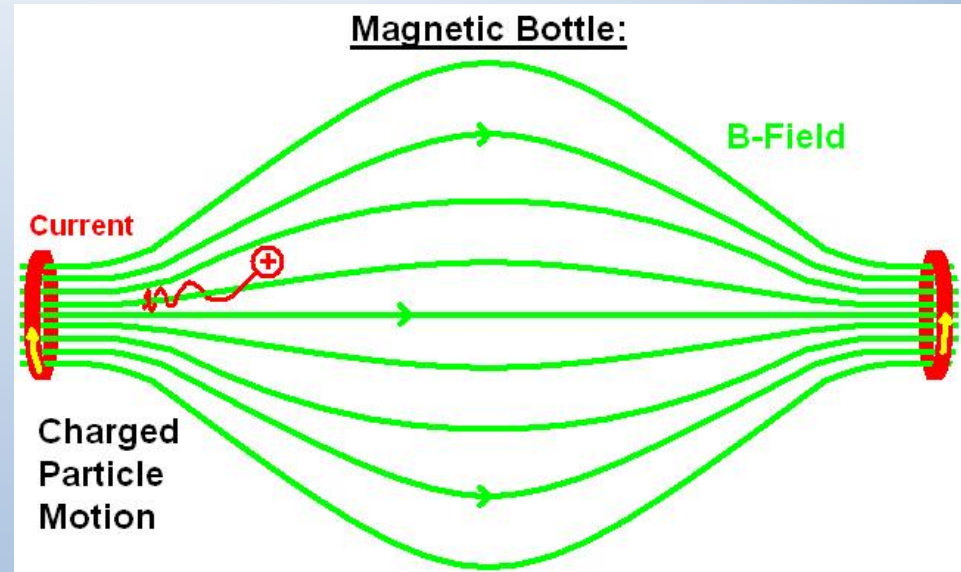
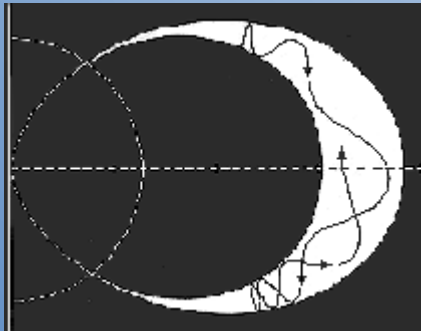
$$f_g = 114 \text{ Hz}$$

