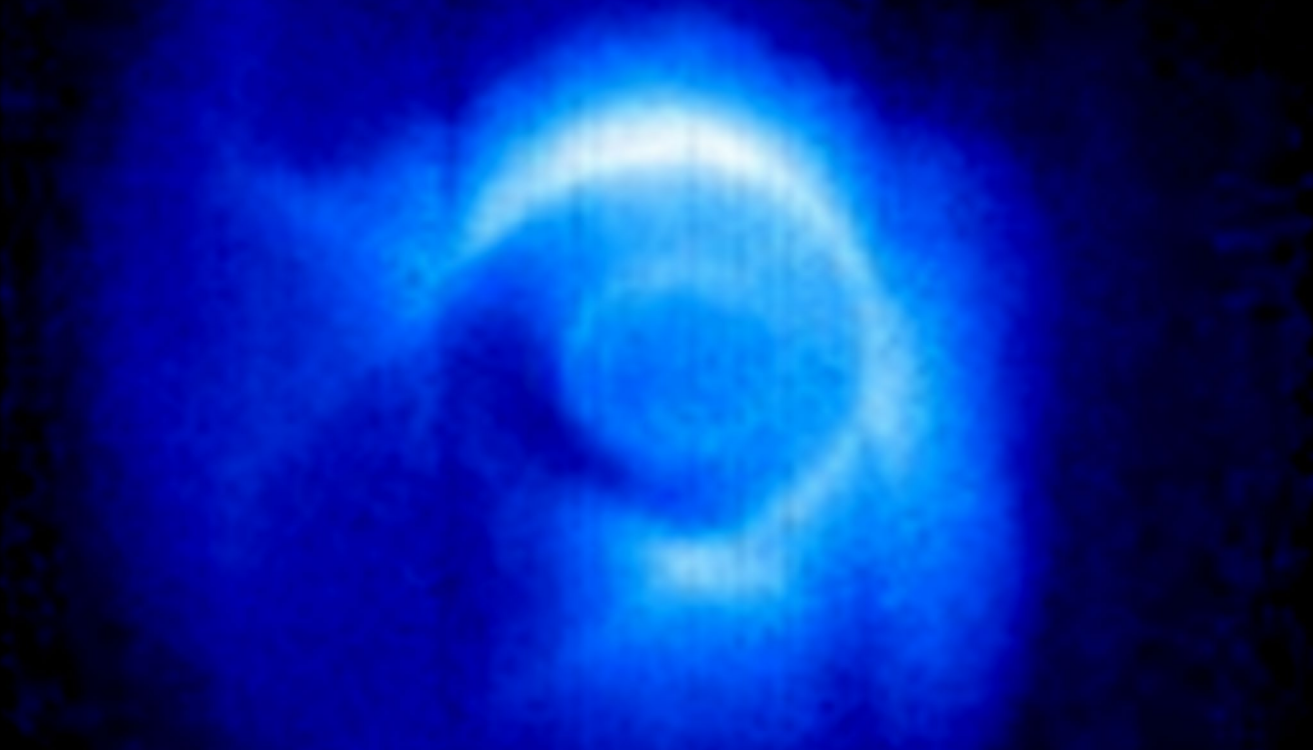


Inner Magnetospheric Physics



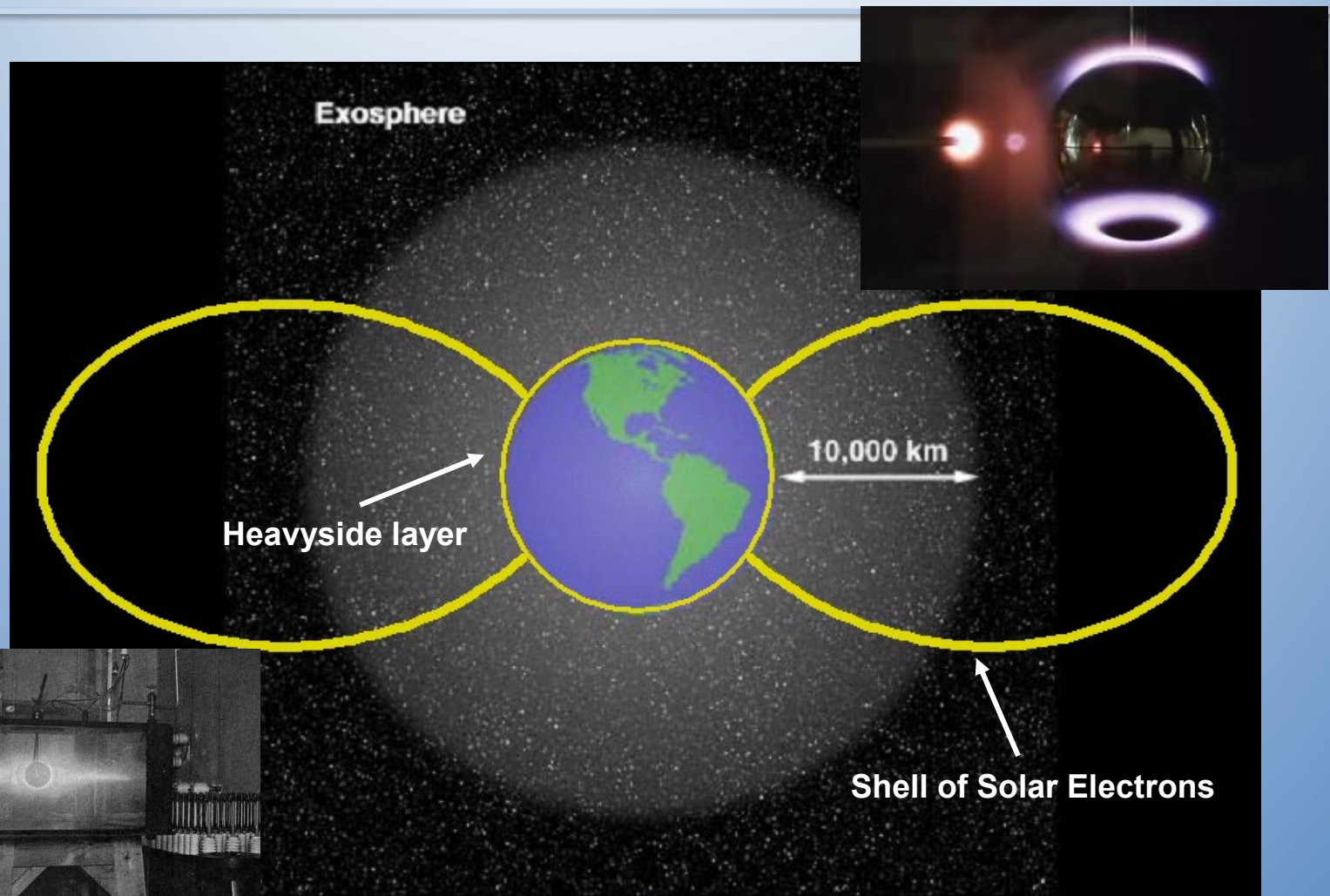
Dennis Gallagher, PhD
NASA Marshall Space Flight Center
dennis.gallagher@nasa.gov

