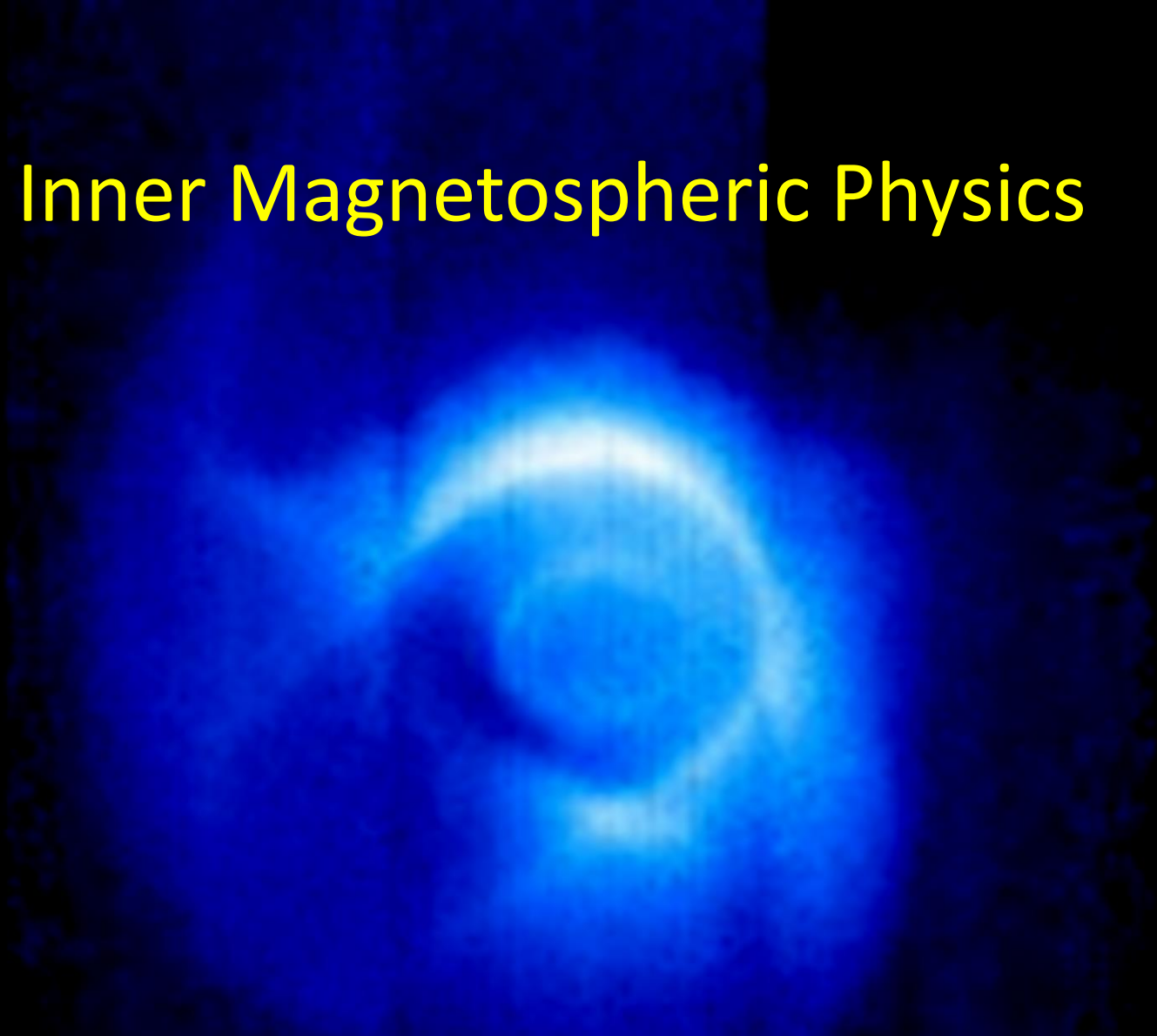
Inner Magnetospheric Physics



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Inner Magnetosphere Effects

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

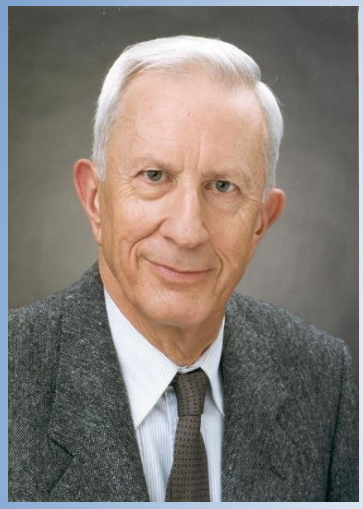
Outline

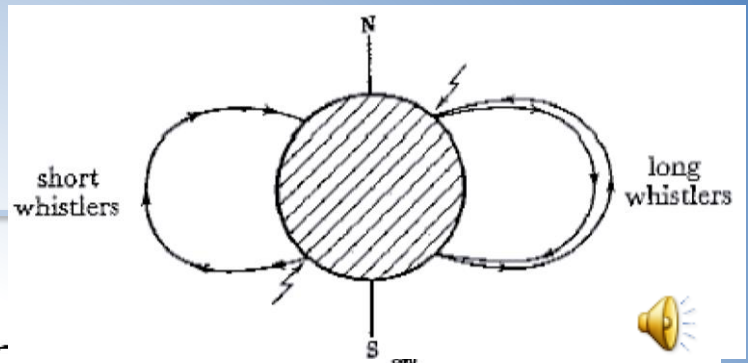
Historical Background: Space in 1950


Kristian Birkeland 1895

Historical Background

Whistlers revealed unexpected plasma





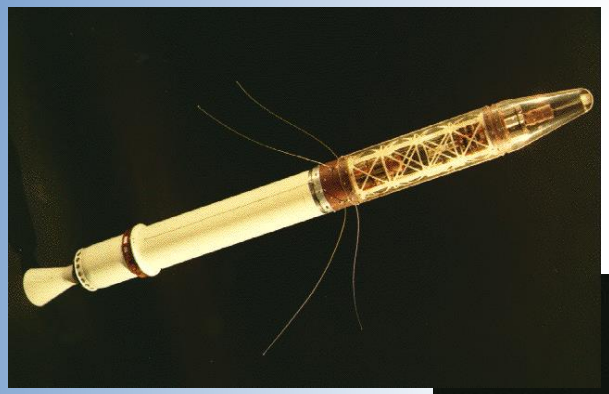
Whistlers

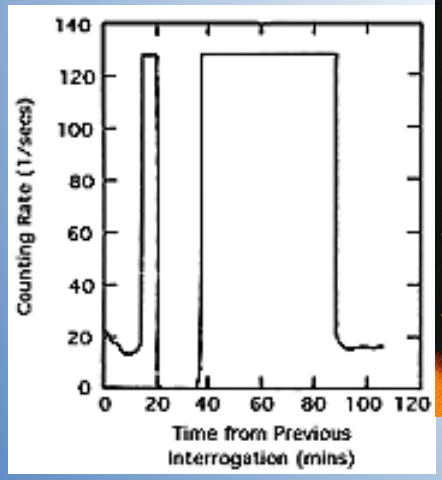
1952
L. R. Owen Storey
Cavendish Laboratory
University of Cambridge

