# Lecture #15 Collisionless Magnetic Reconnection, Geomagnetic Storms and Substorms

## I. Inconsistency in Petschek Model for Magnetic Reconnection

### A. Sweet-Parker Compared to Petschek

1. For both theories, the current sheet thickness $\delta$ is set by resistivity $\eta$ and inflow velocity $U_i$, $\boxed{\delta = \frac{\eta}{\mu_0 U_i}}$
   a. Thus, for small resistivity $\eta$, current sheets are very thin!

2. a. For Sweet-Parker, current sheet length $L$ is set by external boundary conditions (flow geometry, system size, etc.).
   b. For Petschek, current sheet length $L \sim \delta$

3. Results of Numerical Simulations
   a. At intermediate resistivity $\eta$, Sweet-Parker geometry occurs, $L \sim \delta$.
   b. As resistivity is decreased, the current sheets become longer rather than shorter (as would be predicted by Petschek).
   c. Below some threshold value of $\eta$, reconnection becomes unsteady.
   d. Only with enhanced $\eta$ ("anomalous resistivity") is Petschek geometry observed.

4. Inconsistency with Petschek Model
   a. Petschek ignores or inappropriately treats diffusion region.
   b. Proper solution requires matching of ideal solution in external region and resistive solution in diffusion region.
   c. For small resistivity $\eta$, the Petschek solution does not match the diffusion layer
   d. Only with enhanced "anomalous resistivity" near the X-point does one obtain a Petschek solution.
   e. In general, non-steady reconnection for low $\eta$ makes analytical treatment difficult.

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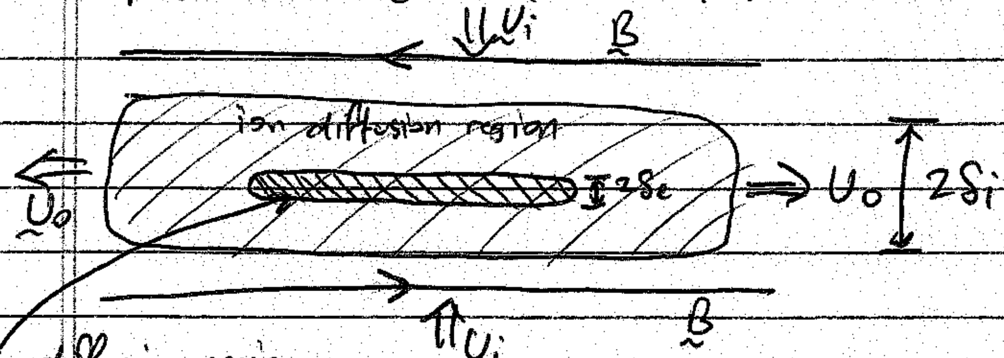
MHD is a <u>single-fluid model!</u>

I. B. 3-D, Collisionless Reconnection

1. Sweet-Parker & Petschek models are strictly MHD models.
2. In a weakly collisional plasma, relevant for magnetospheric and other astrophysical reconnection, MHD breaks down due to reconnection layers $\delta < \rho_s$, where $\rho_s$ is <u>ion sound Larmor radius</u>, $\rho_s \equiv \frac{\sqrt{T_e/m_i}}{\Omega_i}$.
3. For $\delta < \rho_s$, within the ion diffusion region, two-fluid effects become important
   a. The Hall term in Ohm's Law, responsible for <u>dispersive wave effects</u> at scales $l \lesssim \rho_s$ (<u>whistler</u> or <u>Kinetic Alfvén waves</u>), plays an important role in enabling faster reconnection rates (see GEM Reconnection Challenge).
   b. The diffusion region becomes structured, with different physics at characteristic ion & electron scales:




electron diffusion region
(where reconnection actually takes place!)

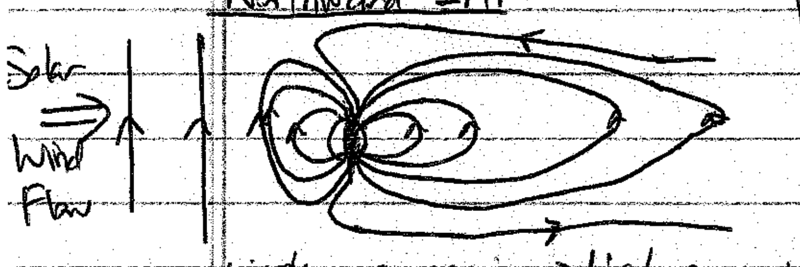
4. Three-Dimensional
   a. Sweet-Parker & Petschek Models are 2-D for antiparallel fields.
   b. Reconnection physics may be 3-D, with a possible guide magnetic field parallel to the current sheet flow.