Inner Magnetosphere Effects

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

All audio files come from the University of Iowa (<https://space-audio.org/>) under a Creative Commons License (<https://creativecommons.org/licenses/by/4.0/>) where the narration has been removed from the AKR audio file.

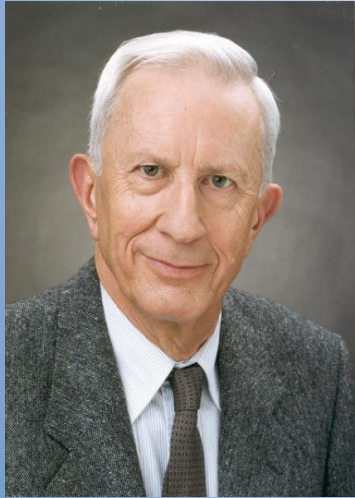
Historical Background: Space in 1950



Kristian Birkeland 1895

Historical Background

Whistlers revealed unexpected plasma



1952

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

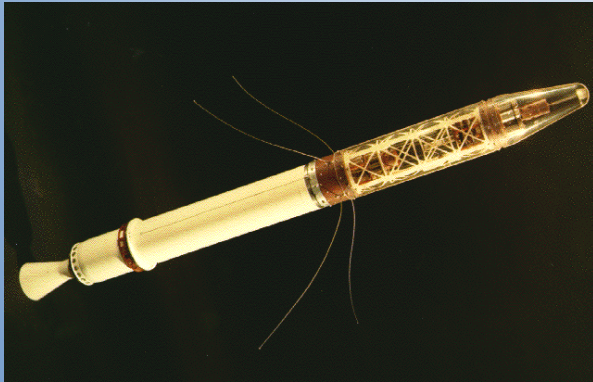


Whistlers

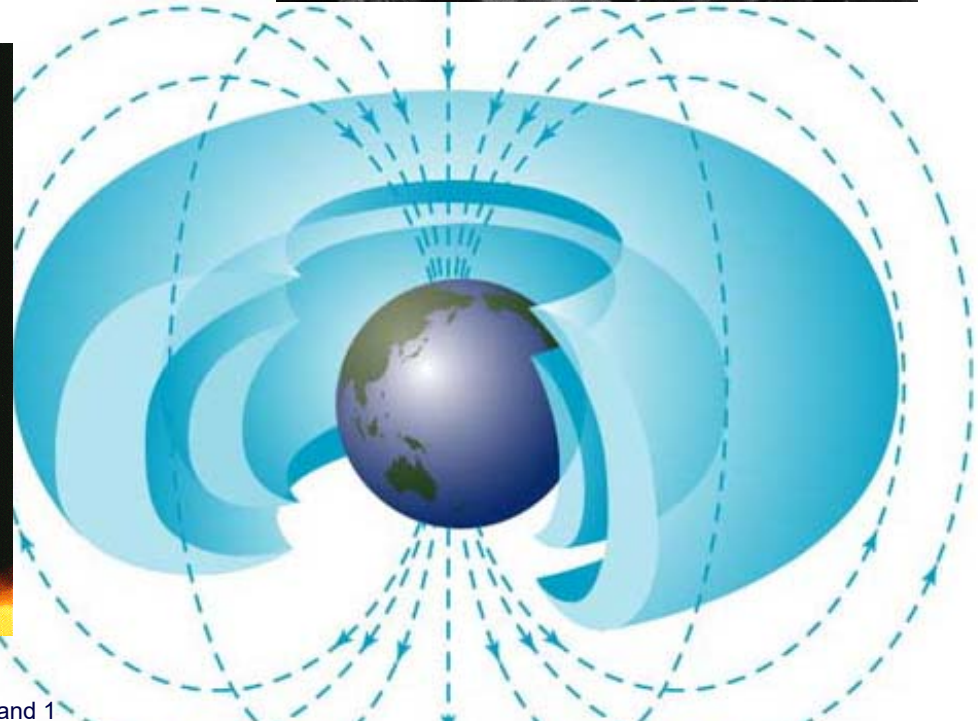
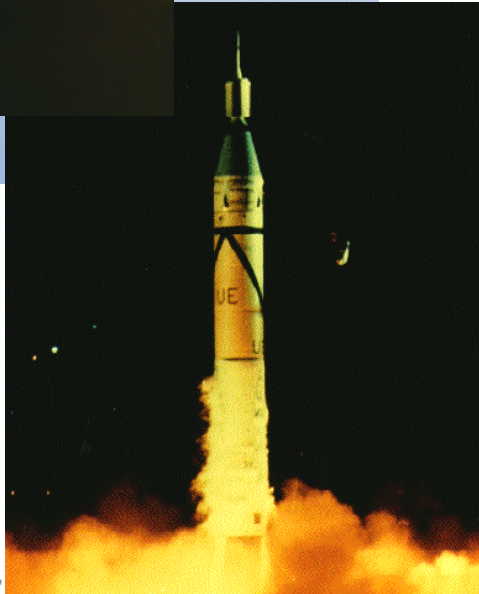
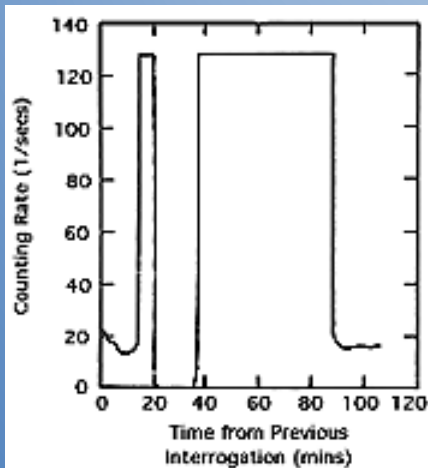
Historical Background