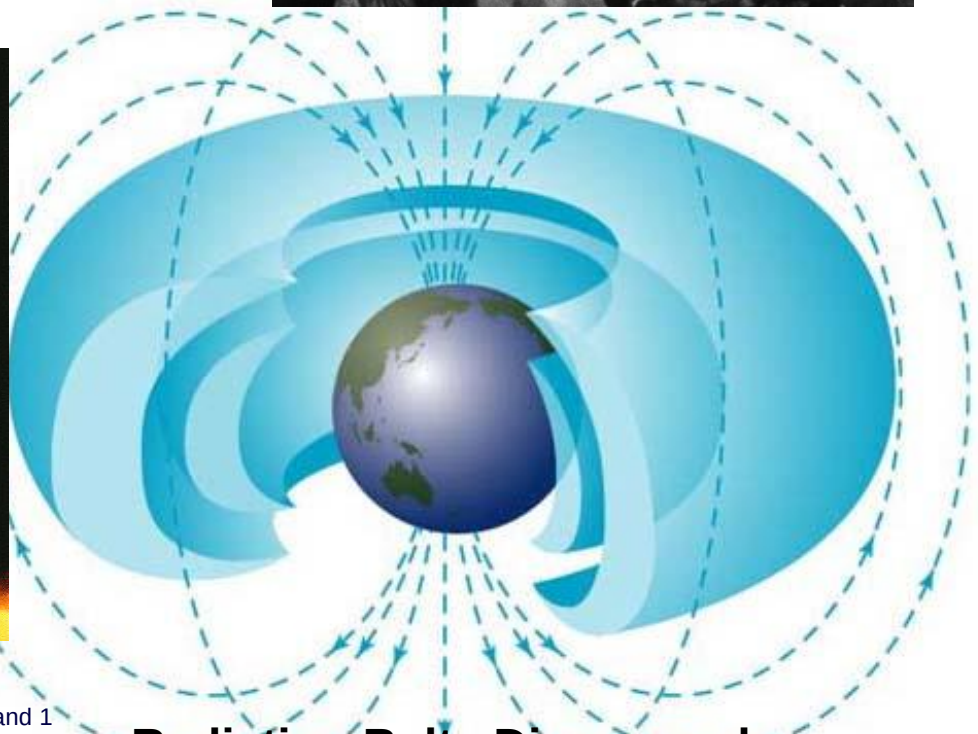
L. R. O. Storey, Phil. Trans. R. Soc. Lond. A 1953 246 113-141; DOI: 10.1098/rsta.1953.0011. Published 9 July 1953