# II. Geomagnetic Storms and Substorms

## A. Magnetospheric Activity

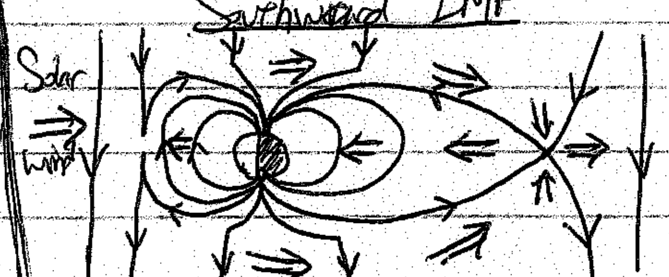
1. The magnetic field direction and magnitude in the solar wind is highly variable.
2. Activity in the magnetosphere is primarily driven by the amount of magnetic flux that undergoes reconnection at the dayside magnetopause.
3. a. The direction of the SW magnetic field with respect to the northward geomagnetic field is the primary controlling factor for magnetospheric activity
   b. The solar wind dynamic pressure, which relates to the convection electric field, also plays a role.
4. The magnetospheric convection (Lecture #12) is not steady:
   a. Prolonged periods of a northward interplanetary magnetic field (IMF) result in a quiet magnetosphere where convection essentially ceases.
   b. When a lot of magnetic flux merges on the dayside (usually during prolonged southward IMF), magnetospheric activity is strong.

Northward IMF




Little reconnection ⇒ little convection

Southward IMF




Significant reconnection ⇒ Strong convection

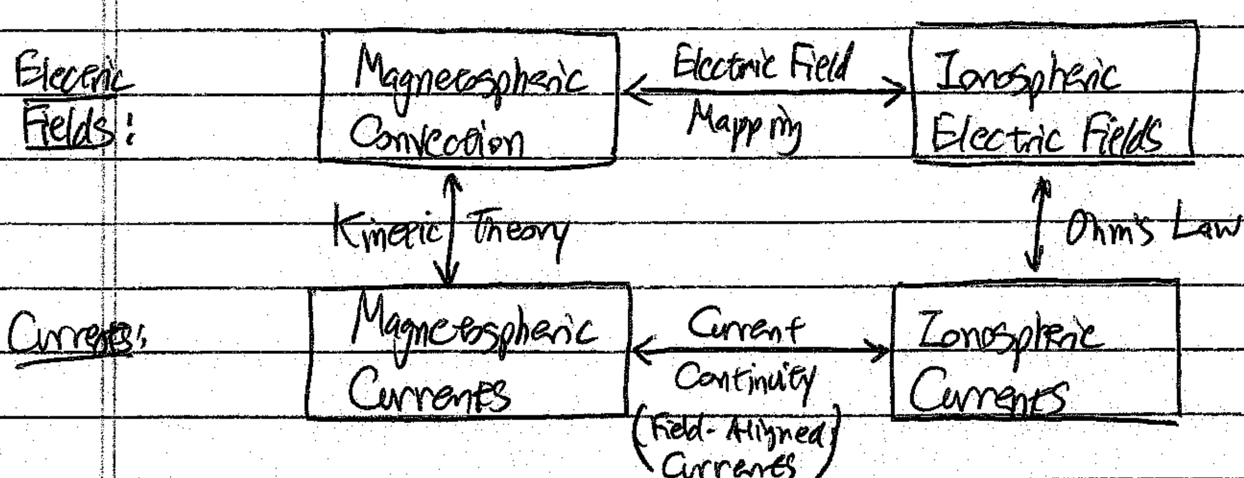
## B. Geomagnetic Storms and Substorms

1. A geomagnetic storm is large, prolonged disturbance of the magnetosphere & ionosphere.

II. B. (Continued)

2. Geomagnetic storms are caused by:
   a. Long periods (several hours or more) of Southward IMF
   -or- b. Interaction of coronal mass ejection (CME) with magnetosphere
3. Enhanced magnetospheric convection increases injection of high energy particles into the ring current
4. Dramatic increase of the ring current can lead to a large depression of the horizontal magnetic field at equatorial surface of several hundred nT (100's nT) that lasts from a few hours to one day
5. Geomagnetic storms typically consist of a series of "substorms" that follow a characteristic evolution over 3 hours.
   a. Isolated substorms can also occur that are not associated with a large geomagnetic storm—generally when IMF is southward for a shorter period (an hour or so, but not much more).

