Inner Magnetospheric Physics

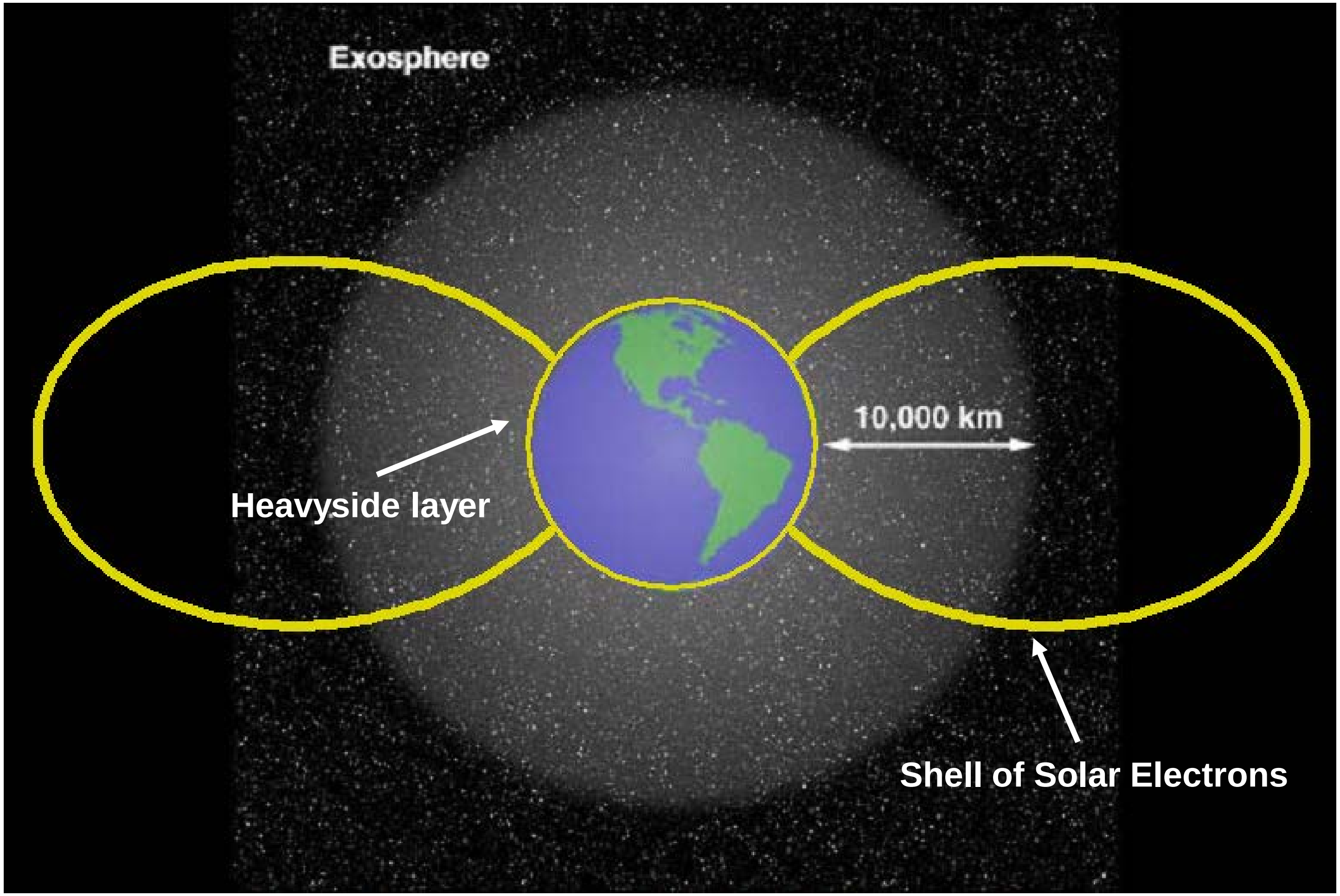
Dennis Gallagher, PhD
NASA Marshall Space Flight Center
Dennis.gallagher@nasa.gov

Inner Magnetosphere Effects

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

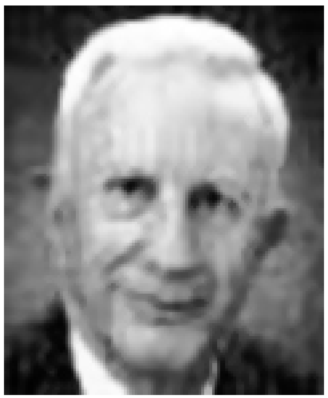
Outline

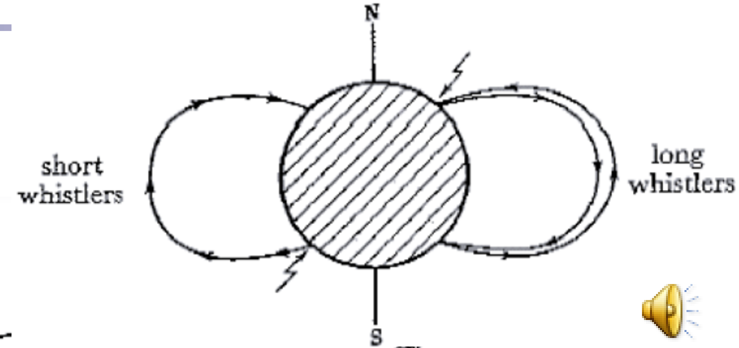
Historical Background: Space in 1950



Historical Background

Whistlers revealed unexpected plasma



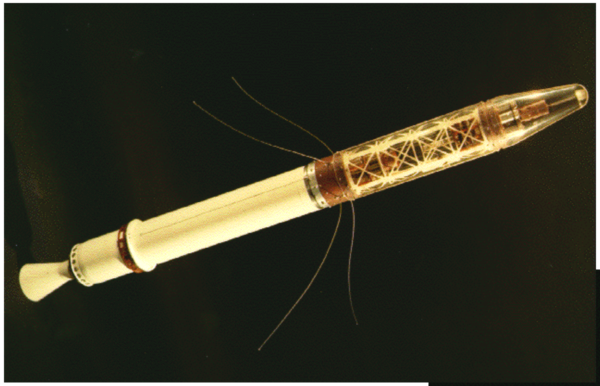


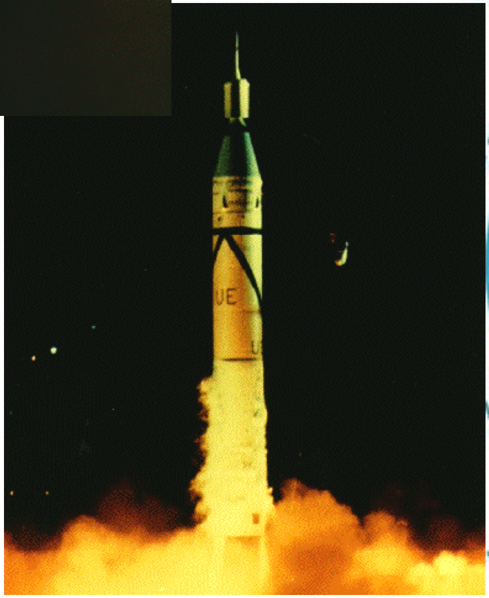
1952
L. R. Owen Storey
Cavendish Laboratory
University of Cambridge