Historical Background

Explorer 1
January 31, 1958







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

$X + \gamma \rightarrow X^+ + e^-$

$X^- + Y \rightarrow XY + e^-$

$XY + \gamma \rightarrow X + Y$

$X^+ + YZ \rightarrow YX^+ + Z$

$X^+ + e^- \rightarrow X$

$X^+ + e^- \rightarrow X + \gamma$

$XY + e^- \rightarrow Y + X$

$X + e^- \rightarrow X^-$

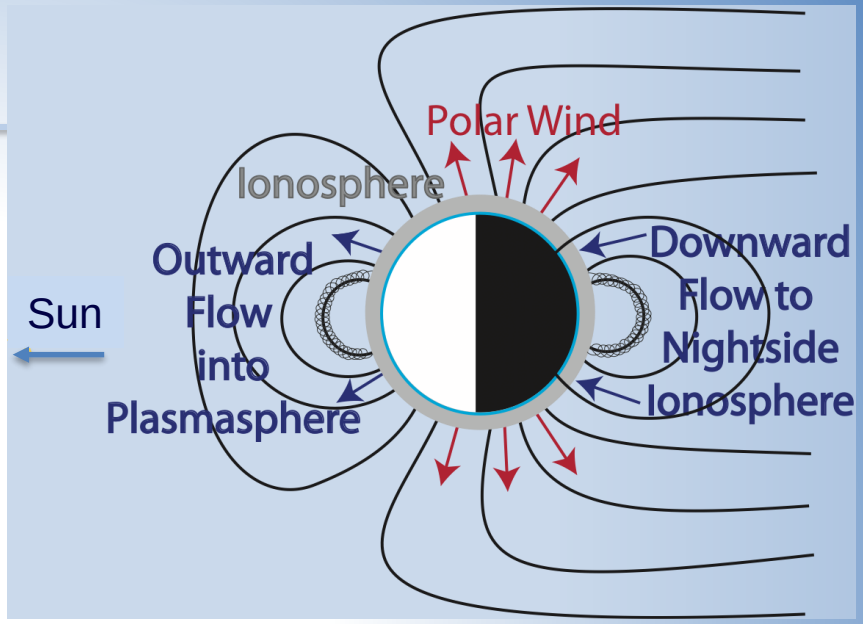
Common Constituents

X-rays, EUV, O, N, O_2, N_2, NO, H, O_3

- 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

Main regions and transport processes

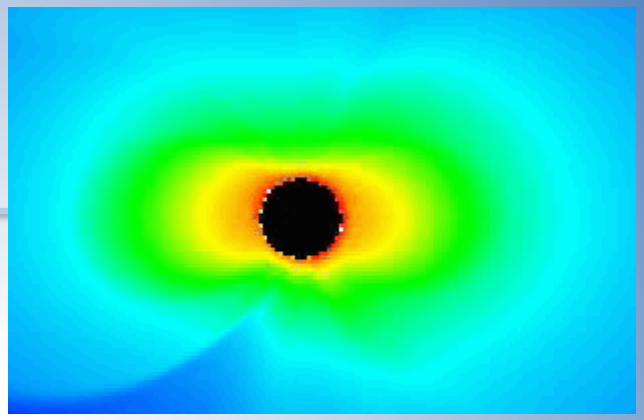
Ionosphere outflow



- 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

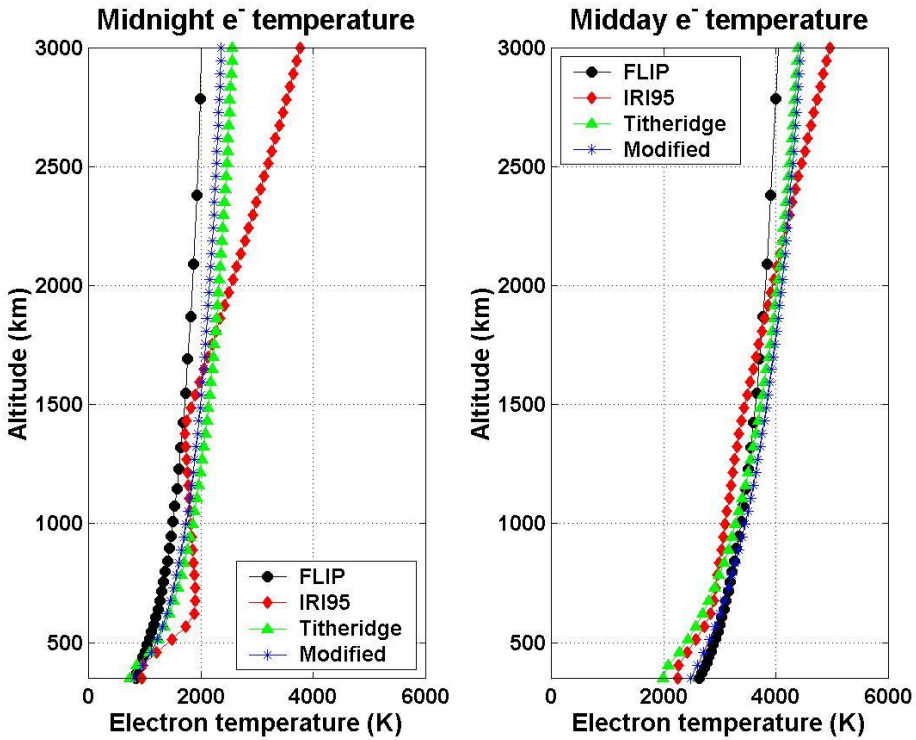
Main regions and transport processes

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

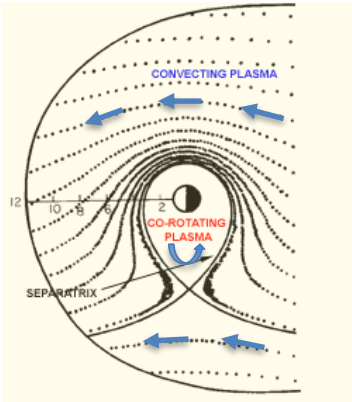
Main regions and transport processes

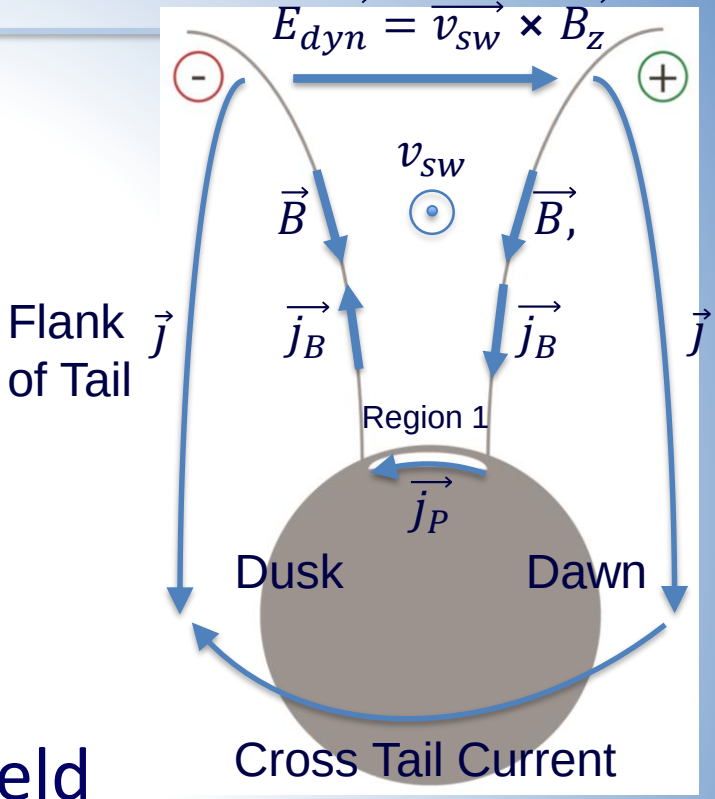
Solar wind dynamo

$$\overrightarrow{F_{Lorentz}} = q\vec{E}$$

$$\overrightarrow{E_{dyn}} = \overrightarrow{v_{sw}} \times \overrightarrow{B_z}$$

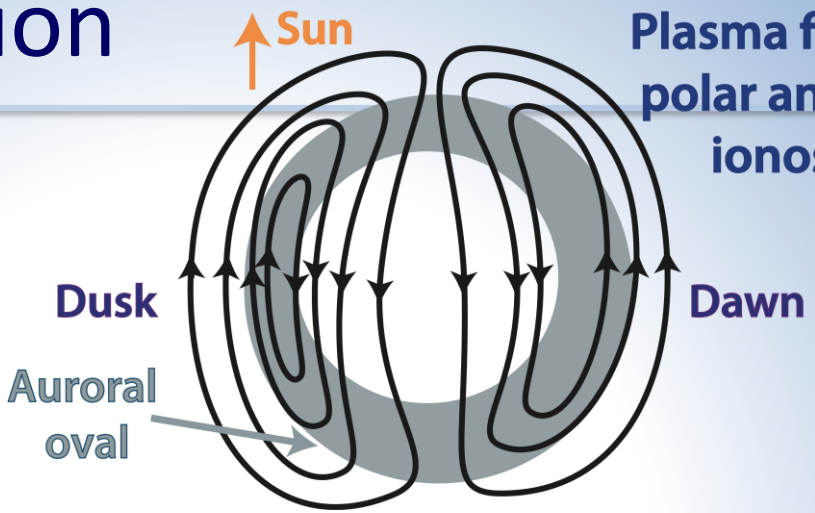
- Highly conducting plasma in the solar wind flows across polar geomagnetic field lines
  - Induces an electric dynamo field
  - Plasma and B-field lines are transported: Frozen-in flux concept





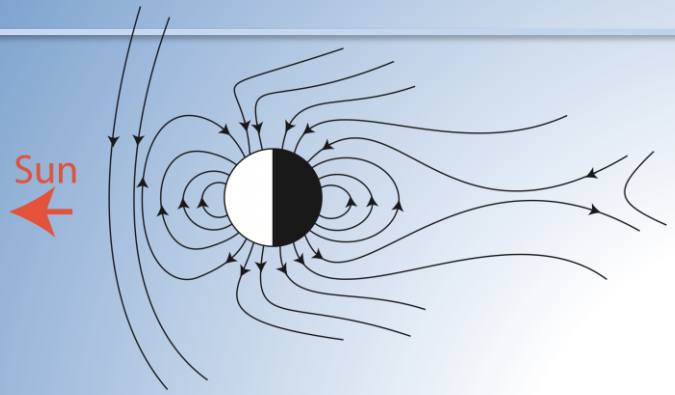
Main regions and transport processes

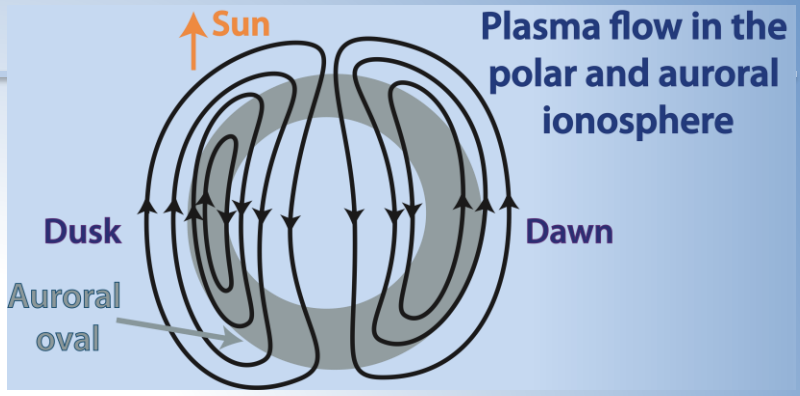
Global convection



- 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

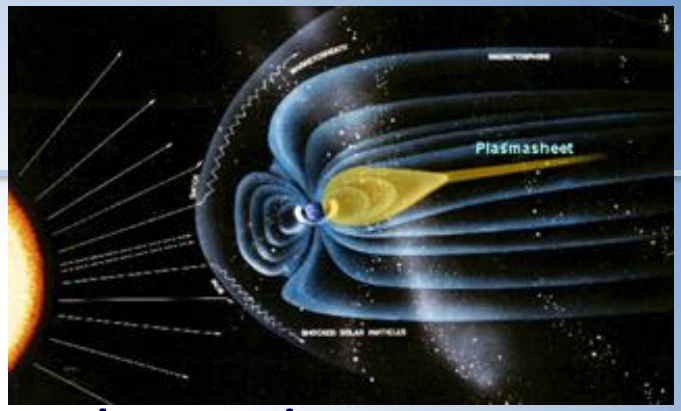
Reconnection





- If the polar geomagnetic field lines are open
  - The electric field produces an anti-sunward ExB 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

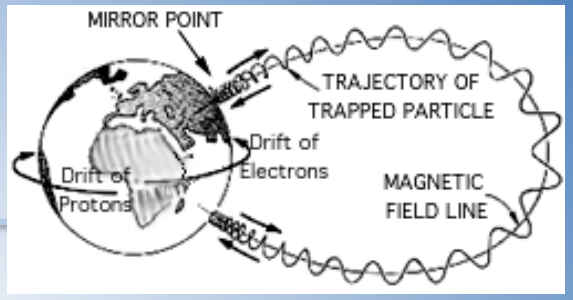
Plasma sheet



- 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

AKR

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:

$$\mu = \frac{m v_{\perp}^2}{2B}$$

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:

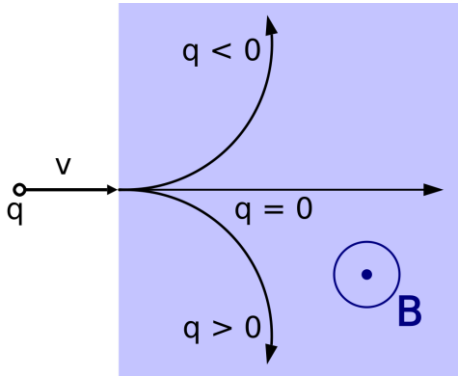
Φ = the total magnetic flux enclosed by a drift surface