$$r_g = 13.6 \text{ m}$$

# Second Adiabatic Invariant

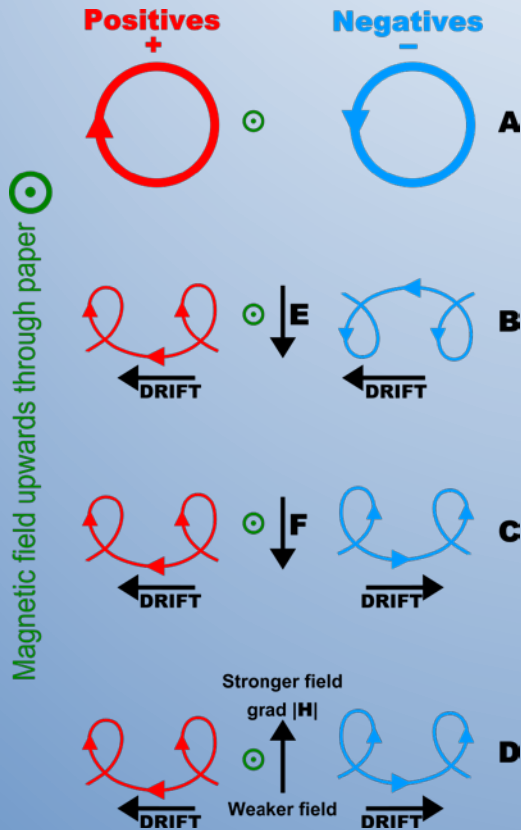
$$J = m \oint v_{\parallel} ds$$

Bounce Period ~1 s



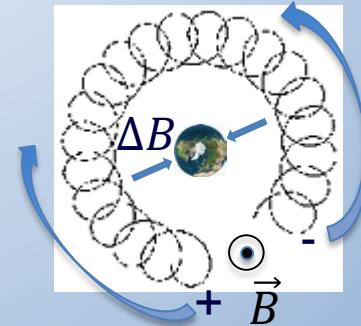
*Main regions and transport processes*

# Third Adiabatic Invariant $\Phi = \pi R^2 B$ Flux conservation inside the drift surface



Gradient-B Drift

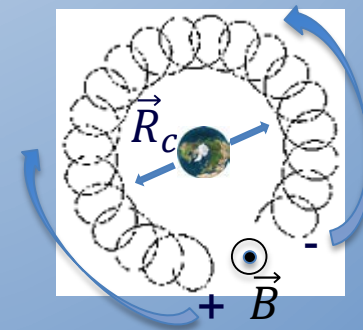
$$\vec{v}_{\nabla B} = \frac{\epsilon_{\perp}}{qB} \frac{\vec{B} \times \Delta B}{B^2}$$



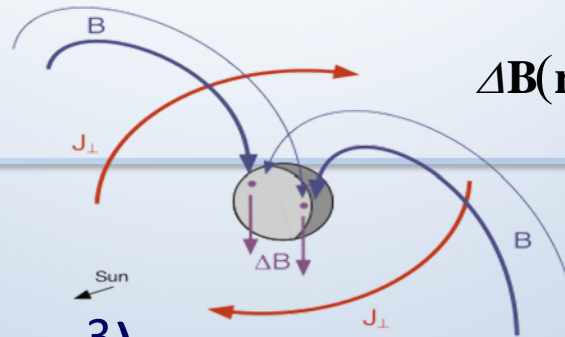
10s seconds

Curvature-B Drift

$$\vec{v}_R = \frac{\epsilon_{\parallel}}{qB} \frac{\vec{R}_c \times \vec{B}}{R_c^2 B^2}$$

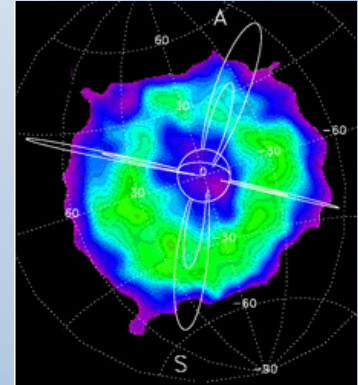


# Ring Current



$$\Delta \mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi V} \int \frac{\mathbf{J}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} d\mathbf{r}'$$

- Hot (1-400 keV)  
tenuous ( $1-10 \text{ s cm}^{-3}$ )
- diamagnetic current produced  
by motion of plasma trapped  
in the inhomogeneous geomagnetic field
  - Torus-shaped volume extending from  $\sim 3$  to  $8 R_E$
  - Main Source: plasma sheet particles
  - Loss Mechanisms: charge exchange, coulomb collisions, atmospheric loss, pitch angle (PA) diffusion, and escape from magnetopause

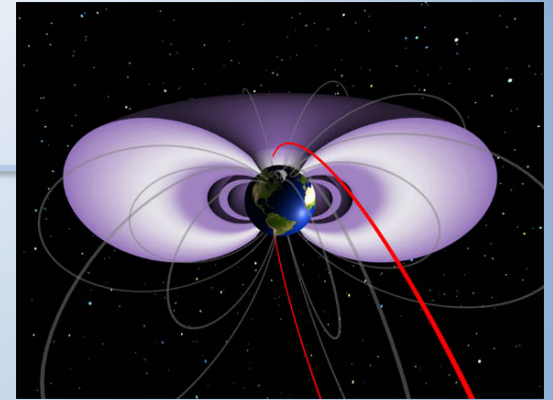


Chorus

Main regions and transport processes

# Radiation Belt

- Very Hot (100s keV - MeV)
- Extremely tenuous:  $\ll 1 \text{ cm}^{-3}$ 
  - Outer belt: very dynamic region
    - ✦ Mostly electrons located at 3-6  $R_E$
  - Inner belt: fairly stable population
    - ✦ Protons, electrons and ions at 1.5-2  $R_E$
- Source: injection and energization events following geomagnetic storms
- Loss Mechanisms: Coulomb collisions, magnetopause shadowing, and PA diffusion