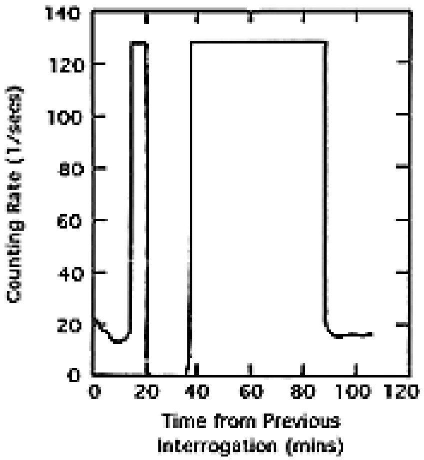
L. R. O. Storey, Phil. Trans. R. Soc. Lond. A 1953 246 113-141; DOI: 10.1098/rsta.1953.0011. Published 9 July 1953

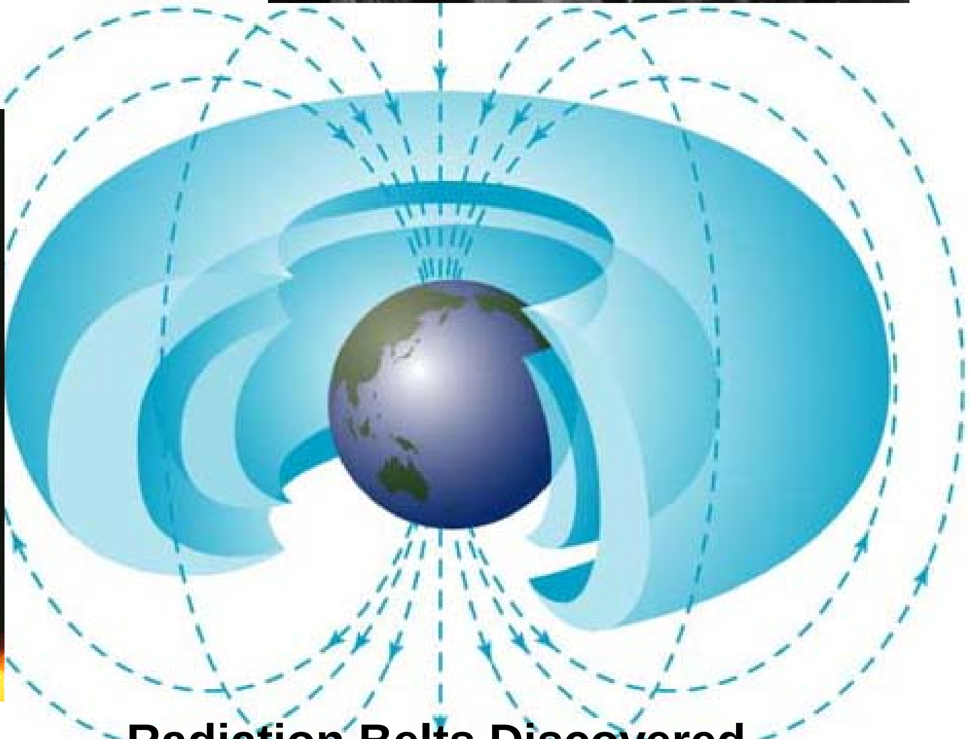
Historical Background

Explorer 1
January 31, 1958









Radiation Belts Discovered

Ionosphere

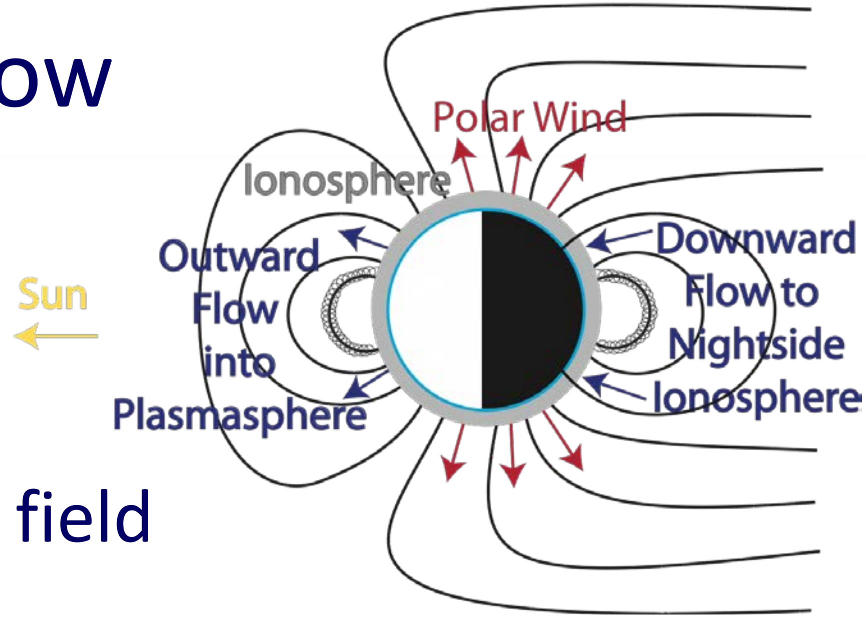
Photoionization

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

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

Main regions and transport processes