First Adiabatic Invariant

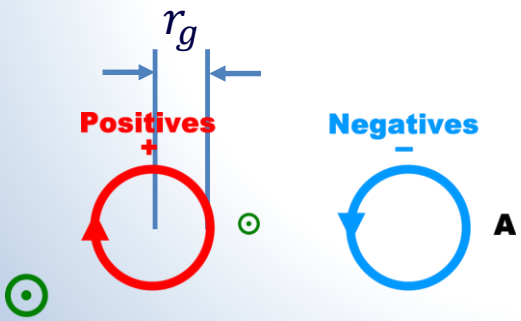
$$F = q\vec{E} = q\vec{v}x\vec{B}$$

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

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



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



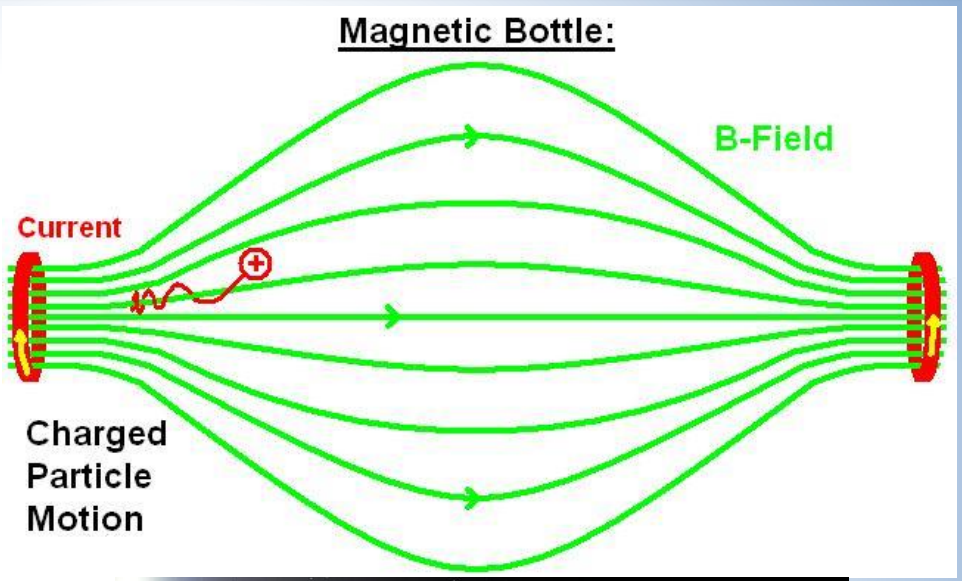
For H^+, T=1eV, L=4

f_g = 114 Hz

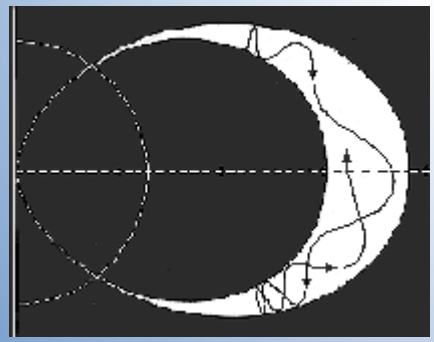
r_g = 13.6 m

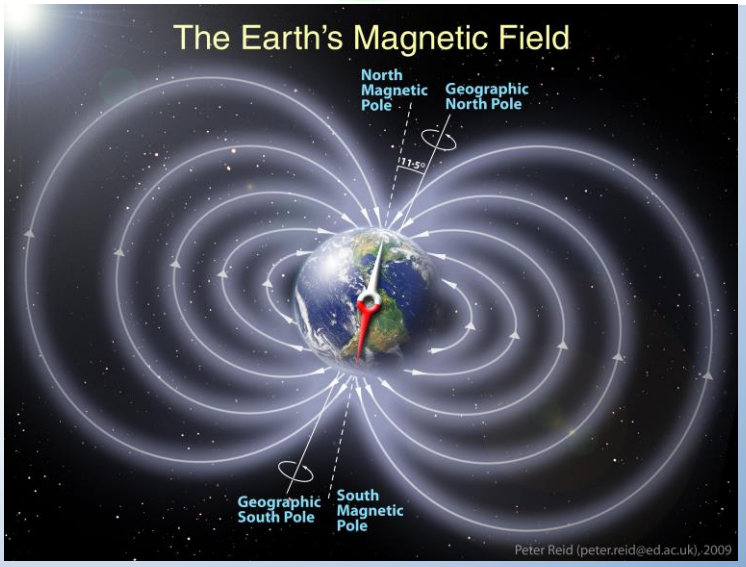
Second Adiabatic Invariant

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



Bounce Period ~1 s

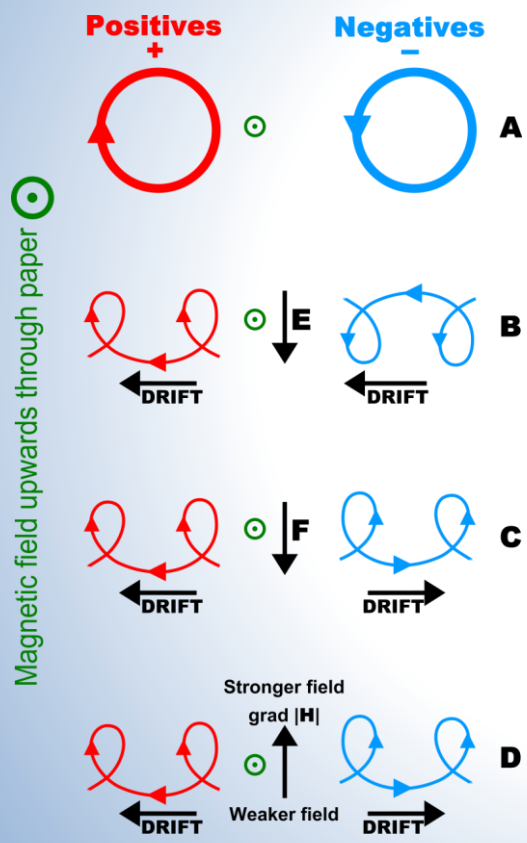




Main regions and transport processes

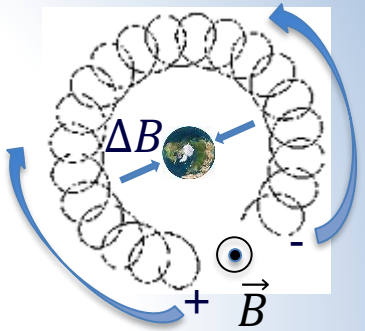
Third Adiabatic Invariant

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



Gradient-B Drift

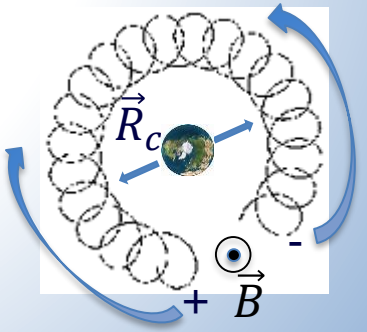
$$\vec{v}_{\nabla B} = \frac{\varepsilon_\perp}{qB}\frac{\vec{B} \times \Delta B}{B^2}$$