6. Magnetosphere – Ionosphere Coupling (M-I Coupling)




a. Coupling between electric fields and currents in the magnetosphere and ionosphere leads to a very complex system
b. Rice-Convection Model attempts to solve for the coupled M-I system in near equilibrium systems. → dynamic situations yet to be solved.

## II.C. Effects of Strong Geomagnetic Storms:

1. There are three major effects geomagnetic storms can cause:
   a. Increased density of very high energy particles in the radiation belts (penetrating radiation)
   b. Increased density of both trapped magnetospheric and ionospheric plasmas
   c. Significant changes of the Earth's surface magnetic field.

2. Increased radiation belt density:
   a. Damage to spacecraft instrumentation and electronics
   b. Harmful, and possible lethal, radiation doses for manned space exploration.

3. Increased plasma density:
   a. Since plasma frequency $\omega_{pe} = \left(\frac{n_e e^2}{\epsilon_0 m_e}\right)^{\frac{1}{2}}$, an increase in plasma density leads to an increase of plasma frequency
   b. Since radio waves cannot propagate through a plasma with $\omega < \omega_{pe}$, the increased plasma freq $\omega_{pe}$ can cut off radio communications.
   c. Geosynchronous satellites, such as communication & GPS satellites, can be cutoff from communication with Earth.
   d. Great-circle aircraft flights over the poles can lose radio communication due to enhanced upper atmosphere ionization.

4. Changes in Earth's Magnetic Field:
   a. Faraday's Law: $\nabla \times \underset{\sim}{E} = -\frac{\partial B}{\partial t}$

   When magnetic field changes, $\frac{\partial B}{\partial t}$ can induce a large EMF in a circuit.

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II. C.4. (Continued)

b. Closed circuits that encompass a large area can experience a very large inductive voltage → the Earth's magnetic field behaves like part of a transformer.

c. The electrical power grid, with closed loops consisting of electrical power lines, can encircle a large area, and may be susceptible to large voltages that can seriously damage components.

⇒ Carrington Event, 1859: Most powerful solar storm on record

1. Aurora seen globally, even down to the Caribbean
2. Telegraph systems in Europe and North America failed, shocking telegraph operators and causing fires in some locations.
3. Such an event today could cause hundreds of billions of dollars in damage, and could take years to fully recover.

d. Long distance pipelines may also experience large induced voltages.

5. a. In general, we are unprepared to handle the effects of a geomagnetic storm of similar magnitude to the Carrington Event.

b. It is not impossible that we could potentially experience an event of even greater magnitude (500 yr flood, anyone?).

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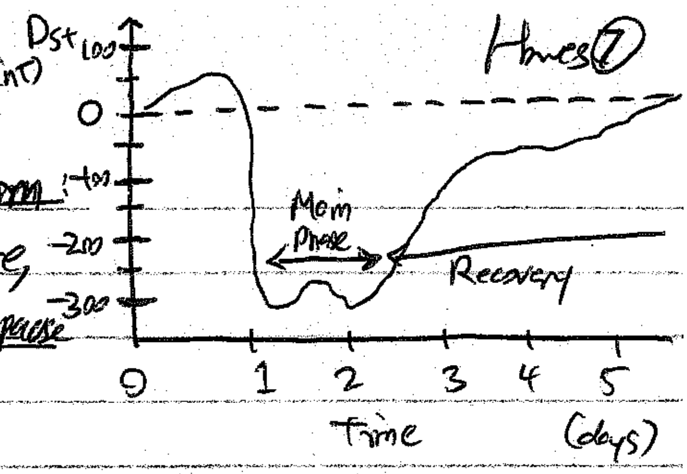
II. (Continued)




D. Anatomy of a Geomagnetic Storm

1. CME compresses magnetosphere, causing sudden increase of magnetopause current and increase in Dst (duration: 2–8 hours)
2. Southward component of IMF leads to increased dayside reconnection, allowing penetration of convection electric field and strong magnetospheric convection

Main Phase {
3. Enhanced duskward electric field increases injection of particles into ring current and earthward expansion of ring current ($r_{sp} = \frac{3W_\perp}{qE_c}$, lec#12)
4. Horizontal $\underline{B}$ at equatorial surface, or Dst, experiences a large depression of hundreds of nT (duration: few hours to 1 day)
}

5. When Southward component of IMF weakens or disappears, ring current decays.
   a. Reconnection rate decreases → Convection Electric field decreases
   b. Decreased injection of new ring current particles
   c. Convection boundary moves outward, $r_{sp} = \frac{3W_\perp}{qE_c}$
   d. Ionosphere fills expanding plasmasphere with cold ionospheric plasma, and energetic ring current ions are lost due to scattering by unstable growth of plasma waves.
6. This recovery phase typically takes several days.