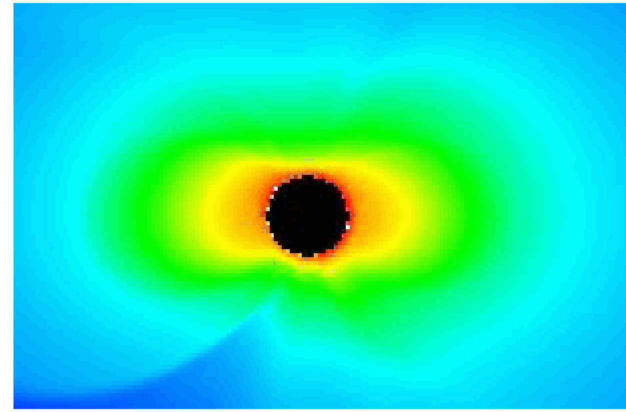
Ionosphere outflow



- 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

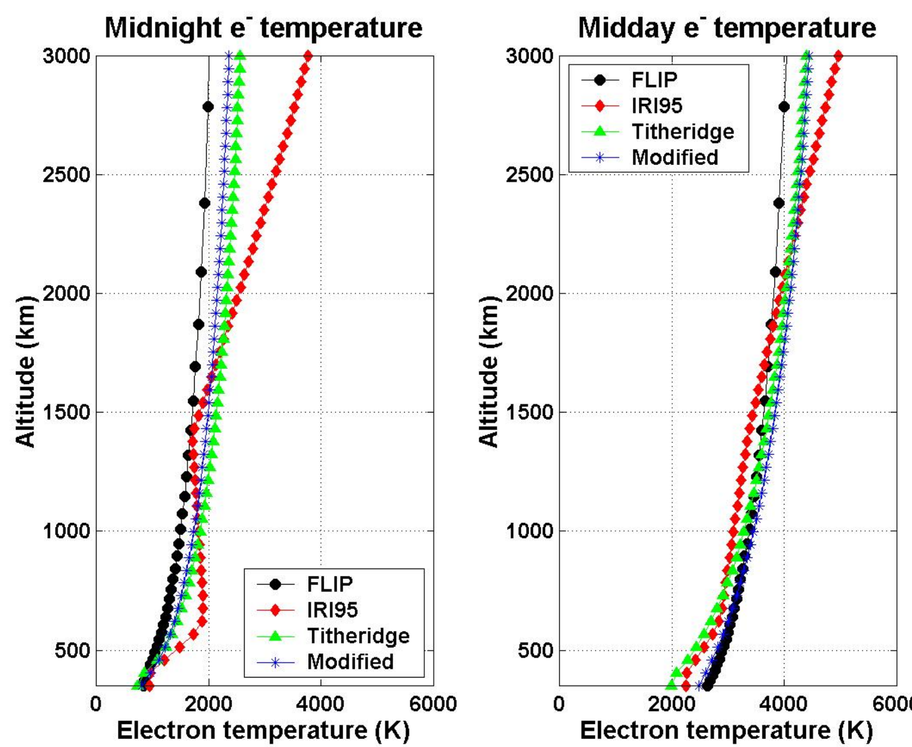
Plasmasphere Formation: Diffusive Equilibrium



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

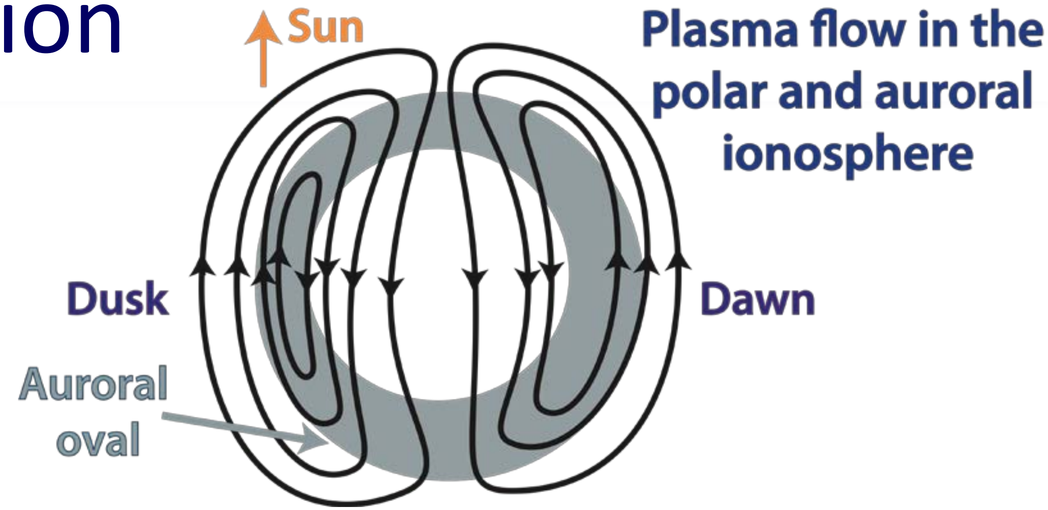
Titheridge (1972)

- 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



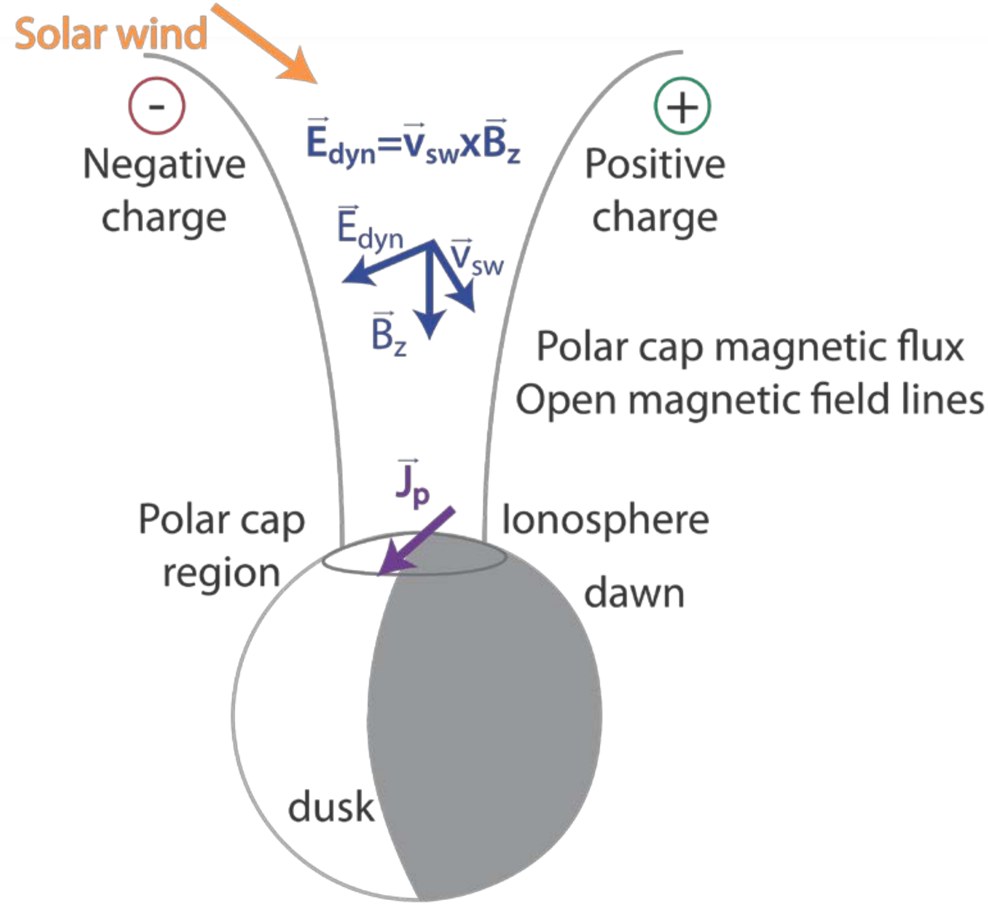
Source: Webb and Essex, Modelling the Plasmasphere

