Lecture 3
Introduction to Magnetic Storms
• An isolated substorm is caused by a brief (30-60 min) pulse of southward IMF.

• Magnetospheric storms are large, prolonged disturbances of the magnetosphere caused by variations in the solar wind.
  – Many storms follow coronal mass ejections.
  – Storms also can be caused by high speed streams (interplanetary shocks).

• The impulse from the interplanetary disturbance impulsively compresses the magnetosphere.
  – The sudden compression rapidly increases the magnetopause current increasing the H- component of the magnetic field.
  – The *sudden commencement* can be seen in midlatitude magnetograms.
  – The rise time is a few minutes and corresponds to the propagation time of MHD waves from the magnetopause to the point of observations.
  – The compressive phase of the storm lasts 2 to 8 hours.
  – When not followed by the other phases of the storm this part is called a *sudden impulse*
• The ring current causes decreases the horizontal component of the magnetic field at the Earth’s surface.
• The disturbance storm time (Dst) index measures these differences.
• Note other currents (e.g. magnetopause currents also can contribute to Dst).

Sudden Commencement

Main Phase

Recovery Phase
• Extended periods (several hours) of southward IMF lead to the **main phase** of the magnetic storm.
  – Southward IMF leads to magnetic reconnection.
  – Northward IMF has only minimal dayside reconnection.

• The increased dayside reconnection increases the penetration of the solar wind into the magnetosphere.

• The enhanced duskward electric field increases the number of particles injected into the ring current.
  – Stronger electric fields lead to earthward expansion of the ring current region.
  – Heavy ionospheric particles also are added to the ring current population.
• The ring current will grow and $D_{st}$ will decrease ($\frac{\Delta \tilde{B}}{B_0} = -\frac{2}{3} \frac{W_{RC}}{W_{mag}} \hat{z}$) and approach a saturation level when particle sources and losses balance.

• A 100nT depression in the magnetic field is equivalent to $2.8 \times 10^{15}$J.

• The period during which the ring current increases is the **main phase**.
• As the southward component of the IMF weakens or disappears, the ring current starts to decay. This is the *recovery phase* of the storm.

• The recovery phase has several steps.
  - The reduction of the southward IMF causes the reconnection rate to decrease.
  - The reduction of the southward IMF results in a decreasing electric field, which leads to a reduction in the injection of new particles into the ring current.
  - The convection boundary moves outward.
– The ionosphere fills the depleted flux tubes within this expanded boundary with cold ionospheric particles.
– The interaction between the two plasma populations (hot ring current and cold ionospheric) causes plasma waves which scatter the ring current particles into the loss cone. This causes a loss of ion ring current particles.
– Another loss mechanism for ring current particles is charge exchange.
  □ Charge exchange occurs between energetic ring-current ions and cold hydrogen atoms.
  □ The result is energetic neutral atoms and cold ions.
  □ Detectors which can detect the energetic neutral atoms have been developed. They enable us to image the ring current in three dimensions.
– The result of the last two processes is a gradual decrease of the ring current over several days.

Energetic Ring Current Ion $\rightarrow$ Thermal Ion

Thermal Neutral Atom $\rightarrow$ Energetic Neutral Atom (leaves the system)
• During quiet times the solar wind provides ~65% of the ring current energy density and the ionosphere only ~35%. (H$^+$ dominant).

• During small and moderate storms the ionospheric contribution becomes ~50% (H$^+$ dominant).

• During intense storms ($D_{st}<-150$ nT) the ionospheric contribution increases to ~70%. (O$^+$ dominant).

• The O$^+$ dominance during intense storms is greater during solar maximum.
  - Increased solar EUV irradiation causes increased ionospheric and atmospheric scale heights which favors the escape of O$^+$.
  - Increased heating of neutral atmosphere and increased ionization rates.
• Ring current injection can be explained primarily in terms of inward transport of plasma sheet and pre-existing ring-current particles.

• None of the models currently includes the ionosphere.

• Diffusion has been used successfully to study the injection of radiation belt particles during a storm (see figure at the right). However, the diffusion calculations don’t seem to work for the lower energies of the ring current.
New Radiation Belt formed by October 2003 Magnetic Storm- SAMPEX observations

- The radiation belts are centered at about 4\(R_E\) and about 1.5\(R_E\).
- Storms can both decrease and increase the belts.
- The region between the belts is normally without particles.
- It filled with particles during the Halloween storm.

![SAMPEX: ELO/Electrons, 2-6 MeV](image_url)
• During magnetic storms precipitation of auroral particles expands toward lower latitudes.