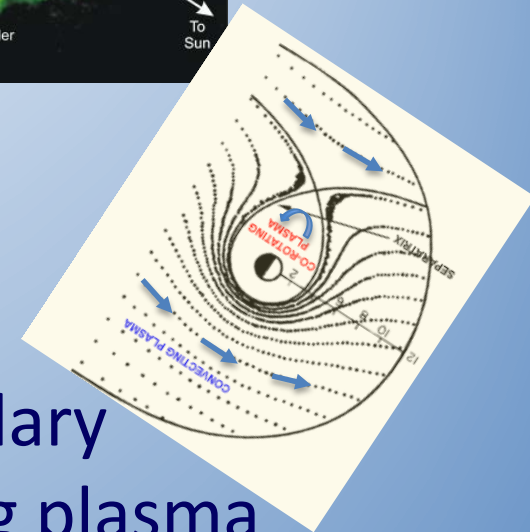
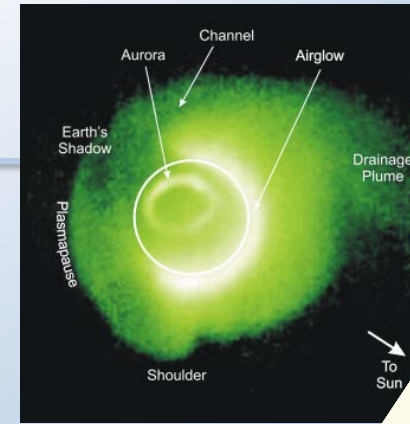


Hiss

Main regions and transport processes

# Plasmasphere

- Cool ( $<10$  eV)
- High density (100s-1000s  $\text{cm}^{-3}$ )
- Co-rotating plasma
  - Torus-shaped, extends to 4-8  $R_E$
  - Plasmapause: essentially the boundary between co-rotating and convecting plasma
- Main Source: the ionosphere
- Loss Mechanism: plasmaspheric erosion and drainage plume



Main regions and transport processes

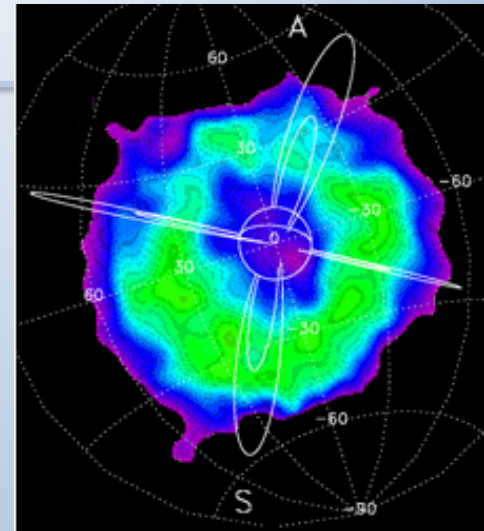
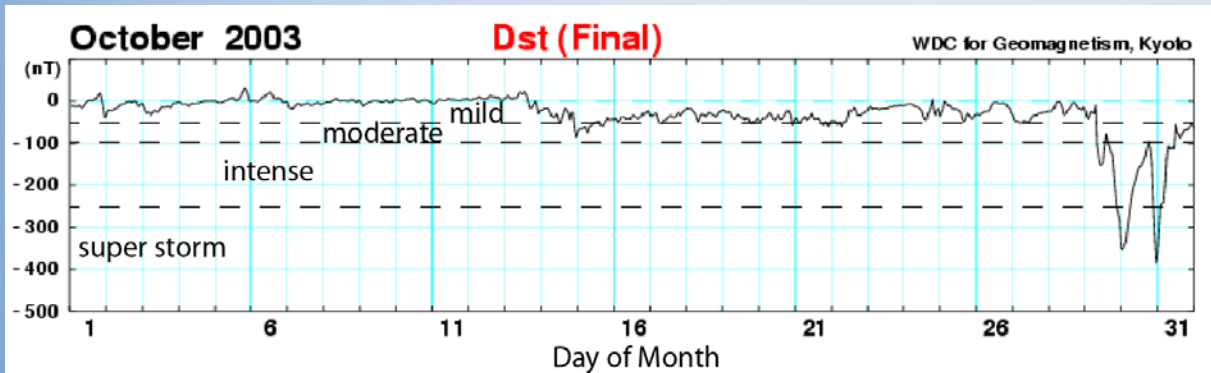
# Geomagnetic storms