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

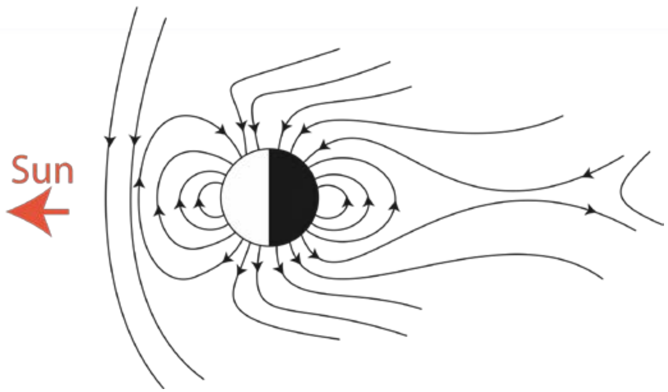
Solar wind dynamo

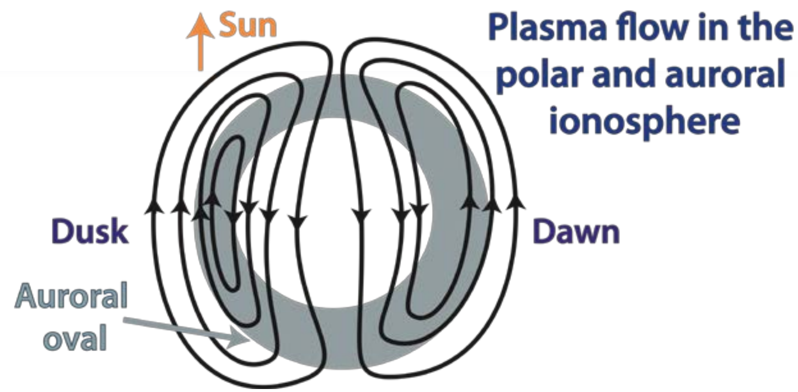


- Highly conducting plasma in the solar wind flows across polar geomagnetic field lines
  - Induces an electric dynamo field
  - Frozen-in flux concept

Main regions and transport processes

Reconnection

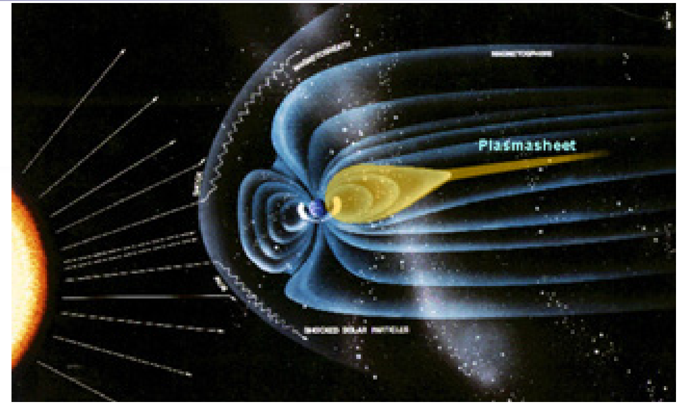




- If the polar geomagnetic field lines are open
  - The electric field produces an anti-sunward ExB drift of solar wind and magnetospheric plasma across the polar cap
  - Reconnection occurs down tail
  - Closed geomagnetic field lines flow back towards Earth at lower latitudes

Main regions and transport processes

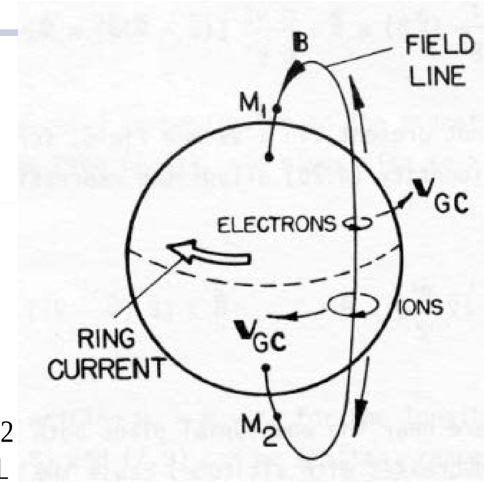
Plasma sheet



- 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 collide with ionosphere producing aurora

AKR

Adiabatic Invariants



- Energetic plasma near the center of the plasma sheet gyrates closer to the Earth

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

  - Become trapped on closed dipole like field lines
  - Encounter increasing magnetic field strength
  - Bounce between hemispheres

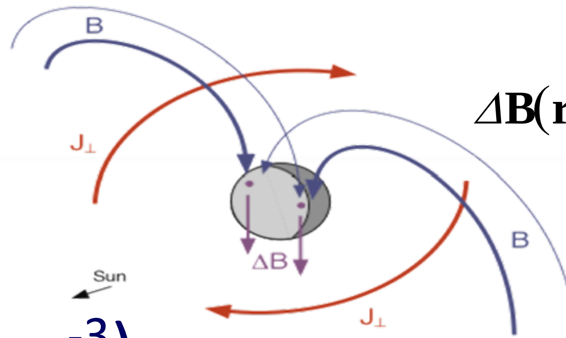
$$J = \oint_{bounce} \vec{v} \cdot d\vec{l} = \oint_{bounce} v_\parallel dl$$

