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

Exosphere

10,000 km

Heavyside layer

Shell of Solar Electrons

Historical Background
Historical Background

Whistlers revealed unexpected plasma

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

Historical Background

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

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

Photoionization
\[ O + h\nu = O^+ + e^- \]
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
- \( T_t \): 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

Main regions and transport processes
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

\[ \mu = \frac{W_\perp}{B} = \frac{mv_{\perp}^2}{2B} \]
\[ J = \oint \mathbf{v} \cdot d\mathbf{l} = \oint v_{\parallel} d\mathbf{l} \]
\[ \Phi = \oint \mathbf{B} \cdot d\mathbf{A} \]
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 Rₑ
  – Main Source: plasma sheet particles
  – Loss Mechanisms: charge exchange, coulomb collisions, atmospheric loss, pitch angle (PA) diffusion, and escape from magnetopause

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

Main regions and transport processes
Radiation Belt

- Very Hot (100s keV - MeV)
- Extremely tenuous: $<<1 \text{ cm}^{-3}$
  - 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
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
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
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
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