Historical Background

Explorer 1
January 31, 1958



Pick



Radiation Belts Discovered

Van Allen, James A., Observation of high intensity radiation by satellites 1958 alpha and 1 958 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

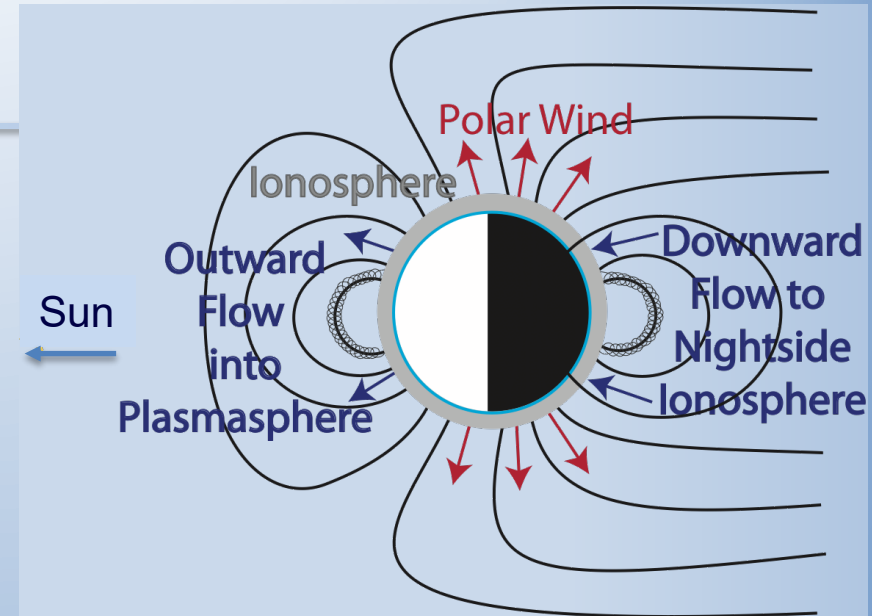
Ionosphere

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

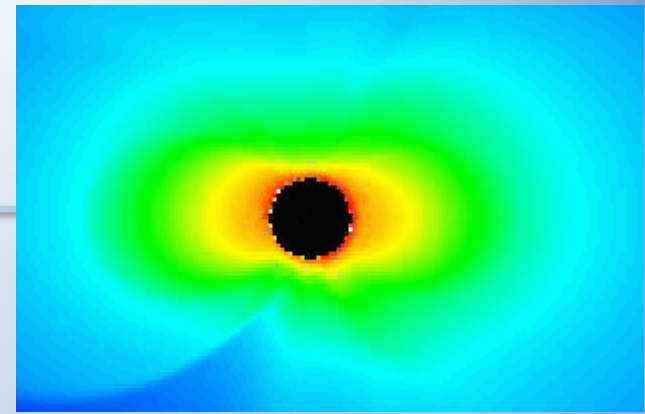
- Ionosphere: ionized portion of upper atmosphere
 - Extends from around 60 km to beyond 1000 km
 - Completely encircles the Earth
 - Main Source: photoionization of neutrals
 - ✦ Other production processes dominate in different ionospheric regions
 - Loss Mechanism: ionospheric outflow, recombination

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

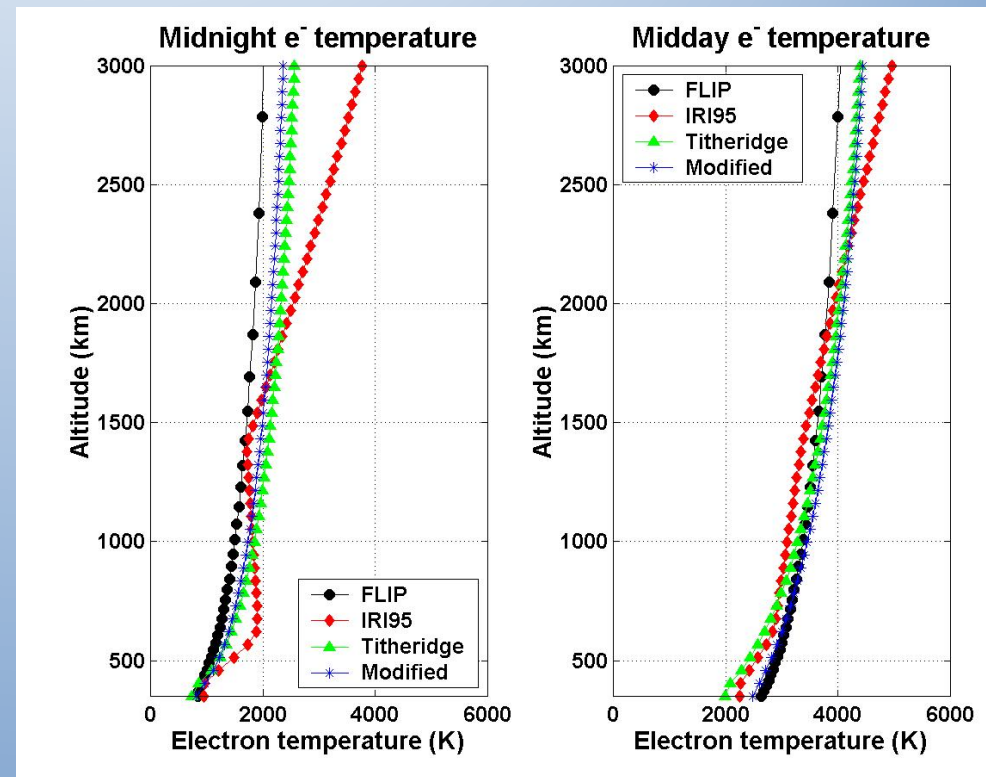
m_j = j 'th ion mass

g = gravitational constant

m_a = mean ion mass

T_e = electron temperature

$T_t = T_i + T_e$ total temperature



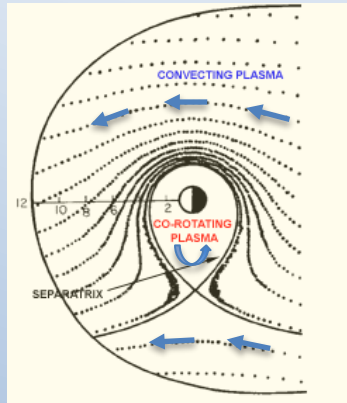
Titheridge, J.E., Planetary and Space Science, 20 (1972), pp. 353-369