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- Large ( $\geq 100$ s nT – reduced B-field on Earth's surface due to ring current)
- Prolonged (days)
- Magnetospheric disturbances
  - Caused by variations in the solar wind
  - Related to extended periods of large southward interplanetary magnetic field (-IMF Bz)
    - ✦ Increasing the rate of magnetic reconnection
    - ✦ Enhancing global convection

# Geomagnetic storms

## Halloween Storm of 2013



- Enhanced convection

- Increased rate of injection into the ring current

- ✦ The ring current then expands earthward

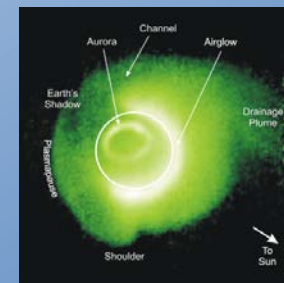
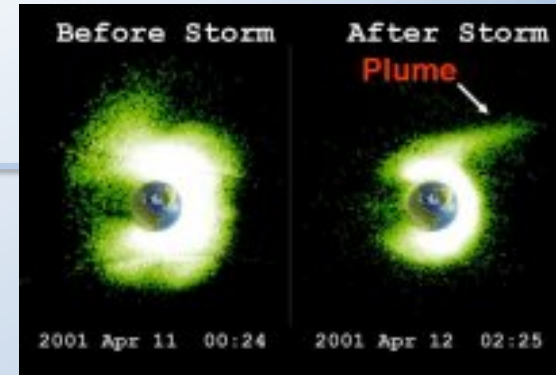
- ✦ Induced current can reduce the horizontal component of the geomagnetic field (100s nT)

- ★ Used to calculate Dst

Geomagnetic Activity

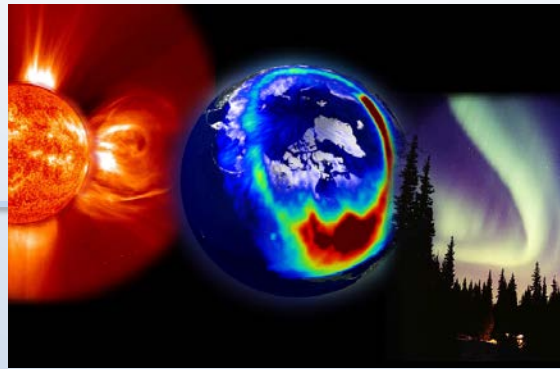
# Plasmaspheric Plumes

- Enhanced convection also causes the co-rotating plasmaspheric material to surge sunward
  - Decreasing the night-side plasmapause radius
  - Extending the dayside plasmapause radius
- Creates a plume extending from ~12 to 18 MLT
- For continued enhanced convection less material remains to feed the plume and it narrows in MLT
  - Dusk edge remains almost stationary
  - Western edge moves eastward