10s seconds

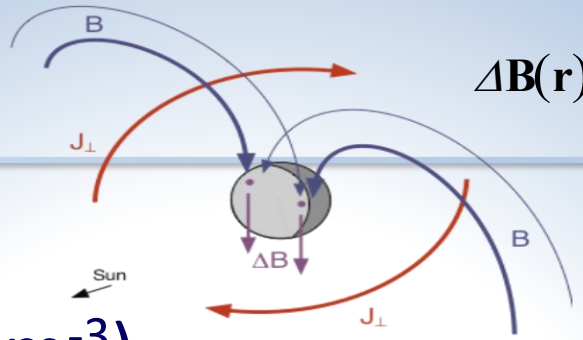
Curvature-B Drift

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

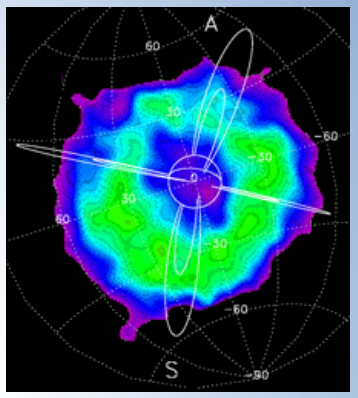


Main regions and transport processes

Ring Current



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

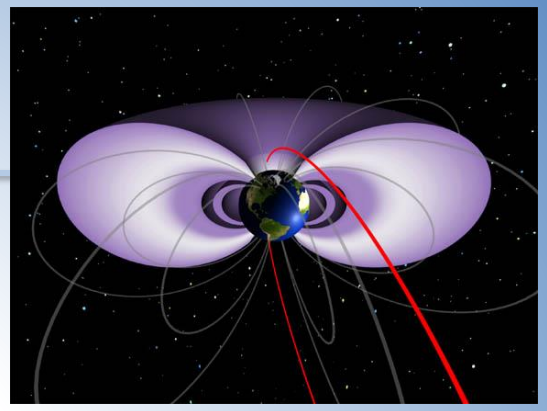


- Hot (1-400 keV) tenuous (1-10s cm^{-3})
- diamagnetic current produced by motion of plasma trapped in the inhomogeneous geomagnetic field
  - Torus-shaped volume extending from ~3 to 8 R_E
  - Main Source: plasma sheet particles
  - Loss Mechanisms: charge exchange, coulomb collisions, atmospheric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

Chorus

Main regions and transport processes

Radiation Belt

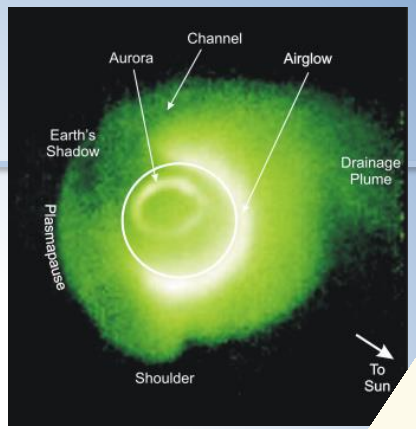


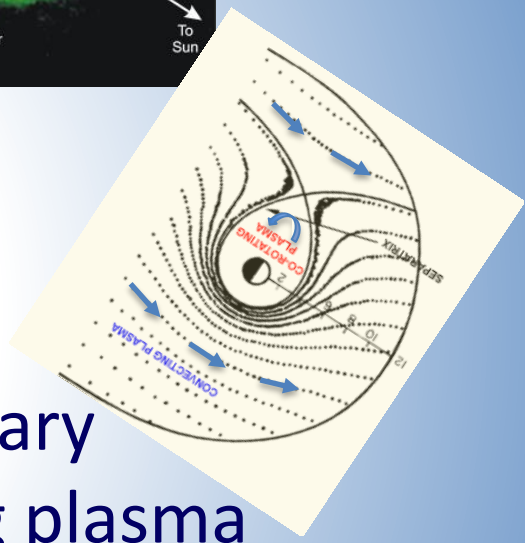
- Very Hot (100s keV - MeV)
- Extremely tenuous: <<1 cm^{-3}
  - Outer belt: very dynamic region
    - Mostly elections located at 3-6 R_E
  - Inner belt: fairly stable population
    - Protons, electrons and ions at 1.5-2 R_E
- Source: injection and energization events following geomagnetic storms
- 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

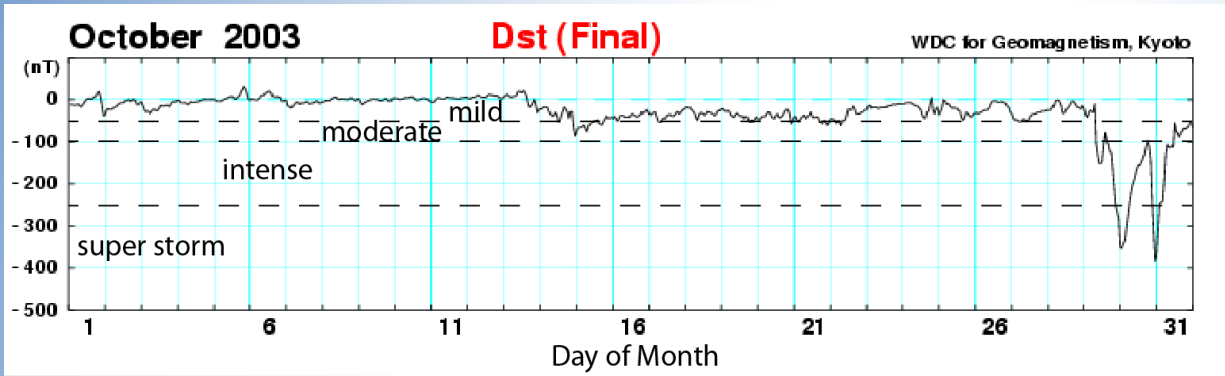
Main regions and transport processes

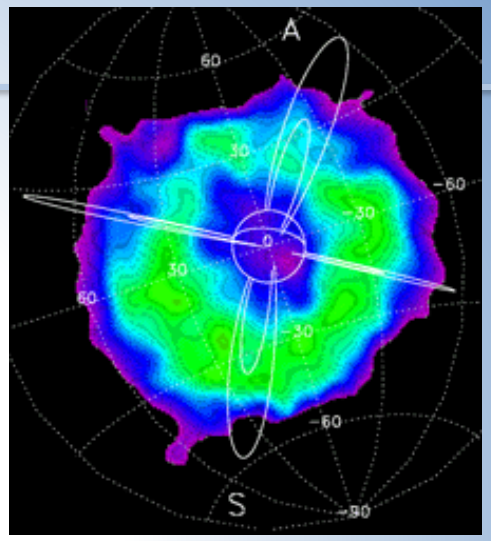
Geomagnetic storms

- Large (≥100s 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

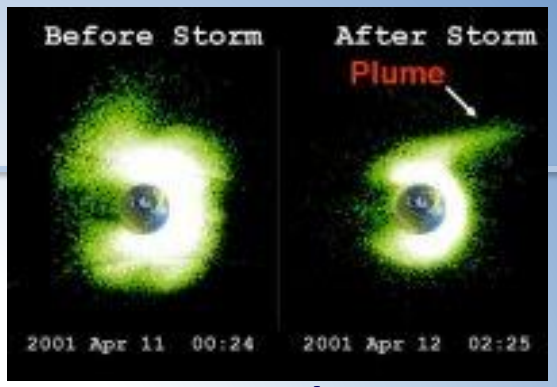
Halloween Storm of 2013



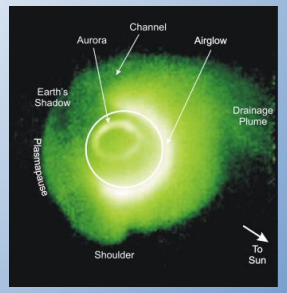


- Enhanced convection
  - Increased rate of injection into the ring current
    - The ring current then expands earthward
    - Induced current can reduce the horizontal component of the geomagnetic field (100s nT)
      - Used to calculate Dst