  - Gradient and curvature drift

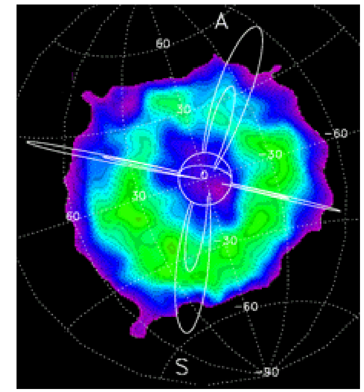
$$\Phi = \int_{drift} \vec{B} \cdot d\vec{A}$$

    - Divert ions and electrons in opposite directions
    - Form the ring current and radiation belts

Ring Current



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

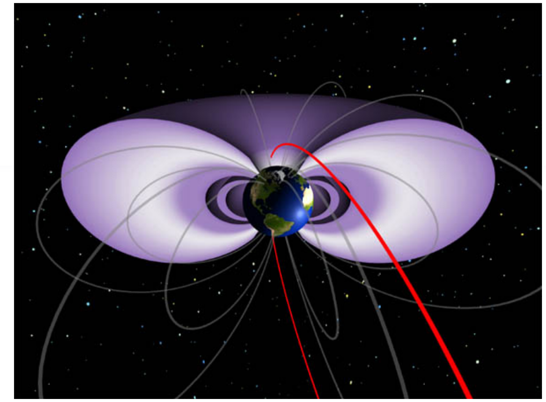


- Hot (1-400 keV)
  tenuous (1-10s cm^{-3})
- diamagnetic current produced by motion of plasma trapped in the inhomogeneous geomagnetic field
  - Torus-shaped volume extending from ~3 to 8 R_E
  - Main Source: plasma sheet particles
  - Loss Mechanisms: charge exchange, coulomb collisions, atmospheric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

Chorus

Main regions and transport processes

Radiation Belt

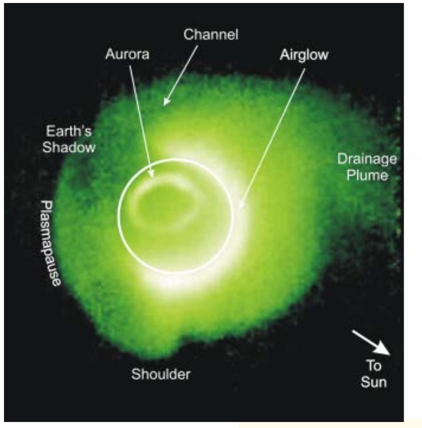


- Very Hot (100s keV - MeV)
- Extremely tenuous: <<1 cm^{-3}
  - Outer belt: very dynamic region
    - Mostly elections located at 3-6 R_E
  - Inner belt: fairly stable population
    - Protons, electrons and ions at 1.5-2 R_E
- Source: injection and energization events following geomagnetic storms
-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

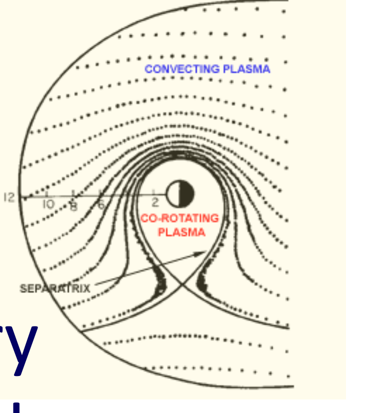
Hiss

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



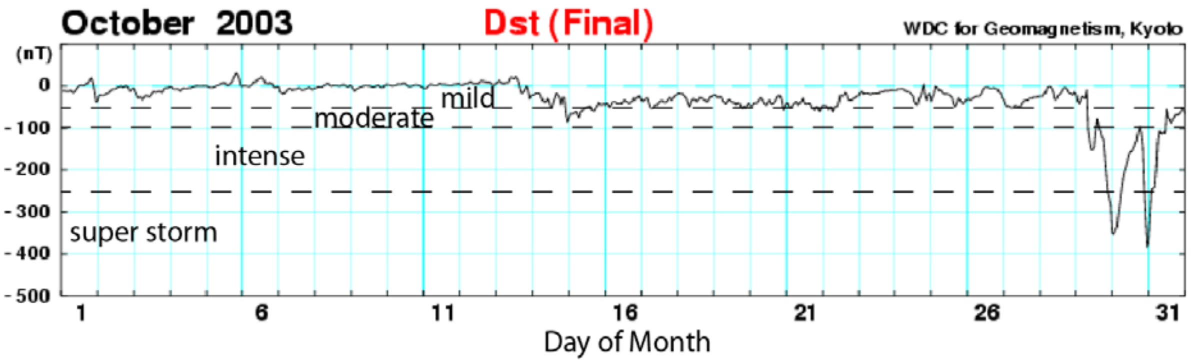
Main regions and transport processes

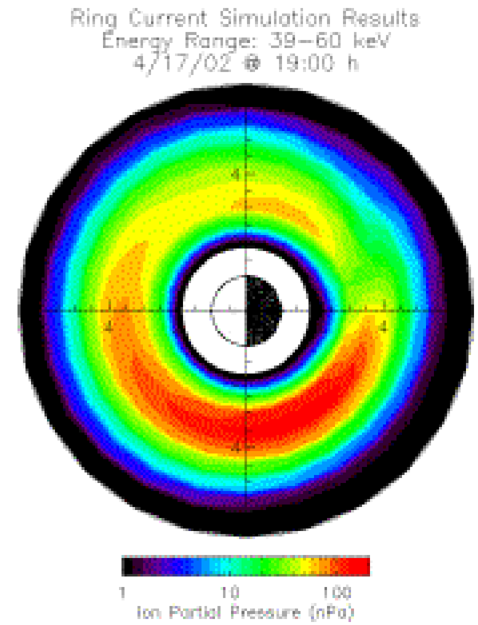
Geomagnetic storms

- Large (100s nT)
- 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

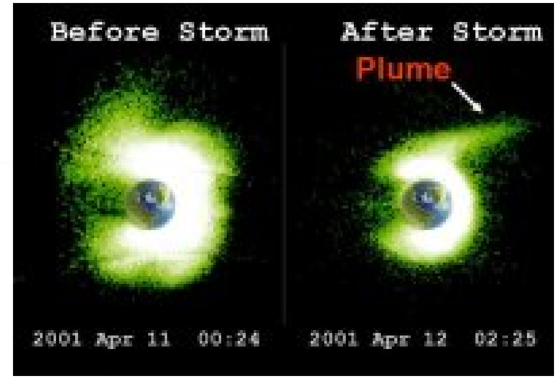
Halloween Storm of 2013



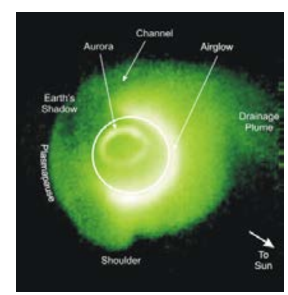


- Enhanced convection
  - Increased rate of injection into the ring current
    - The ring current then expands earthward
    - Induced current can reduce the horizontal component of the geomagnetic field (100s nT)
      - Used to calculate Dst