Geomagnetic Activity

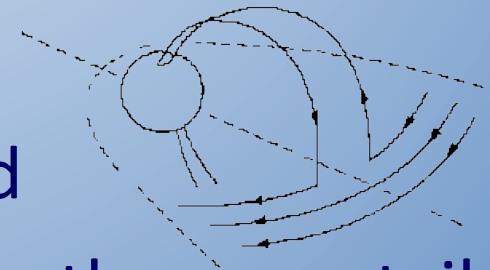
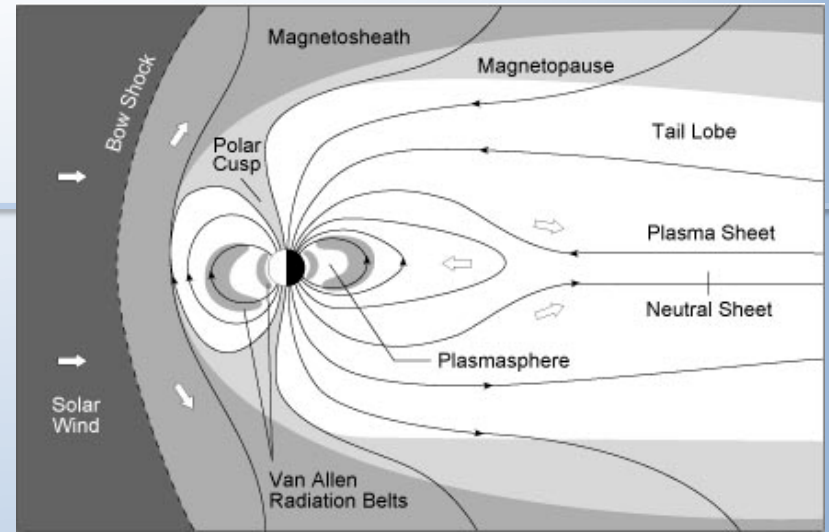
# Substorms



- A relatively short (hours) period of increased energy input and dissipation into the inner magnetosphere
  - Events may be isolated or occur during a storm
  - Associated with a flip from northward to southward IMF  $B_z$
- Increased rate of reconnection
- Increased flow in magnetospheric boundary layer
- Release of energy accumulated in the near-Earth tail