• Intense red and green-line auroral emissions are found at the equatorward most part of the expanded auroral oval.
• Magnetic storms can be caused by high speed solar wind.

• On September 24, 1998 a strong interplanetary shock associated with a CME reached the Wind spacecraft 185R_E upstream of the Earth.
  – When this hit the Earth the pressure at the nose of the magnetosphere went from 2nPa to 15nPa.
  – The x-component of velocity was -900 km/s
  – The IMF initially was horizontal but after 2 hours it turned southward and a strong storm began.
A CIR Related Storm

- Usually the storms associated with high speed streams are smaller.
- This one had a Dst of -70nT.
- Note that the magnetic field oscillates.
An example – the Halloween Storm of 2003 (Baker et al., 2004)

• Top - Radiation belts over 12 years.
• Second – Blow up showing new radiation belt.
• Third - Blow up of new belt
  – Belts initially depleted at all L shells.
  – Regenerated to high levels in the slot.
• Bottom – Fluxes at various L-shells.
• Acceleration occurred during intense wave activity.
• For this storm Dst <-400
Plasmapause during Halloween storm

- He\(^+\) images of plasmasphere.
- During the storm the plasmapause moved from 4-5R\(_E\) to inside of 2R\(_E\)
- Plasmapause tracks well the inner edge of the radiation belts.
Acceleration of electrons (Shprits et al., 2006)

- Mechanisms for acceleration of relativistic electrons
  - Radial diffusion caused by ULF waves.
  - Local stochastic acceleration driven by VLF waves
  - Shock induced acceleration

- Loss mechanisms
  - Pitch angle scattering by EMIC waves, chorus outside the plasmapause and plasmaspheric hiss.
  - Inward gradients in phase space density due to particle loss at the magnetopause.
Electron and plasma wave observations

- top- 2-6MeV electron flux
- second- Log of compressional ULF wave power.
- third $K_p$ index
- bottom – Dst index
- ULF wave power was very high at the storm onset, it was very weak during slot region flux enhancement.
Effect of reduction in the ULF power

- Radial diffusion gives a monotonic increase in phase space density with L.
- At larger L diffusion dominates over losses and the phase space density becomes flat.
- At smaller L loses dominate over diffusion.
- A decrease in the rate of diffusion will move the diffusion dominated region outward.
- Radial diffusion cannot lead to increase in slot region.
- Acceleration by VLF waves excited outside of the compressed plasmasphere.
The Burton Equation [1975] - An empirical relationship between interplanetary conditions and Dst

- The rate of change of Dst is given by
  \[ \frac{d}{dt} Dst = -a \left\{ Dst - b \left[ P'(t) \right]^\frac{1}{2} + c \right\} + F \left[ E'(t) \right] + \frac{d}{dt} \left\{ b \left[ P'(t) \right]^\frac{1}{2} \right\} \]

  - First term gives ring current decay proportional to the ring current.
  - Second term describes ring current injections dependent on solar wind E field.
  - Third term describes changes in Dst resulting from changes in magnetopause currents.
  - E'(t) and P'(t) are measured at an upstream monitor not the magnetopause so a delay must be introduced.
  - Magnetospheric response may be frequency dependent – \( \mathcal{H}(\omega) \)
Parameters in the Burton et al., equation

- $a$ – measure of current decay
- $b$ – measure of response to dynamic pressure of solar wind
- $c$ – measure of quiet day currents
- $t_m$ – response time of the magnetosphere to applied E-field
- $H(\omega)$ frequency response of magnetosphere to the applied E-field
- $F(E)$ rate of ring current injection as a function of delayed and filtered E-field
- Recent version by Temerin and Li [2002].
  - $\text{Dst} = \text{dst}_1 + \text{dst}_2 + \text{dst}_3 + (\text{pressure term}) + (\text{IMF} \, B_z)$
  - $\text{Dst}(t+dt) = \text{dst}(t) + \text{driver term} - \text{decay term}$
The biggest storm (Li et al., 2006)

- An extremely bright solar flare occurred on September 1, 1859 and a very large magnetic storm followed.
- Magnetic field observations from Mumbai, India indicate that the H-component decreased by -1600nT.
- For smaller storms the H-component roughly gives Dst (Siscoe et al., 2006).
- Time from flare to the peak in the Mumbai magnetogram gives the velocity of the shock and empirical formulas give the speed of the ICME.
- B is inferred from global MHD simulations and relationship peak $B_{sh} = 0.08 (V_{\text{max}} - V_{SW})$ where $V_{SW}$ is the normal solar wind.
- Density uses normal shocked solar wind values.
Modeled Dst

- Added a large density plug following the shock to get rapid rise in Dst.