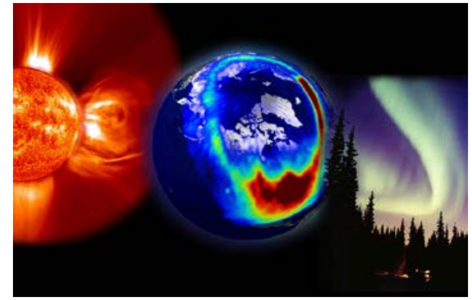
Plasmaspheric Plumes



- 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

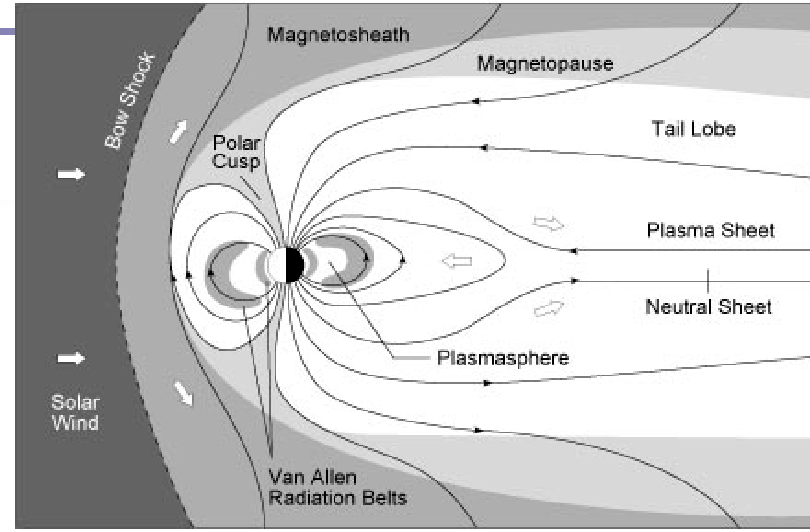


Substorms

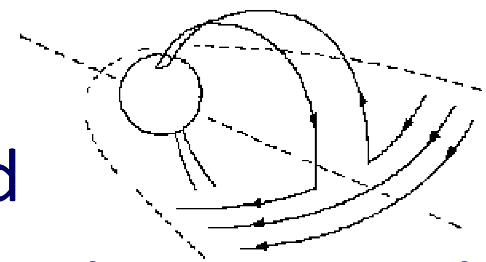


- A relatively short (hours) period of increased energy input and dissipation into the inner magnetosphere
  - Events may be isolated or occur during a storm
  - Associated with a flip from northward to southward IMF Bz
- Increased rate of reconnection
- Increased flow in magnetospheric boundary layer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

Substorms

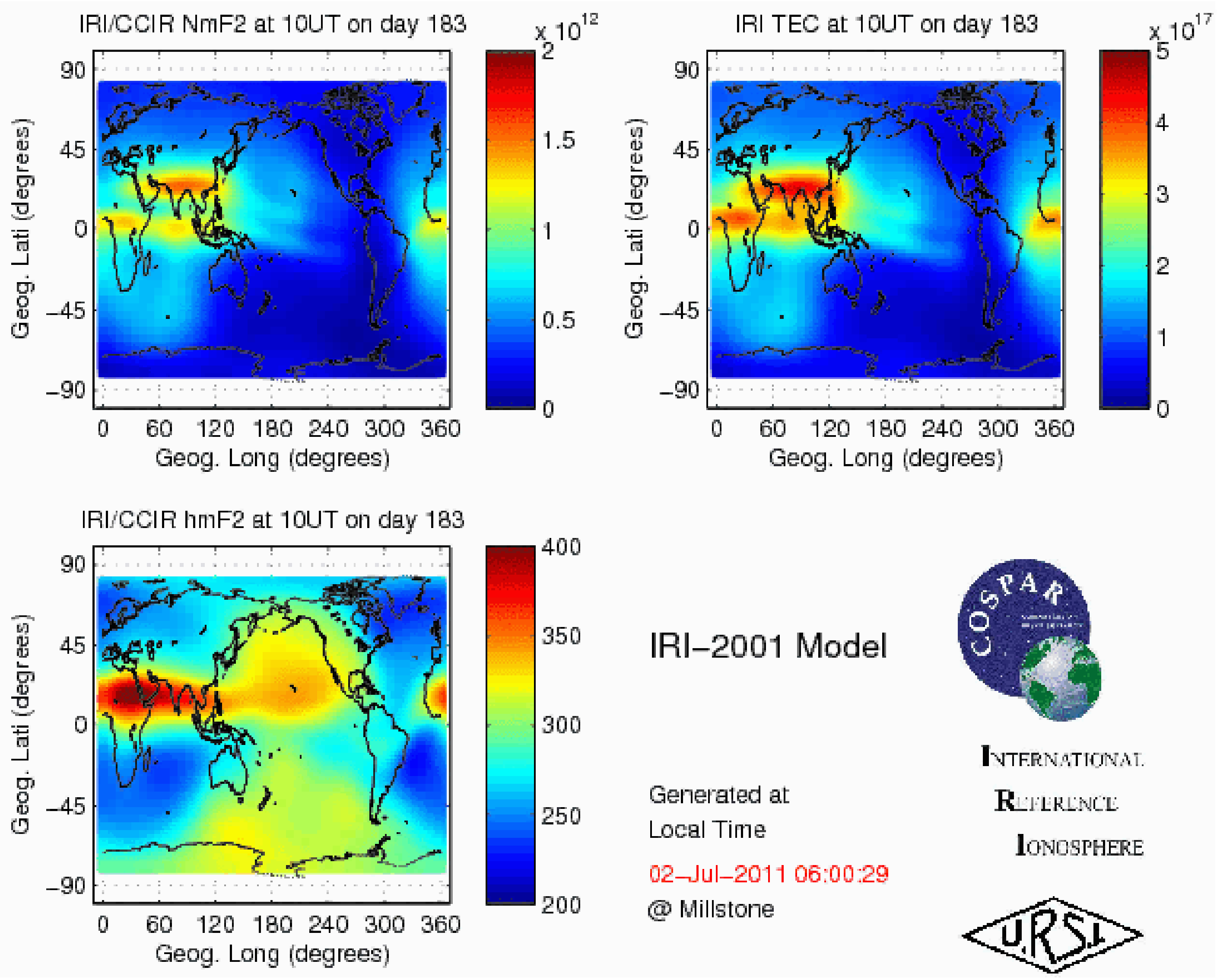


- Additional magnetic flux in the tail lobes causes the cross-tail current sheet thickness to decrease
  - When the current sheet thickness reaches its threshold reconnection occurs
  - The cross-tail current is disrupted