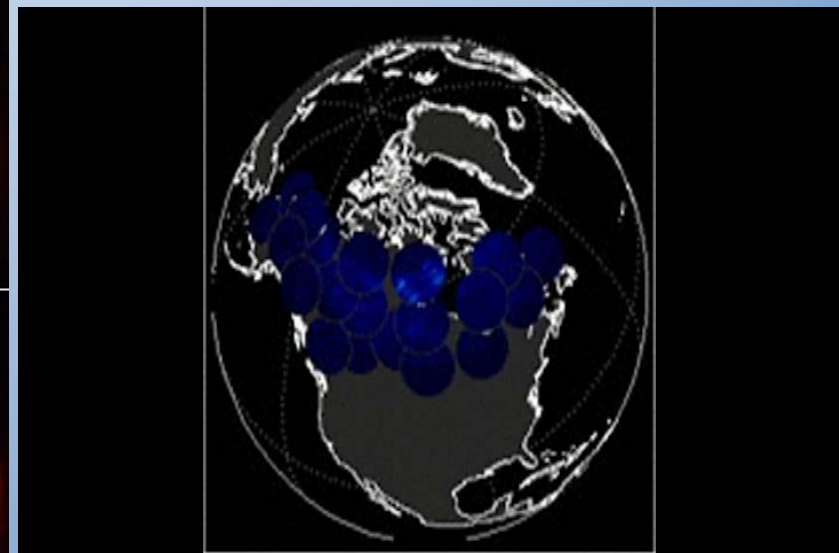
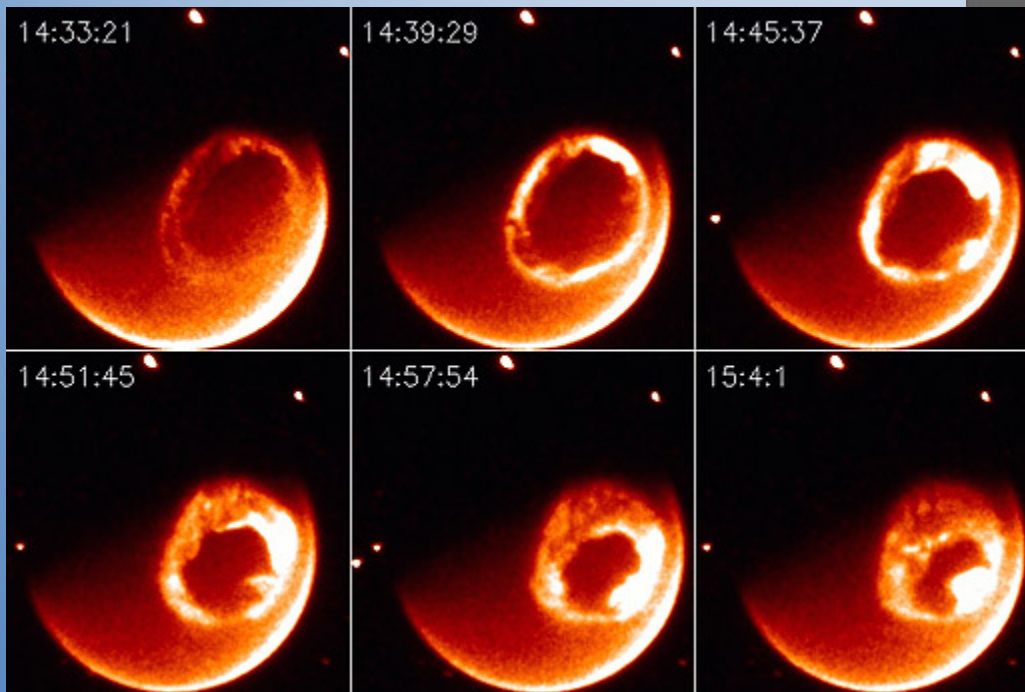
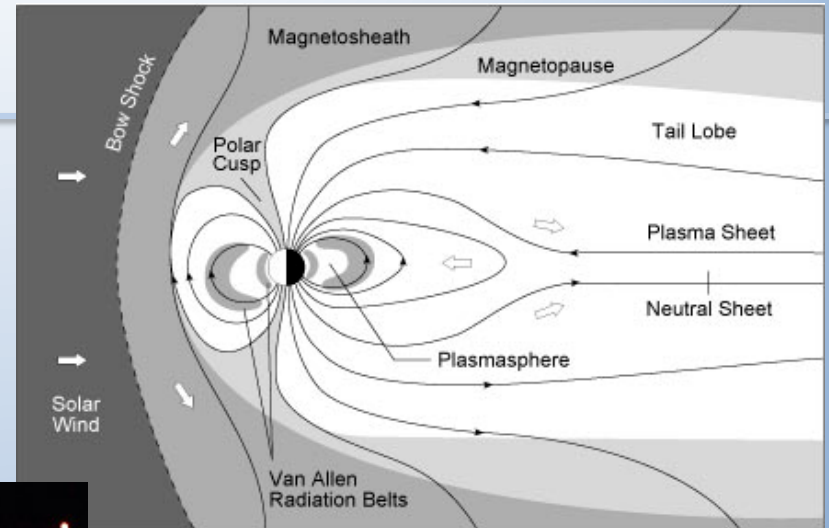
# Substorms

- Additional magnetic flux in the tail lobes causes the cross-tail current sheet thickness to decrease
  - When the current sheet thickness reaches its threshold reconnection occurs
  - The cross-tail current is disrupted
- The substorm current wedge closes the cross-tail current through the ionosphere
- Particle precipitation increases Auroral activity



# Substorms

Reconnection in the magnetotail initiates a depolarization event. Inward transport causes plasma to be energized and lost into the atmosphere. Drift fills the ring current. Wave-particle interactions scatter plasma into the atmosphere. The auroral fills the auroral oval.