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

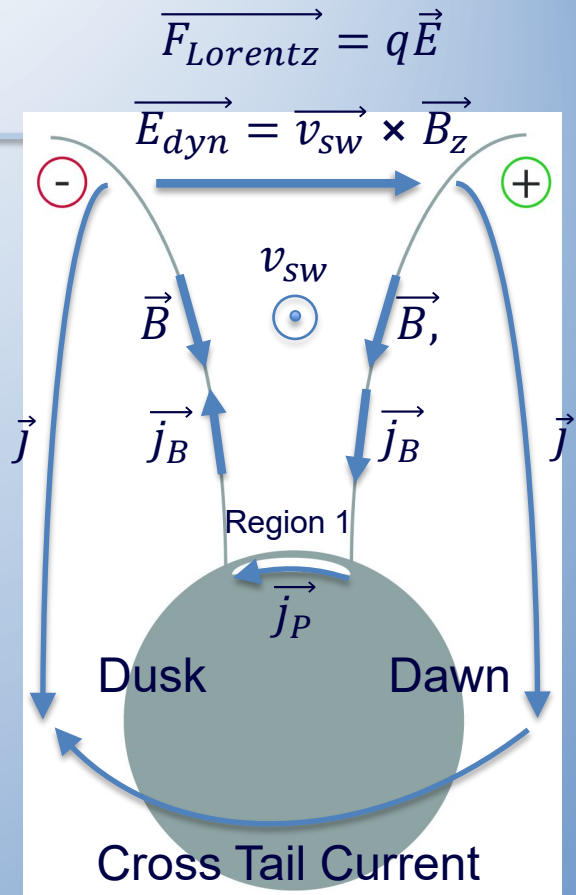
Main regions and transport processes

Solar wind dynamo

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

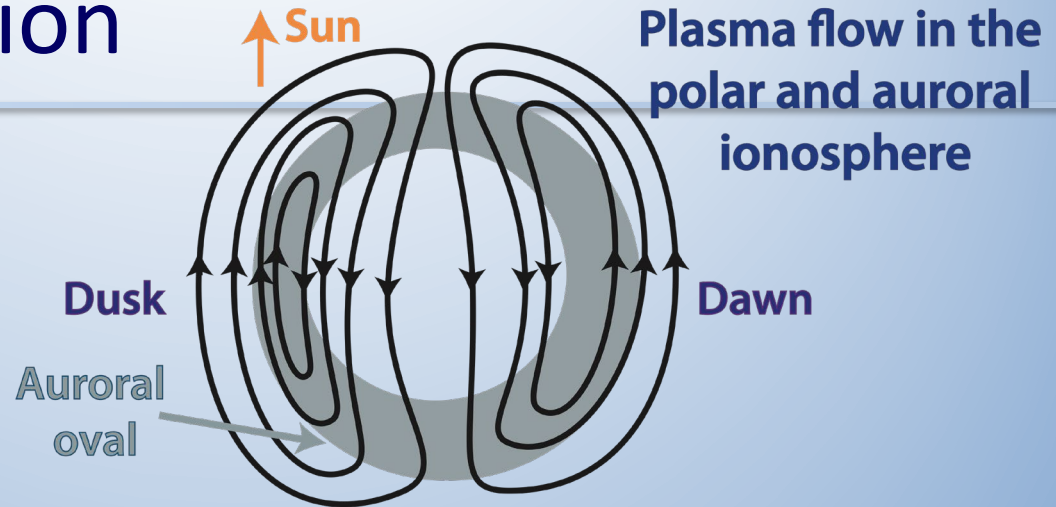


Flank
of Tail



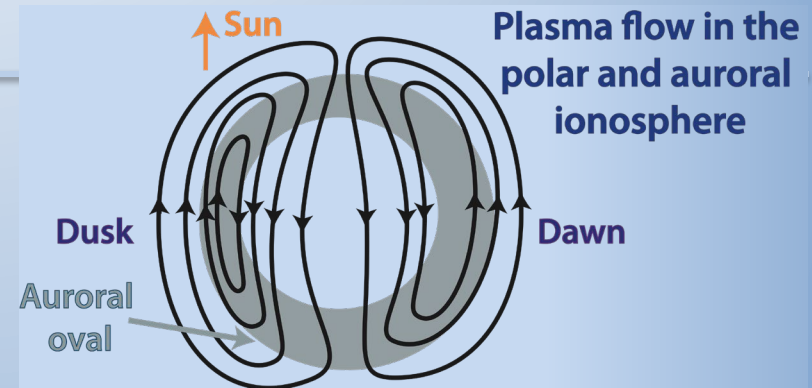
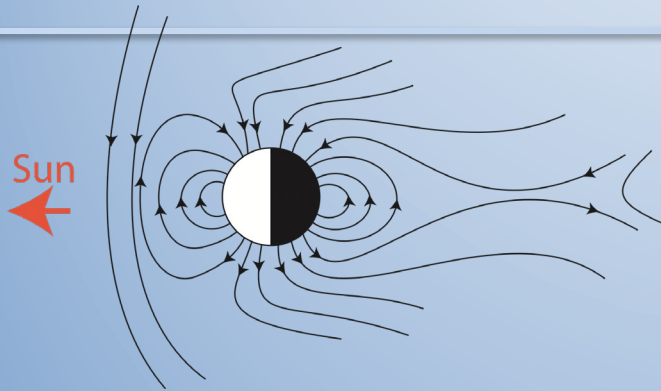
- Induces an electric dynamo field
- Plasma and B-field lines are transported:
Frozen-in flux concept

Global convection



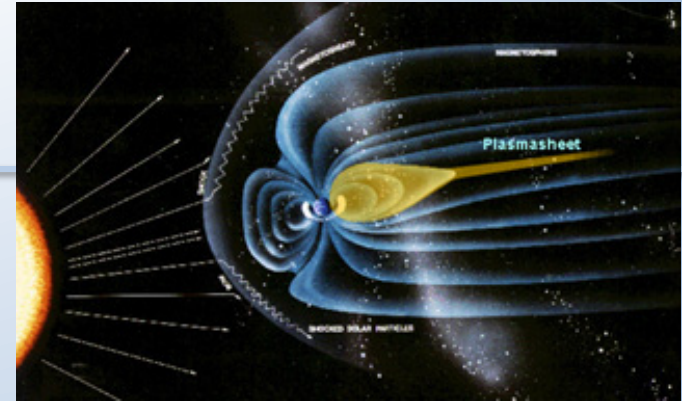
- In the Late 50s, ground-based measurements revealed the plasma flow pattern in the polar and auroral ionosphere
 - Anti-sunward flow over the polar cap and
 - Return flow equatorward of the auroral oval
- In 1959 Gold introduced the term convection
 - Resemblance to thermally driven flow cells

Reconnection



- If the polar geomagnetic field lines are open
 - The electric field produces an anti-sunward $\mathbf{E} \times \mathbf{B}$ 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 (μ, J, Φ).