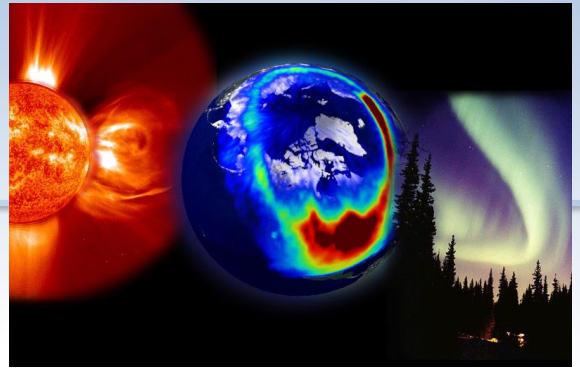
Plasmaspheric Plumes



- 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

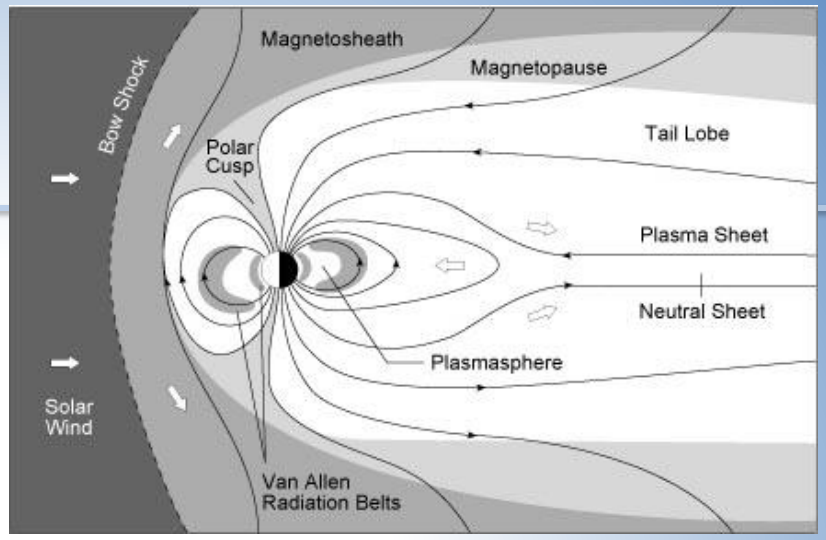


Substorms

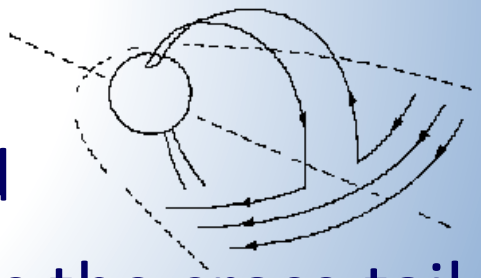


- A relatively short (hours) period of increased energy input and dissipation into the inner magnetosphere
  - Events may be isolated or occur during a storm
  - Associated with a flip from northward to southward IMF Bz
- Increased rate of reconnection
- Increased flow in magnetospheric boundary layer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

Substorms



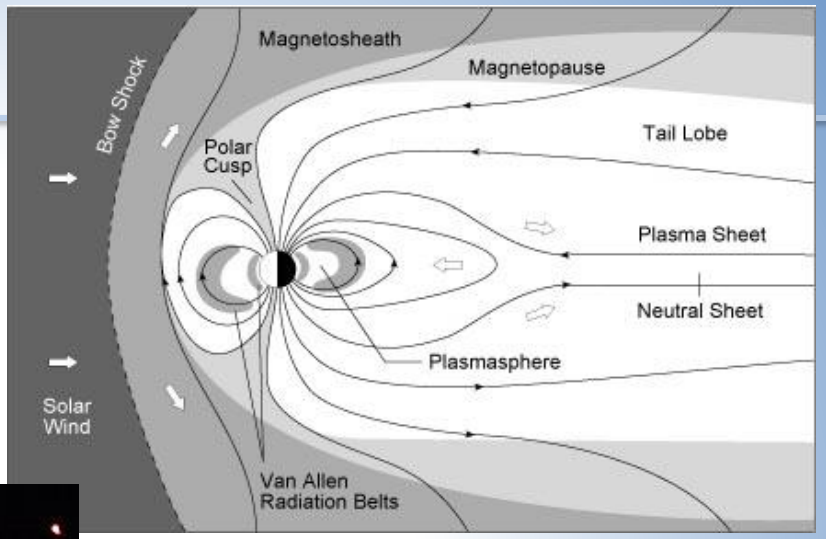
- Additional magnetic flux in the tail lobes causes the cross-tail current sheet thickness to decrease
  - When the current sheet thickness reaches its threshold reconnection occurs
  - The cross-tail current is disrupted

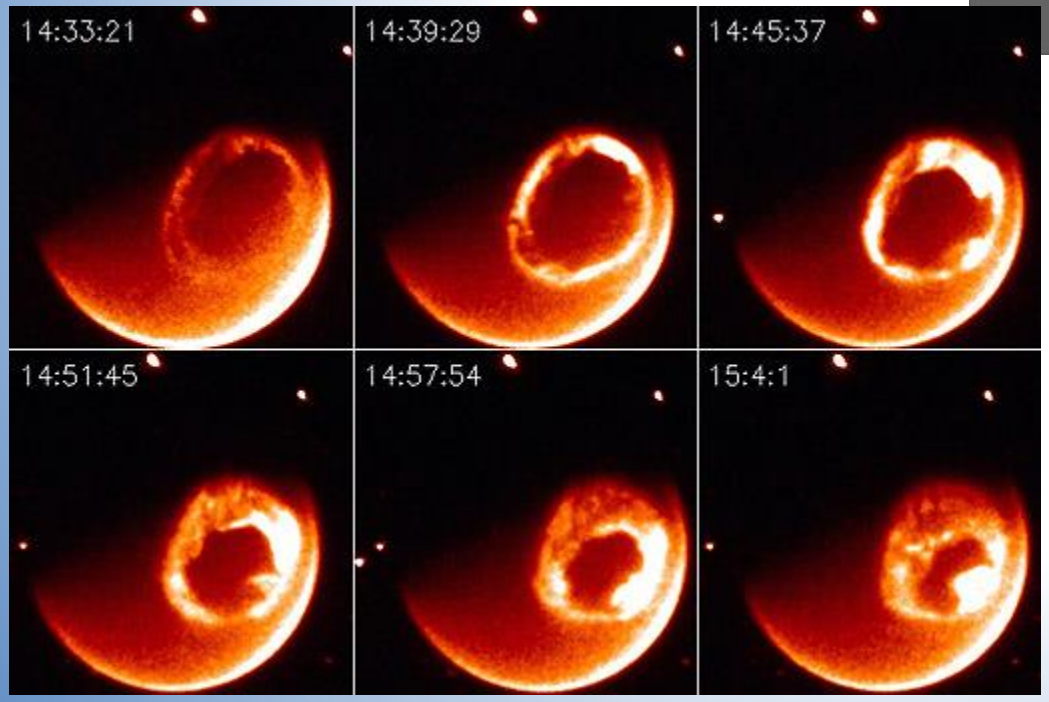


- The substorm current wedge closes the cross-tail current through the ionosphere
- Particle precipitation increases Auroral activity

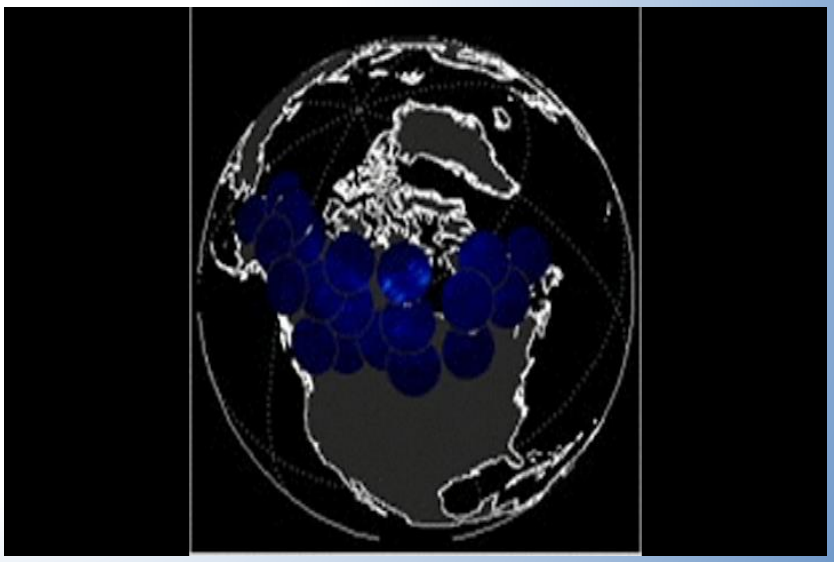
Substorms

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.





