• Magnetospheric Physics Overview continued
  – Review (reconnection concepts)
  – Continue consequences of magnetospheric convection idea

• Begin Single Particle motion in E and B fields
Now let's examine plasma processes at the magnetopause.
Three topologically different regions

Connected to the sun and the Earth

Connected to the sun

Connected to Earth
Reconnection: Consequences

Polar Rain
Magnetospheric Convection ($E_{\text{dawn-dusk}}$)
Transient Reconnection: Flux Transfer Events
Polar cap electric field puts ionosphere in motion: direct momentum transfer
Closure in Tail: magnetospheric substorms/auroras
Remember: Frozen in Condition

\[ \vec{E} = - \nabla \times \vec{B} \]

Plasma and B-field move together

\[ \frac{\partial \vec{B}}{\partial t} = \nabla \times (\nabla \times \vec{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \vec{B} \]

Dominated by \( \nabla \times \vec{B} \) term

Another way to think of this is by transforming the E field into the moving frame so Ohms Law is

\[ \vec{E} + \nabla \times \vec{B} = \frac{\vec{J}}{\sigma} \]

Which just becomes the frozen in condition for large \( \sigma \)
Remember:
Tangential E-field Continuous at a boundary

• Faraday’s Law is:

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]

• Or in integral form when B=constant

\[ \oint \vec{E} \cdot d\vec{l} = 0 \]

Ask me to Draw it on board if you don’t understand
Three topologically different regions

Connected to the sun and the Earth

Connected to the sun

Connected to Earth
FIG. 1 (color). The geometry of the reconnection region with the results of the present experiment included. Note the coordinate description with $X$ along the normal to the magnetopause. Ions are decoupled from the electrons and magnetic field in the ion diffusion region, creating the Hall magnetic and electric field patterns. Electrons are demagnetized in the electron diffusion region.
Magnetospheric convection, as described by Dungy:

Process starts at the nose, and closes in the tail, making a complete circulation pattern, allowing solar wind plasma and energy to enter the magnetosphere.
Polar rain of solar wind electrons

Fig. 4. Typical electron precipitation event during the period of strongly northward IMF. The burst-type soft precipitations ($E_{\text{ave}} < 500$ eV) are seen entirely in the higher-latitude side of the hard electron precipitation region ($E_{\text{ave}} \geq 500$ eV) in this interval.
Multiple MP crossings

Fig. 1. Seven hours of electric and magnetic field data during which time the ISEE-1 spacecraft passed from the solar wind to the magnetosphere.
Fig. 2. Five minutes of electric and magnetic field data plotted in a frame of reference oriented along the average magnetopause, during the passage of the magnetopause back and forth over the spacecraft. The error bars in the electric field data are the standard deviations of a single point in the sine wave least squares fit of six seconds of data.
Why is the plasma energized in the reconnection process?

• Because, once the B-field diffuses away, the particles are not gyrating, and they simply gain energy according to Lorentz force $F=\mathbf{qE}$ (dawn to dusk field remains throughout the MP region, as well as other E-fields related to charge separations).
ISEE Observations of Flux Transfer Events - "Standard" FTEs

[Graphs showing magnetic field data for different dates: October 21, 1980, October 26, 1980, August 18, 1981, December 23, 1984. Each graph includes data for BL, BM, BN, and IBI (nT) with time axes ranging from 1200 to 1300 and 2100 to 2200.]
Fig. 10.6. Horizontal component of electric field perpendicular to the sun-earth line during two traverses of the OGO-6 satellite across the north magnetic pole. (Heppner 1972)
<table>
<thead>
<tr>
<th></th>
<th>Magnetosheath</th>
<th>Tail Lobe</th>
<th>Plasma-Sheet Boundary Layer</th>
<th>Central Plasma Sheet</th>
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<td>10</td>
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<tr>
<td>( \beta )</td>
<td>2.5</td>
<td>(3 \times 10^{-3})</td>
<td>(10^{-1})</td>
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Next: Start learning about the difference between Cold and Hot plasma motions – they are VERY different in the magnetosphere
Magnetosphere Configuration