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

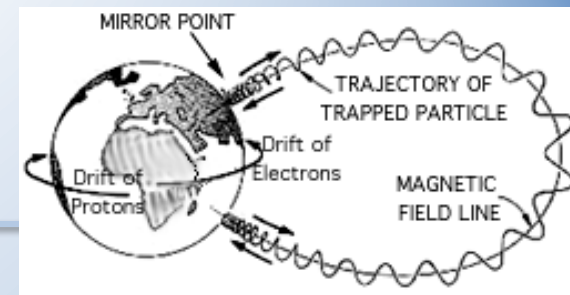
$$\mu = \frac{mv_{\perp}^2}{2B}$$

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:

Φ = the total magnetic flux enclosed by a drift surface

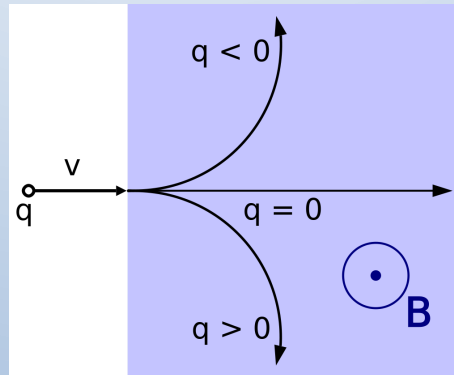


First Adiabatic Invariant

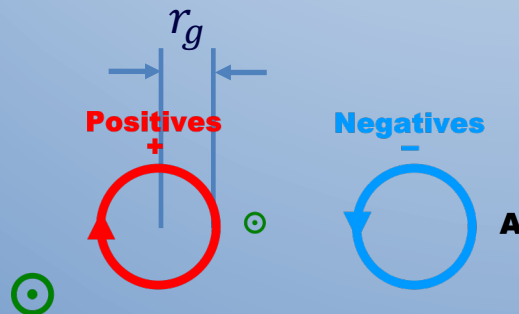
$$\vec{F} = q\vec{E} = q\vec{v} \times \vec{B}$$

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

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



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



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

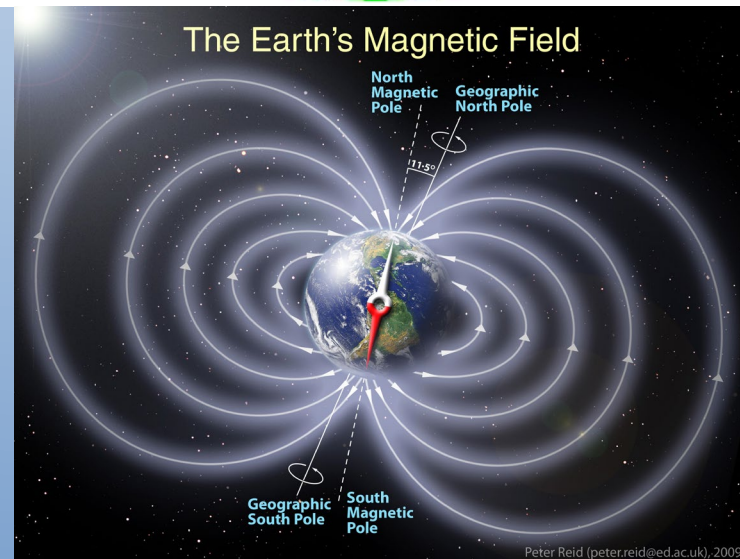
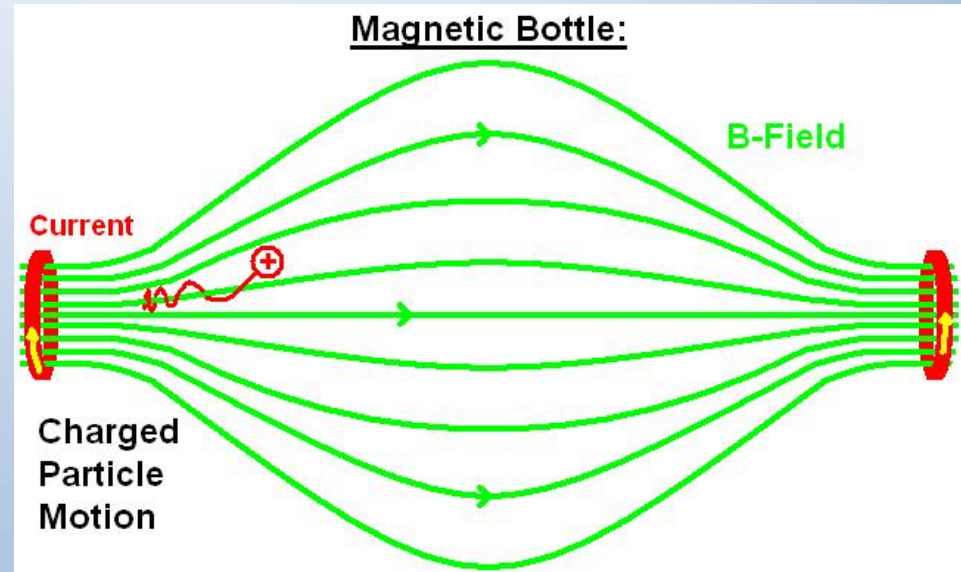
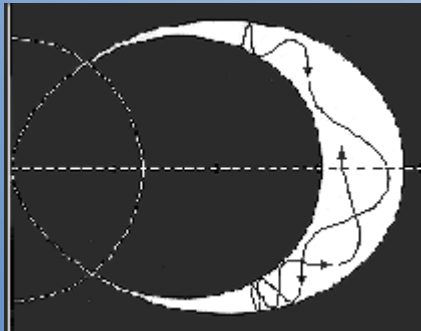
$$f_g = 114 \text{ Hz}$$