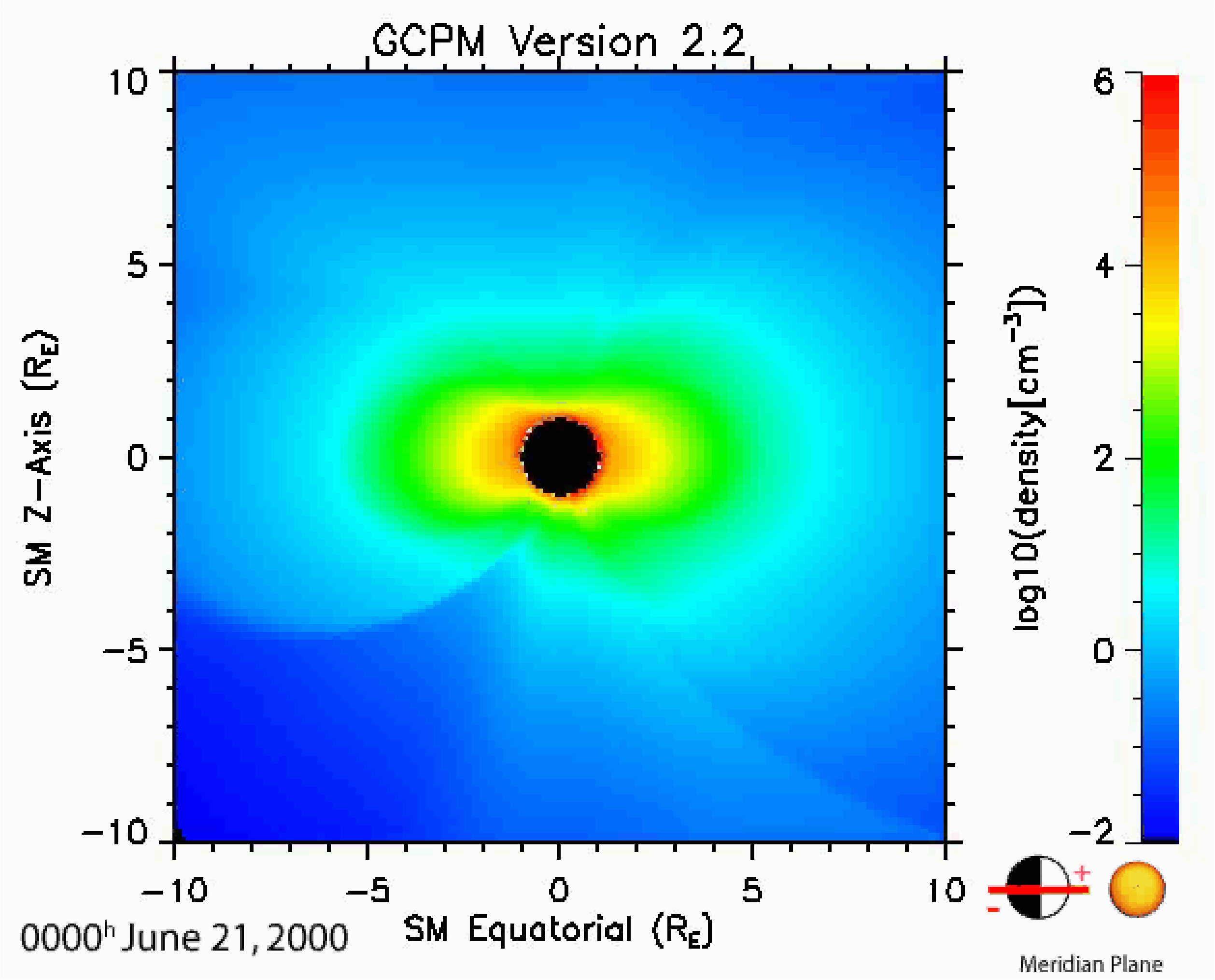


- The substorm current wedge closes the cross-tail current through the ionosphere
- Particle precipitation increases Auroral activity