E. Magnetic Substorms:

1a. Auroral manifestations known as auroral substorm
b. Magnetic signature known as polar magnetic substorm
c. Complete phenomenon: Magnetospheric Substorm { auroral, ionospheric, magnetospheric }

Lecture #15 (Continued)

II. E (Continued)

2. Substorms span ~ 3 hours:

~1h { a. Growth phase: Dayside reconnection and transport of flux to Tail
Stores energy in increased tail field, thinning plasma current sheet.

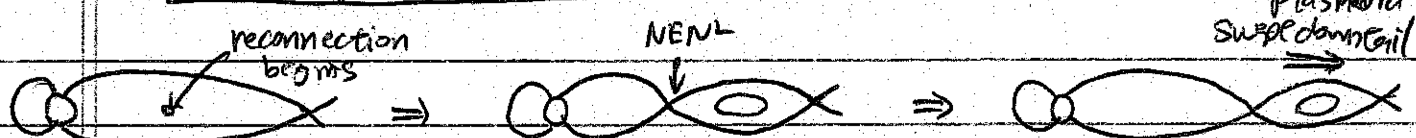
b. Substorm onset: Tail current becomes unstable and releases energy through reconnection.

~½ - 1 h { c. Expansion phase: Auroral activity increases dramatically, intensifying and moving westward from midnight and poleward.
Ionospheric current is greatly enhanced: auroral electrojet, substorm current wedge

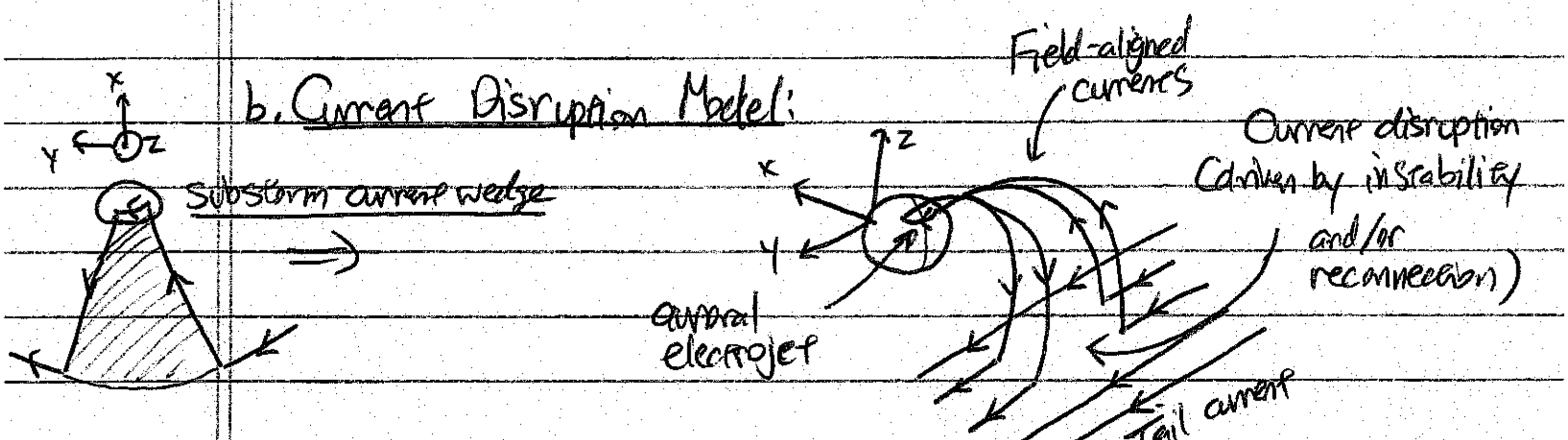
~1-2h { d. Recovery phase: Ionospheric current decreases and aurora dim, eventually returning to the quiet state.

3. Substorm Models:

a. Near Earth Neutral Line Model: (NENL)




b. Current Disruption Model:




c. Magnetosphere - Ionosphere Coupling Model:
Ionospheric feedback has important effect on substorm current wedge.