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

Second Adiabatic Invariant

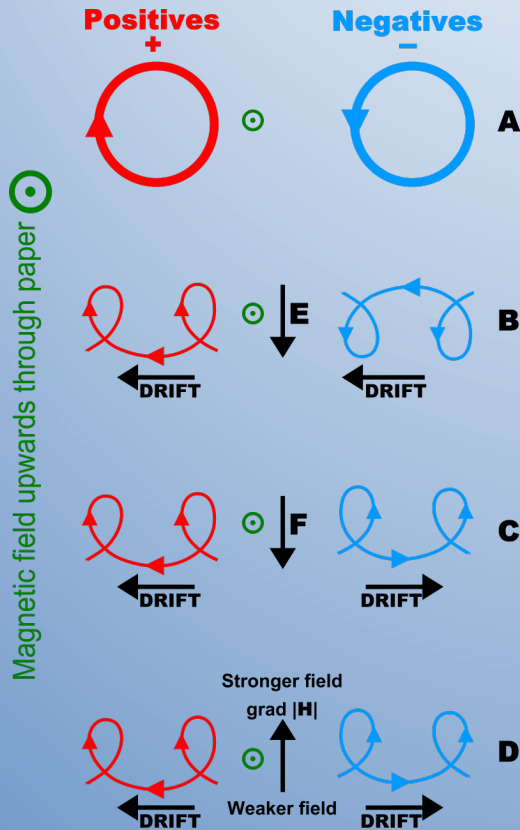
$$J = m \oint v_{\parallel} ds$$

Bounce Period ~ 1 s



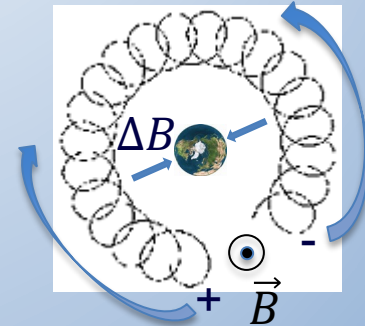
Main regions and transport processes

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



Gradient-B Drift

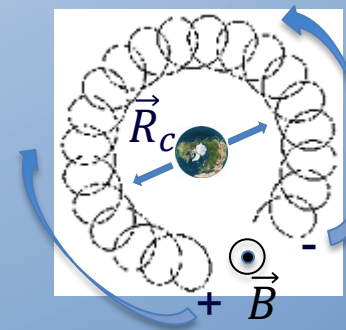
$$\vec{v}_{\nabla B} = \frac{\epsilon_{\perp}}{qB} \frac{\vec{B} \times \Delta B}{B^2}$$



10s seconds

Curvature-B Drift

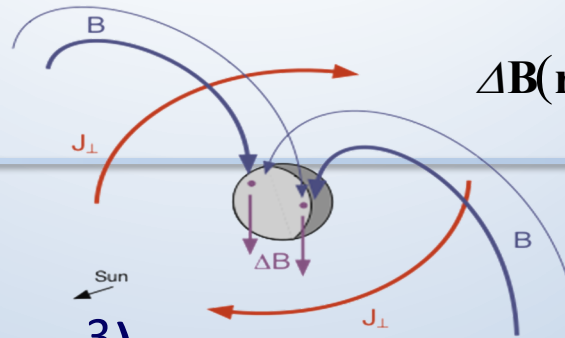
$$\vec{v}_R = \frac{\epsilon_{\parallel}}{qB} \frac{\vec{R}_c \times \vec{B}}{R_c^2 B^2}$$



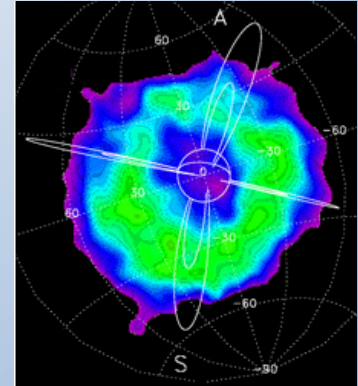
Main regions and transport processes

Ring Current

- 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 ~ 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



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

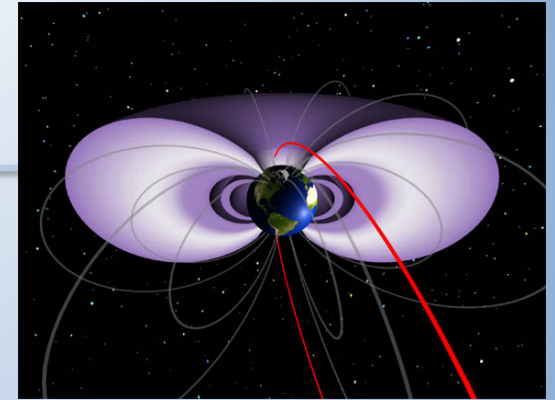


Chorus

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

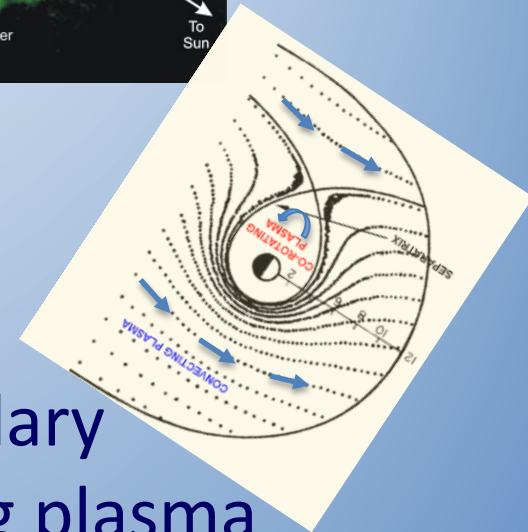
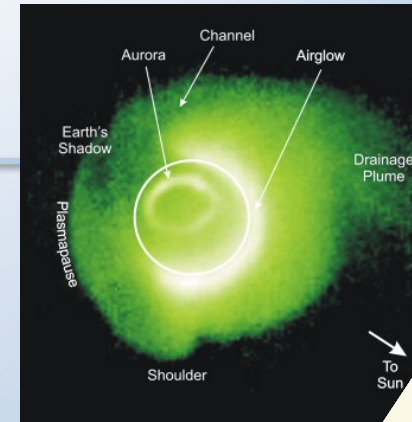