ESA/NASA Cluster Mission

NASA IMAGE Mission

Geomagnetic Activity

# Models – Empirical: IRI

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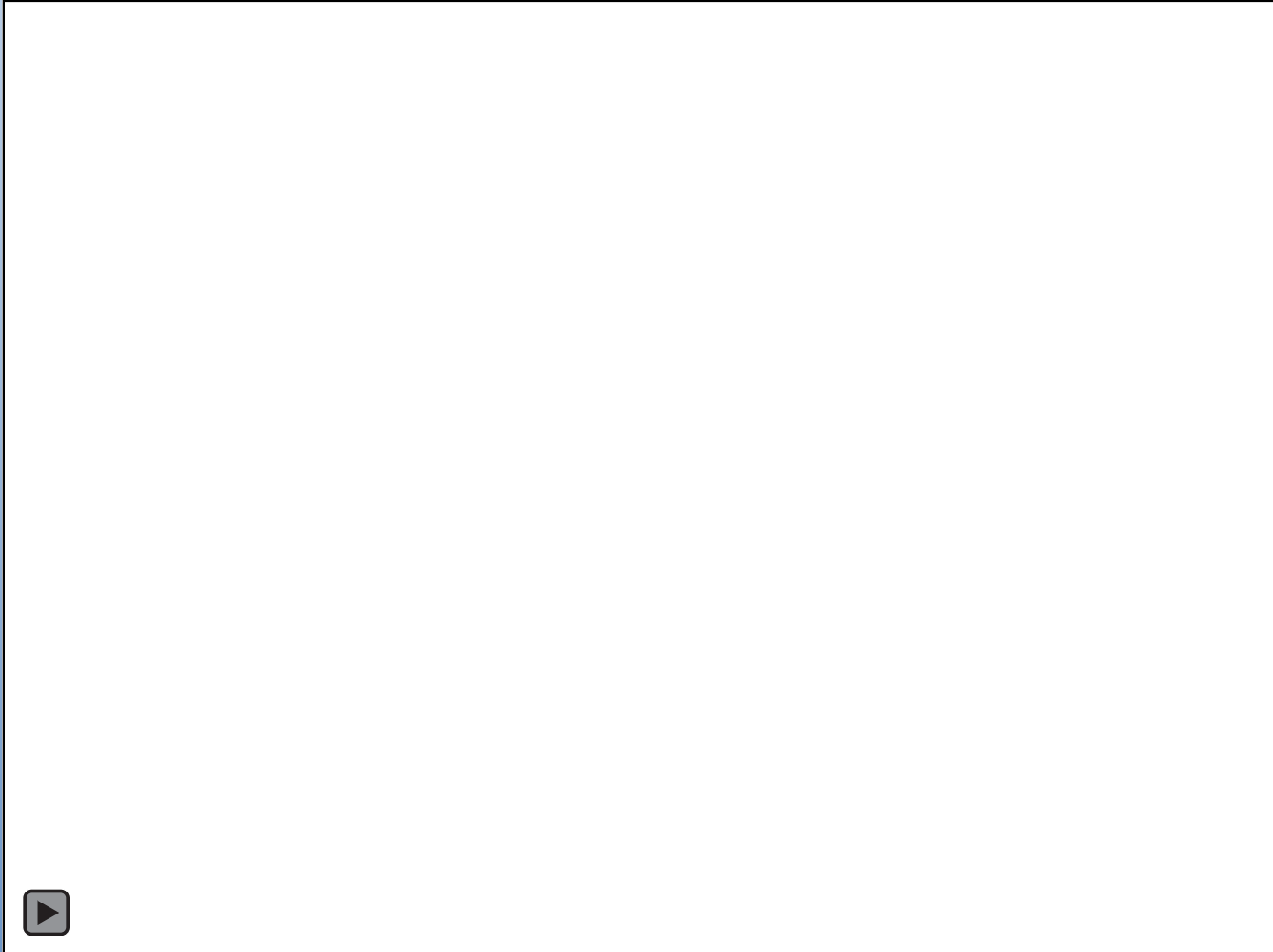
# Models – Empirical: GCPM

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# Models – LFM Model (Multi-Fluid Lyon-Fedder-Mobarry MHD)

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Lyon, Fedder, Mobarry, DOI: 10.1016/j.jastp.2004.03.020

Through the Coordinated Community Modeling Center, NASA/GSFC

# Coupling Models