- High latitude, open field lines, magnetospheric convection, magnetotail
- Middle altitudes: plasma sphere/ radiation belts, ring current
- Ionosphere: aurora, field aligned currents, acceleration mechanisms, field aligned currents
- Global current systems linking them all
FIG. 10.4. Schematic diagram of plasma regions of the earth’s magnetosphere as viewed in the noon–midnight meridian plane. The plasmasphere typically occupies much of the same region of space as the radiation belts. Frequently there is little or no gap between the inner edge of the plasma sheet and the outer boundary of the trapped radiation belts.
By examining data from the OGO 1 spacecraft, V. M. Vasyliunas found that the electron plasma sheet generally has a well-defined inner edge on the duskside; as indicated in the figure, the boundary is less distinct on the dawnside. The average distribution of kilovolt electrons in the inner magnetosphere is sketched in Figure 10.6. The tendency of
\[ \phi(x) = \int E \cdot ds \]

**FIG. 10.18.** Typical patterns of (a) Birkeland current, (b) electric field, (c) horizontal ionospheric current, and (d) \( E \times B \)-drift velocity observed in the earth's ionosphere, as viewed from high above the North Pole. Local noon is toward the top of the page, local dusk to the left, and so forth. These patterns represent the primary ionospheric effects of magnetospheric convection. The
But First: Single Particle Motion in E and B fields

- Lorentz Force
- 1st assume time independent fields
- Gyration
- ExB drift: charge and energy independent
- Grad-B drift: depends on both charge and energy
- Adiabatic invariants of the motion in a dipole field
Single particle motion in B field

Start with Lorentz Force

\[ m \frac{d\mathbf{v}}{dt} = q \mathbf{v} \times \mathbf{B} \]

Simple harmonic oscillator

\[ \omega_c = \frac{eB}{m} \]

\[ r_L = \frac{v_L}{\omega_c} = \frac{m v_L}{eB} \]

(Larmor radius)

Now add \( \mathbf{E} \) field and transform away \( \mathbf{E} \)

\[ \mathbf{E} \rightarrow \mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{\mathbf{c}} \]

\[ \mathbf{E} = -\mathbf{v} \times \mathbf{B} \]

\[ \mathbf{F} = 0 = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]

\[ \mathbf{v} \]

Gyration at \( \frac{eB}{m} \) drift at \( \mathbf{v}_d = \frac{\mathbf{E} \times \mathbf{B}}{\mathbf{c}^2} \)

in general any force \( \mathbf{F} \) (substitute \( \mathbf{F} = qE \))

\[ \mathbf{v}_d = \frac{\mathbf{F} \times \mathbf{B}}{qB^2} \quad \text{for force} \ \mathbf{F} \ \mathbf{B} \]
Non uniform $B$ \[\text{larger gyroradius}\]
\[\text{B out} \quad \text{V B} \quad \text{smaller gyroradius}\]

Acts like a particle slowing down when it moves into V B.

**Force** = $-\mu \text{V B}$  force on magnetic moment $\mu$

$\mu = \frac{E_L}{B} = \frac{1}{2} m v_L^2$  $= \text{current x area}$

assume $\alpha \propto \frac{1}{L}$  and $L \gg r_c$

**Guiding center equation**

$\textbf{V}_G = -U_{ii} \hat{b} + \frac{E x b}{B^2} - \frac{\mu \text{V B x B}}{q B^2} + \frac{B}{q B^2} \frac{M v_L^2}{B^2} (\hat{b} \cdot \textbf{V}) \hat{b}$

\[\text{ExB} \quad \text{Gradient drift} \quad \text{Curvature drift}\]
Curvature drift

force acts along radius of curvature

Note, when \( \Phi = 0 = \overline{A} \times \overline{B} \)
(e.g. single particle case)
then combine gradient + curvature drifts into one term

\[
\frac{e}{B^3} (\overline{\sigma} \times \overline{B}) \left( E_\perp + 2 E_{||} \right)
\]

\( E_\perp \equiv \frac{1}{2} m v_\perp^2 \quad E_{||} \equiv \frac{1}{2} m v_{||}^2 \)

Note this term is Charge Dependent
(unlike \( E \times B \) drift)

so Gradient/Curvature drift gives a CURRENT
Figure 1: Definition of the gyro-angle $\phi$ (a) and guiding center (b).
Next: Adiabatic invariants of motion

- Gyration
- Bounce
- Drift
- explains most repeated, energetic particle motions in the magnetosphere (e.g. radiation belts)