Hiss

Main regions and transport processes

Plasmasphere

- Cool (<10 eV)
- High density (100s-1000s 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



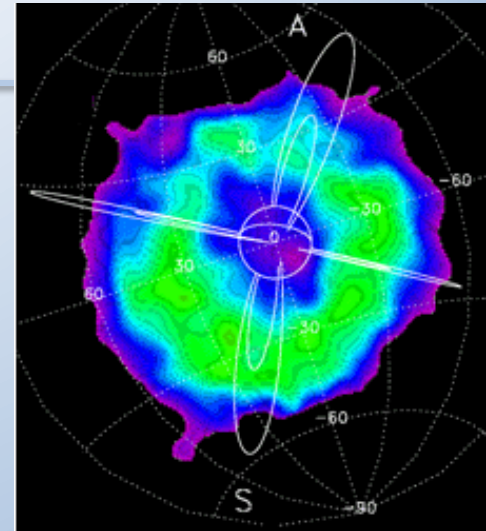
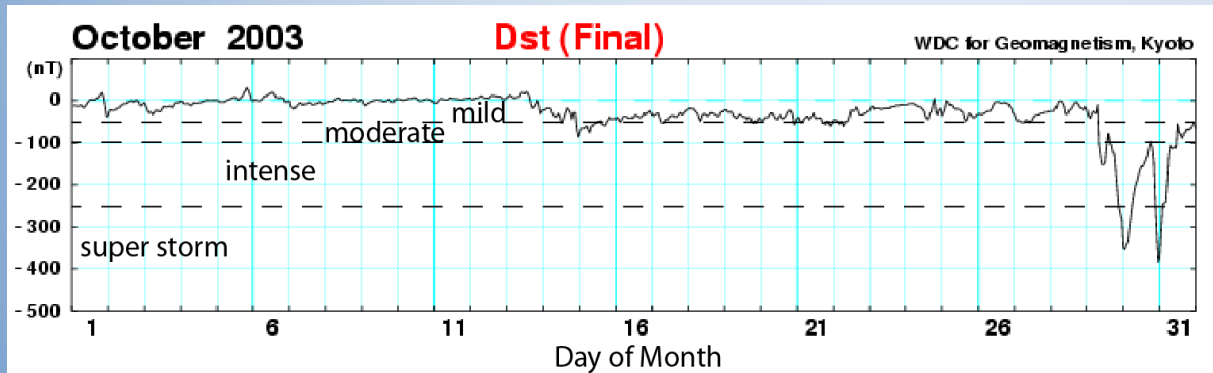
Main regions and transport processes

Geomagnetic storms

- Large (≥ 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 B_z)
 - ✦ Increasing the rate of magnetic reconnection
 - ✦ Enhancing global convection

Geomagnetic storms

Halloween Storm of 2013

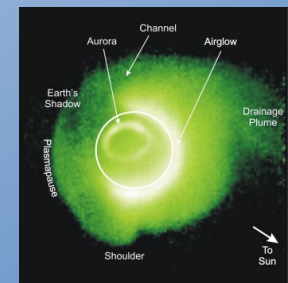
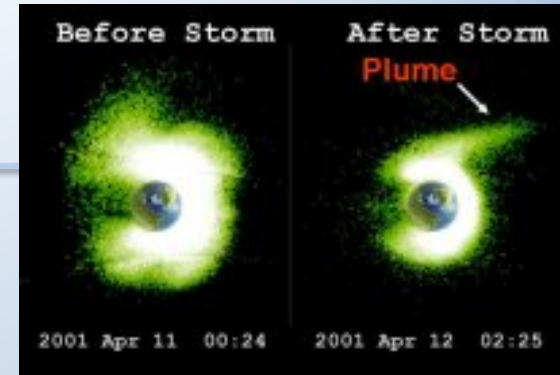


- Enhanced convection
 - Increased rate of injection into the ring current
 - ✦ The ring current then expands earthward
 - ✦ Induced current can reduce the horizontal component of the geomagnetic field (100s nT)
 - ★ Used to calculate Dst

Geomagnetic Activity

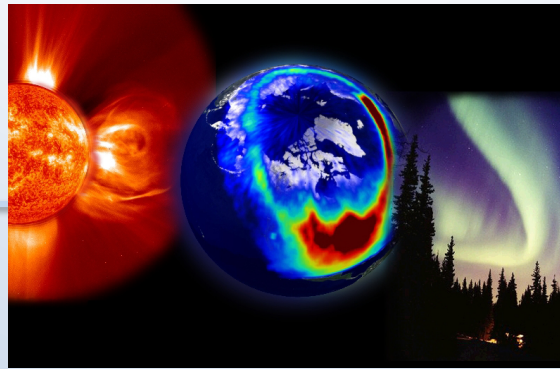
Plasmaspheric Plumes

- Enhanced convection also causes the co-rotating plasmaspheric material to surge sunward
 - Decreasing the night-side plasmopause radius
 - Extending the dayside plasmopause 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

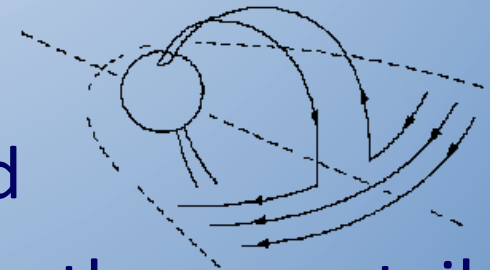
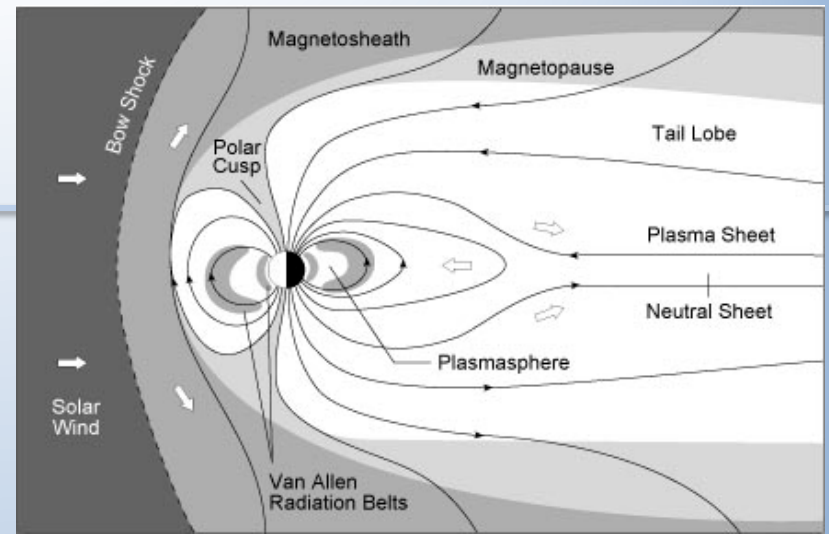
Substorms