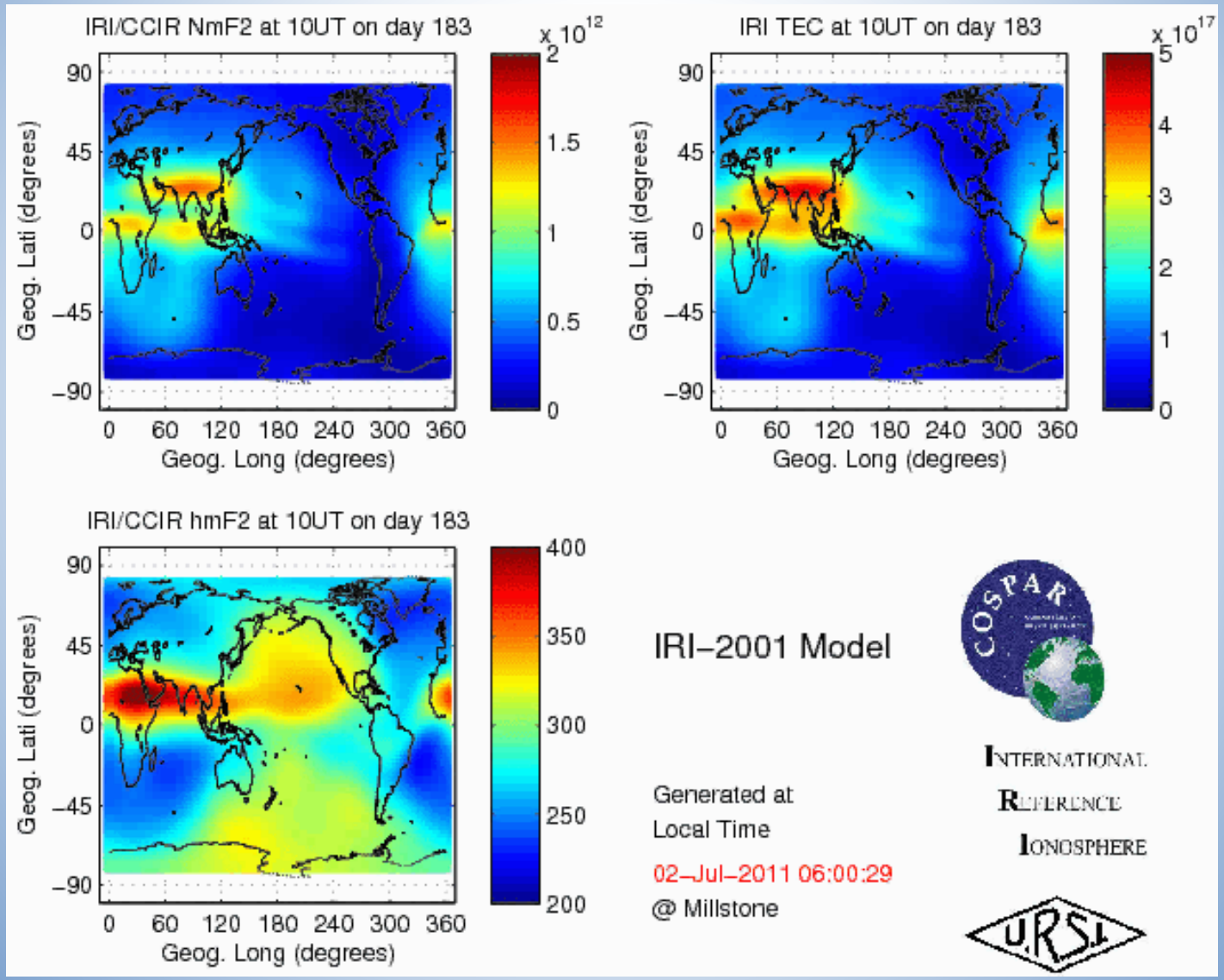
NASA IMAGE Mission



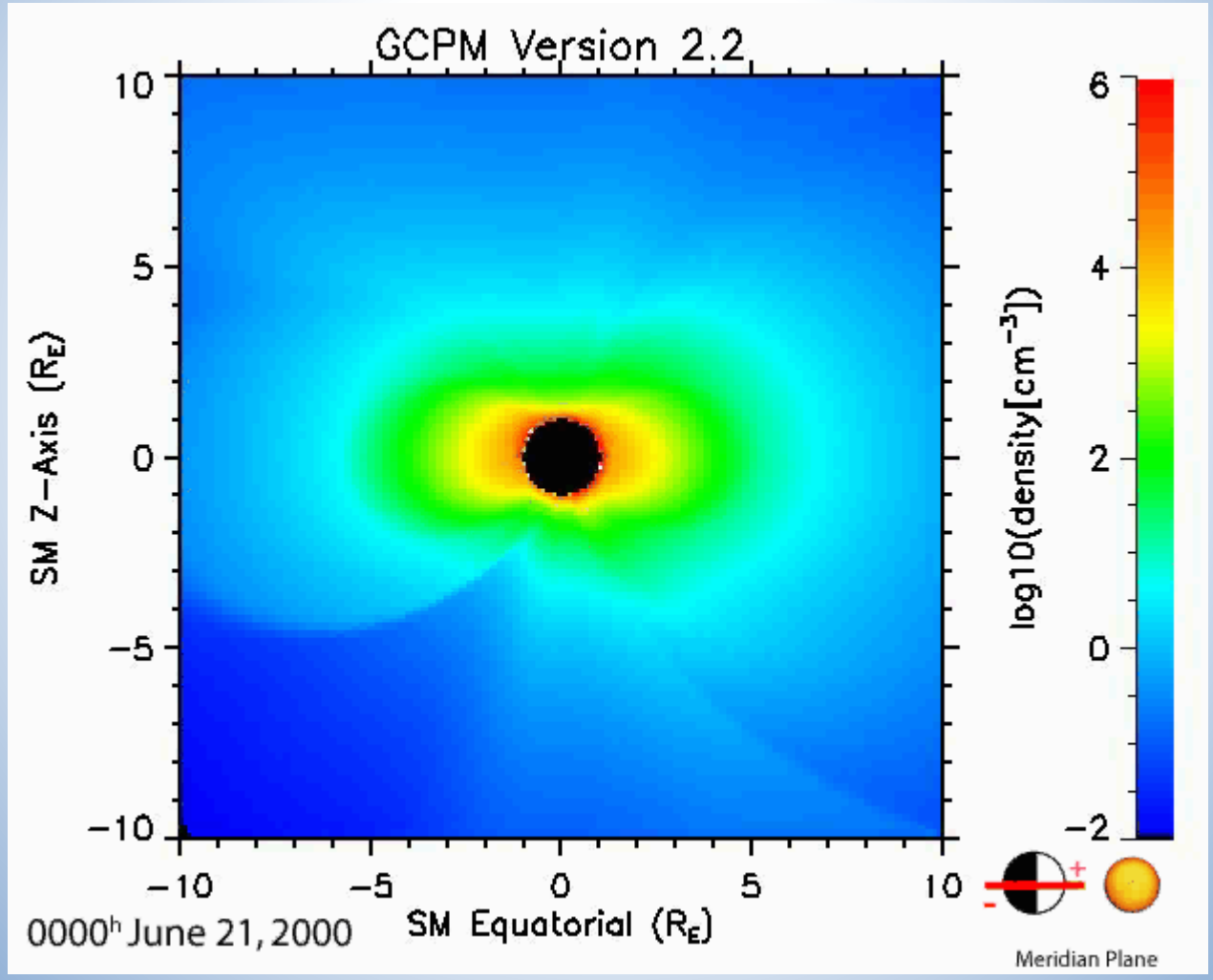
ESA/NASA Cluster Mission

Geomagnetic Activity

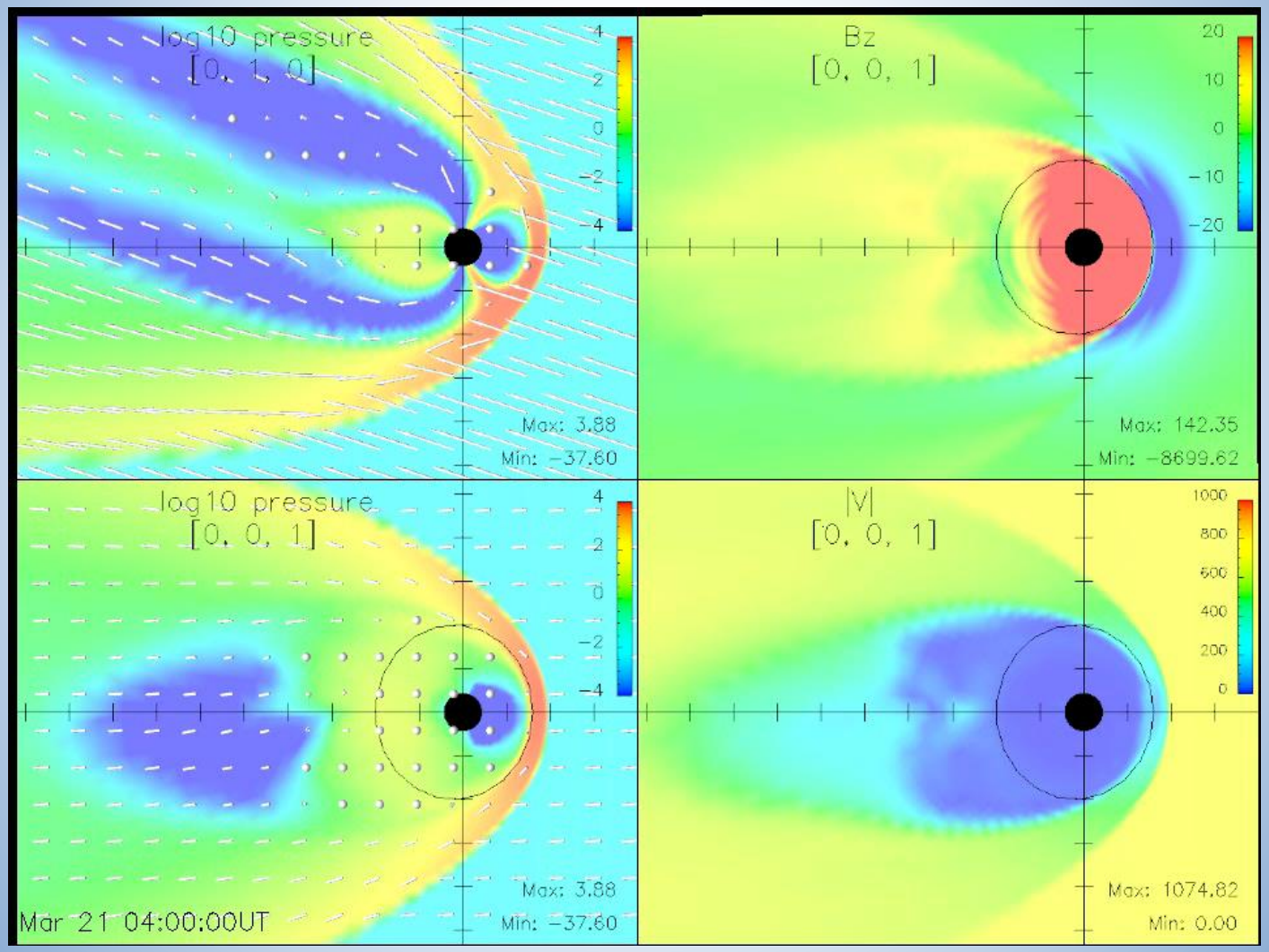
Models – Empirical: IRI



Models – Empirical: GCPM



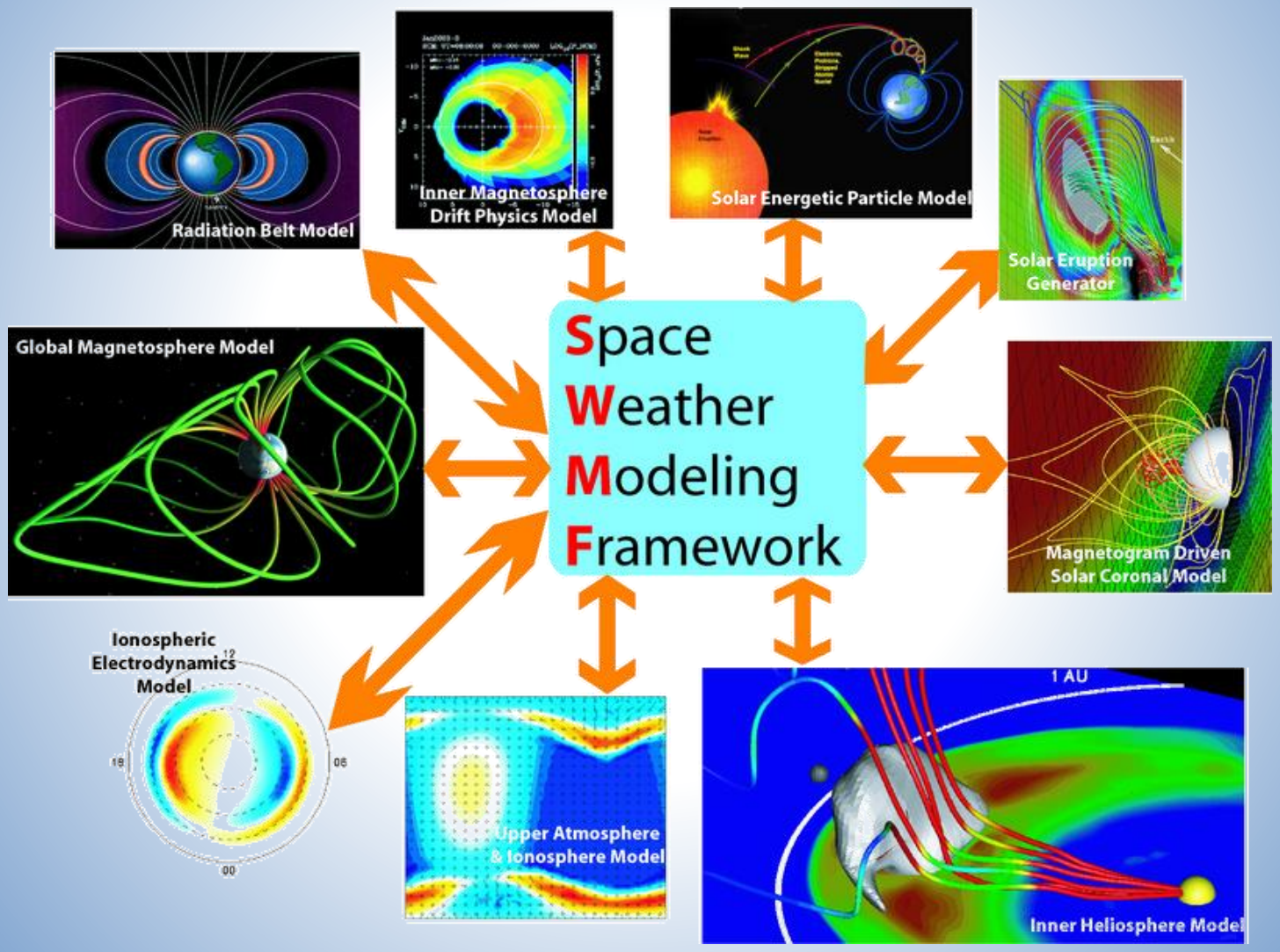
Models –LFM Model (Multi-Fluid Lyon-Fedder-Mobarry MHD)



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

Through the Coordinated Community Modeling Center, NASA/GSFC

Coupling Models



Tóth, et al., The Space Weather Modeling Framework, *Proceedings of ISSS-7*, 26-31, March, 2005