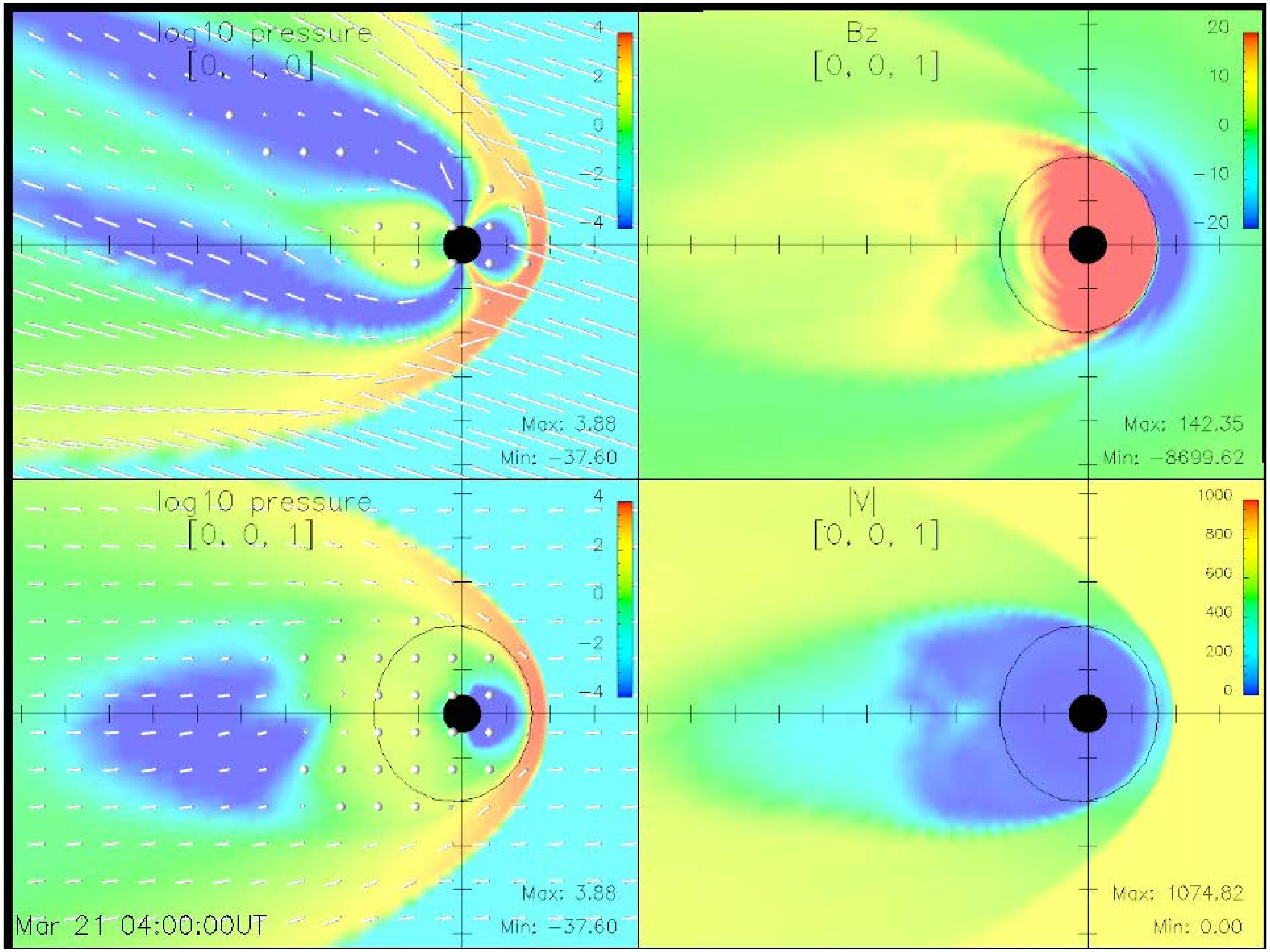
Models – Empirical: IRI



Models – Empirical: GCPM



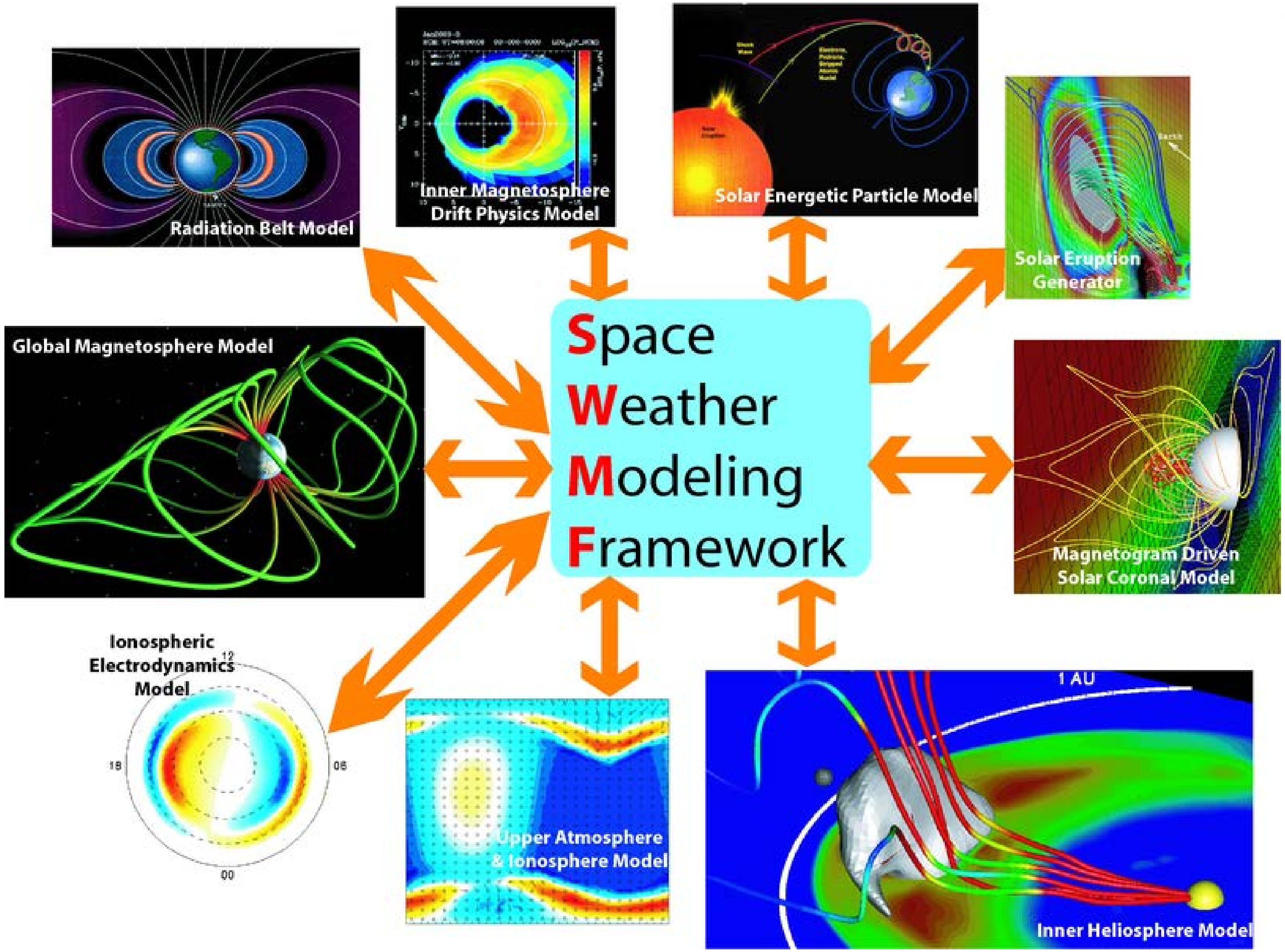
Models –LFM Model (Multi-Fluid Lyon-Fedder-Mobarry MHD)



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