ESS 7
Lecture 13
April 30, 2010
Substorms
**Time Series of Images of the Auroral Substorm**

- This set of images in the ultra-violet from the Polar satellite shows changes that occur during an auroral substorm.
- In aurora substorms go through a series of stages.
- They start with a brightening of an auroral arc nearest the equator.
- Moments later the aurora brightens more, and expands poleward and to the west.
Substorm Auroras from the Ground

B. Freeman: "I captured this movie using a Sony digital 8 camcorder (night shot setting) and played it back at 2X speed to show more movement in a shorter time."
Oct. 1 2002
Eagle Hill, Alberta, Canada

spaceweather.com
Whack a Magnetosphere! (Two Substorms Associated with a Large Increase in Dynamic Pressure.)
The Discovery of the Substorm

• Soon after Akasufu discovered the auroral substorm in 1964 the search began to find the corresponding changes in the magnetosphere and the solar wind.

• The auroral activity is associated with currents in the ionosphere which create magnetic field changes.

• Much of the effort in studying substorms has been to define the solar-wind coupling parameters that can be used to predict the strength of magnetic activity.
A Digression on Field Aligned Currents

• There is one more major set of currents in the magnetosphere-field aligned or Birkeland currents
  – The field aligned currents extend from the magnetosphere to the ionosphere.
  – Region 1 currents are at high latitudes and flow into the ionosphere on the dawn side of the magnetosphere and out on the dusk side.
  – Region 2 currents at lower latitudes flow into the ionosphere on the dusk side and out on the dawn side.
Summary of Magnetospheric Currents

- Magnetopause currents
- Ring current
- Parallel currents
- Tail currents with magnetopause currents removed.

The red and blue currents occur during substorms.
Magnetic Observatories
Data from Magnetic Observatories

- There are over 500 observatories (250 in previous figure)
  - Data from so many sources is difficult to handle.
  - Indices have been generated to organize these observations.

- The primary sources of ground magnetic disturbances during substorms are the electrojets and the substorm current wedge.

- The sources of the midlatitude storm time variations ($D_{st}$) are the magnetopause current, the ring current and the partial ring current.
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Auroral Electrojet Indices

- Positive perturbations are produced by a concentrated current (called an auroral electrojet) flowing eastward. They are observed by stations in the afternoon or evening.
- Negative perturbations are produced by a westward electrojet. They are observed near and past midnight.
- These currents flow at ~120km altitude and are carried by auroral particles.
- The positive and negative envelopes give the AU and AL indices.
Ionospheric Currents in a Substorm

- The polar magnetic substorm is caused by two current systems (DP-2 and DP-1)
- DP-2 consists of two electrojets (east and west) flowing towards midnight
- DP-1 is a current system centered at local midnight that flows within the region of bright aurora
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Magnetic Signature

Canadian Space Agency data for the substorm of the movie. The current flowed over Hudson Bay. Figure out the direction using the right hand rule.

X is the northward part

Z (downward)
Substorms Occur when the Interplanetary Magnetic is Southward

- Correlation analysis between the auroral-electrojet index AE (difference between the envelop of positive -AU- and negative -AL- magnetic perturbations at auroral latitudes) and five solar wind parameters (u, n, B, B_n, B_s)
  - B_n is hourly average of the B_{ZGSM} magnetic field when B_{ZGSM}>0.
  - B_s is hourly average of the B_{ZGSM} magnetic field when B_{ZGSM}<0.

- Activity peaks in B_s for the hour prior to the hour when the activity was measured.

- AL/v^2 as a function of B_s (B_z<0) and B_n (B_z>0). No dependence on B_n but strong dependence on B_s.
Magnetospheric Substorms

- The phenomena associated with substorms in the magnetosphere start before the auroral signatures.

- McPherron interpreted these phenomena as the *growth phase* of the substorm.
  - Energy extracted from the solar wind is stored in the magnetosphere.
  - The initial interval of slowly growing AU and AL.
  - The growth phase usually lasts 30 minutes to one hour.
  - The magnetic perturbations during the growth phase results from increased ionospheric currents.

- The *expansion phase* corresponds to the release and unloading of the stored energy.

- The *recovery phase* is the return of the system to its ground state.
The Events in the Magnetosphere During a Substorm - Growth Phase

- A southward turning of the IMF initiates or increases dayside reconnection.
  - Magnetic flux from the Earth connects to the IMF and is transported over the polar caps into the lobes.
  - The return flow in the magnetosphere is unable to return flux to the dayside as fast as it is removed. The dayside magnetopause is eroded.

- The magnetic field in the tail lobes increases storing energy for later release.

- The plasma sheet thins.
Events in the Magnetosphere During a Substorm – The Late Growth Phase

Some time during the late growth phase reconnection begins on closed field lines in the near-Earth plasma sheet.

- The reconnection is slow at first.
- As closed field lines are cut they reconnect to form a magnetic O region called a plasmoid (technically a magnetic flux rope).
- This stage of the substorm continues until the last closed field line is severed by the reconnection process.
- The reconnection rate increases during the late growth phase.
Events in the Magnetosphere During Substorms – The Expansion Phase

- When the last closed field line is severed the reconnection rate becomes explosive. This is the onset of the expansion phase of the substorm.
  - The current “wedge” may occur at this time.
  - 20%-30% of the open magnetic flux stored in the tail lobes is rapidly reconnected.
  - This is the principal energy conversion process during substorms.
- The severed plasmoid leaves the magnetotail.
- If the reconnection fails to reach the lobe field lines the disturbance is quenched. This is called a pseudobreakup.
Events in the Magnetosphere During Substorms – The Recovery Phase

- The reconnection of open field lines forms closed field lines earthward of the X-line with strong earthward flows.
- Eventually the balance of forces in the plasma sheet changes and the X-line begins to move tailward.
- As the X-line moves toward its distant location, the currents and aurora begin to die at the lower edge of the auroral bulge. This is the beginning of the recovery phase.
- In time all the disturbances die away, the substorm is over, and the magnetosphere returns to its ground state.
The Events Described are Controversial

• The exact sequence of events just described is highly controversial – I’ve presented the most widely accepted picture but not the only one.
• All investigators agree that reconnection drives the system.
• Controversial parts of the sequence of events include whether the expansion phase is caused by reconnection or whether the cause of the expansion phase also causes the tail reconnection.
• In 2007 NASA launched a 5 spacecraft mission called THEMIS
Postions of the THEMIS Spacecraft During a Conjunction on March 1, 2008
Assignment

• Read Chapter 5
• Problems 4.4 and 4.6
• In the solar wind near Earth, the thermal pressure is about $10^{-11}$ Pa. We also know that there are usually about 10 ions/cm$^3$. Estimate the temperature of the solar wind

• Due May 7, 2010