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
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  - Plasma sheet
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- Geomagnetic Activity
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Historical Background: Space in 1950

- Exosphere
- Heavyside layer: 10,000 km
- Shell of Solar Electrons
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

William Pickering
James van Allen
Wernher von Braun

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
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

Main regions and transport processes
Adiabatic Invariants

- Energetic plasma near the center of the plasma sheet gyrates closer to the Earth
  - Become trapped on closed dipole like field lines
  - Encounter increasing magnetic field strength
  - Bounce between hemispheres

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

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

Main regions and transport processes
Ring Current

• 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 \(8\ \text{R}_\text{E}\)
  – Main Source: plasma sheet particles
  – Loss Mechanisms: charge exchange, coulomb collisions, atmospheric loss, pitch angle (PA) diffusion, and escape from magnetopause

\[
\Delta B(r) = \frac{\mu_0}{4\pi} \int_V \frac{J(r') \times (r-r')}{|r-r'|^3} \, dr'
\]
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

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

- 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

Halloween Storm of 2013

October 2003

Dst (Final)

WDC for Geomagnetism, Kyoto

Ion Partial Pressure (nPa)
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 Bz
- Increased rate of reconnection
- Increased flow in magnetospheric boundary layer
- Energy accumulates in the near-Earth tail

Geomagnetic Activity
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

Geomagnetic Activity
Models – Empirical: IRI

IRI/CCIR NmF2 at 10UT on day 183

IRI TEC at 10UT on day 183

IRI/CCIR hmF2 at 10UT on day 183

IRI–2001 Model

Generated at Local Time 02–Jul–2011 06:00:29 @ Millstone
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