- 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

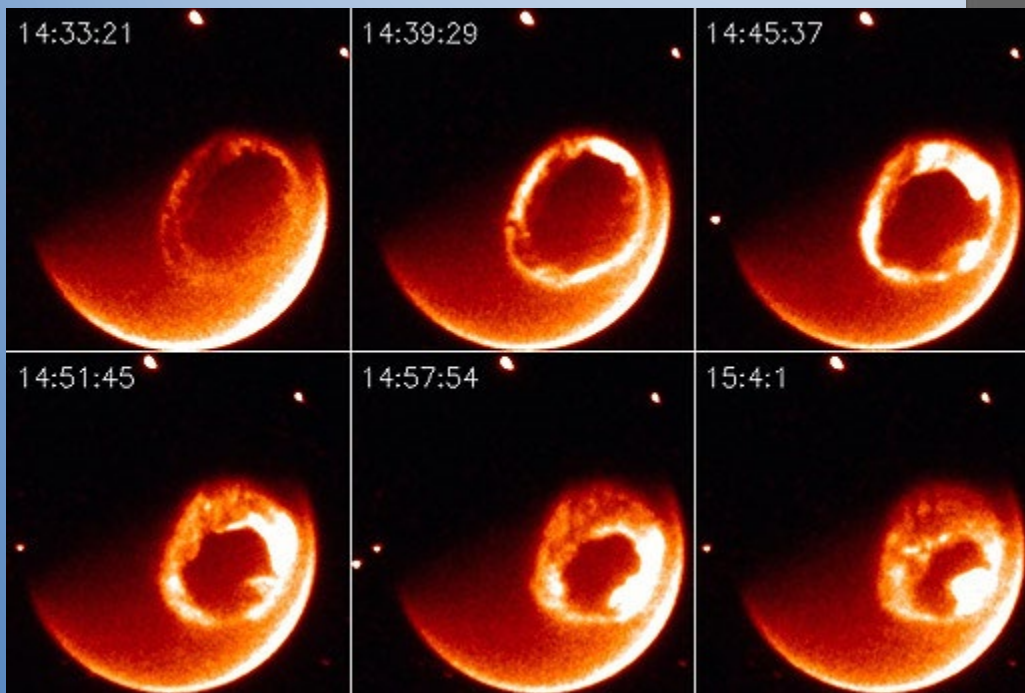
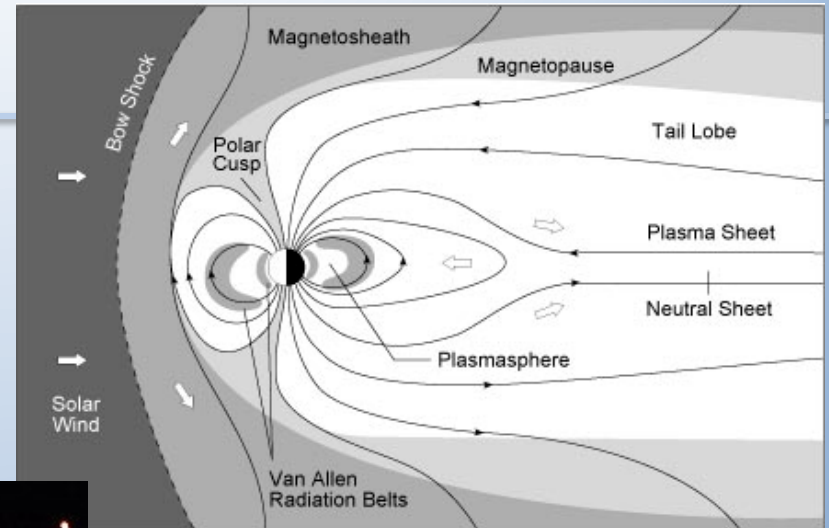
Substorms

- 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

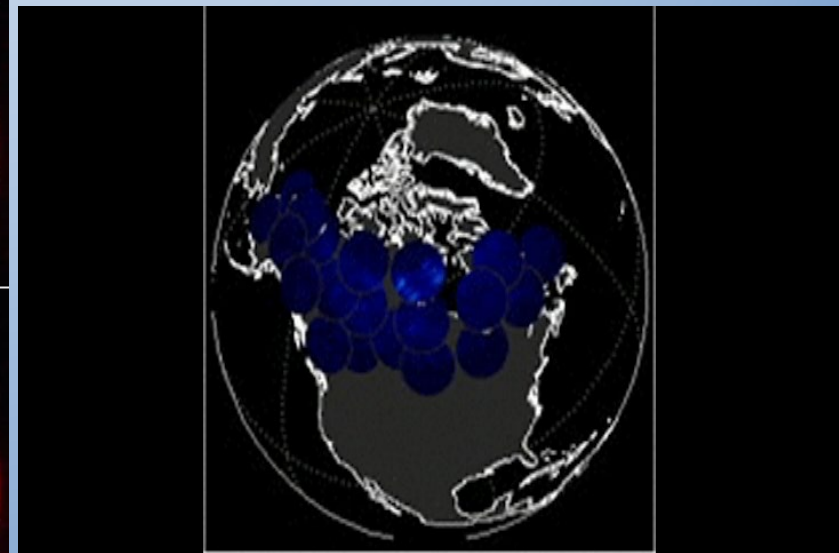


Substorms

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.



NASA IMAGE Mission



ESA/NASA Cluster Mission

Geomagnetic Activity

Models – Empirical: IRI



Models – Empirical: GCPM



Models –LFM Model

(Multi-Fluid Lyon-Fedder-Mobarry MHD)



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

Through the Coordinated Community Modeling Center, NASA/GSFC

Coupling Models

