Recap and Space Weather
In the Magnetosphere (II)

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SW REDI

June 5, 2013
CME, Flares, and Coronal Hole HSS

The Sun: maker of space weather

Three very important solar wind disturbances/structures for space weather

- Radiation storm:
  - proton radiation (SEP) <flare/CME>
  - electron radiation <CIR HSS/CME>
- Radio blackout storm <flare>
- Geomagnetic storm:
  - CME storm (can be severe)
  - CIR storm (moderate)
Outline

• Solar wind + magnetosphere interactions
• CIR/HSS and CME impacts on Earth
• Importance of magnetosphere in space weather

Geomagnetic storm
  o CME storm (can be severe)
  o CIR storm (moderate)
The solar wind pushes and stretches Earth’s magnetic field into a vast, comet-shaped region called the magnetosphere. The magnetosphere and Earth’s atmosphere protect us from the solar wind and other kinds of solar and cosmic radiation.
Two Main Drivers for the Magnetosphere

- CME (you have seen plenty of them already)
- CIR (Corotating Interaction Region) High Speed solar wind Stream (HSS)

Geomagnetic storm
- CME storm (can be severe) Kp can reach 9
- CIR storm (moderate) Kp at most 6
CME Example

• March 7, 2012 CMEs associated with two x-class flares

iSWA layout

Associated with an Active Region
CME from Filament eruption

Northeast (upper left) quadrant starting around 19:00 UT on Feb 10, 2012

A movie
The associated CME

STEREO B

SOHO

STEREO A

Heart-shaped
Is one important space weather contributor too!
Particularly for its role in enhancing electron radiation levels near GEO orbit and for substantial energy input into the Earth’s upper atmosphere.
May be more hazardous to Earth-orbiting satellites than CME-related magnetic storm particles and solar energetic particles (SEP).
Co-rotating Interactive Regions (CIRs) are regions within the solar wind where streams of material moving at different speeds collide and interact with each other. The speed of the solar wind varies from less than 300 km/s (about half a million miles per hour) to over 800 km/s depending upon the conditions in the corona where the solar wind has its source. Low speed winds come from the regions above helmet streamers while high speed winds come from coronal holes.

As the Sun rotates these various streams rotate as well (co-rotation) and produce a pattern in the solar wind much like that of a rotating lawn sprinkler. However, if a slow moving stream is followed by a fast moving stream the faster moving material will catch-up to the slower material and plow into it. This interaction produces shock waves that can accelerate particles to very high speeds (energies).
Figure 6. Schematic illustrating 2-D corotating stream structure in the solar equatorial plane in the inner heliosphere (from Pizzo, 1978).
Forecasting capability enabled by ENLIL

WSA+ENLIL+cone
Predicting impacts of CMEs

WSA+ENLIL
Modeling and predicting the ambient solar wind
In-situ signatures of CME and CIR HSS at L1

ACE and WIND
Electron radiation may be more hazardous to Earth-orbiting satellites than ICME-related magnetic storm particles and solar energetic particles.
Aug 3, 2010
Schematic of the three-dimensional structure of an ICME and upstream shock
Textbook example of ICME in-situ signature

- Shock
- Sheath
- Magnetic cloud
In-Situ signature can be quite complex

1: shock only
2: shock+sheath
3: shock+sheath+MC
4: ejecta?
5: ejecta?
6: MC only
Locating the CIR interface

- increase of solar wind speed
- pile-up of total perpendicular pressure (Pt) with gradual decreases at both sides from the Pt peak to the edges of the interaction region
- velocity deflections
- increase of proton number density
- enhancement of proton temperature
- increase of entropy,
- compression of magnetic field.

Jian et al., 2006 Solar physics
McPherron et al., 2009, JASTP
Figure 3. Superposed epoch plots of selected 1-hour averaged solar wind parameters for 23 CIRs containing abrupt stream interfaces. The flow angle is the azimuthal (east-west) flow angle and the sign convention is that negative flow angles correspond to flow in the direction of planetary motion about the Sun (westward) (from Gosling et al., 1978).

Both CME and CIRs are capable of generating geomagnetic storms. Differs in

Table 1. A Summary of Some of the Important Differences Between CME-Driven Storms (Shock, Sheath, Ejecta, Cloud) and CIR-Driven Storms (CIR, High-Speed Stream)

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>CME-Driven Storms</th>
<th>CIR-Driven Storms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase of the solar cycle when dominant</td>
<td>solar maximum</td>
<td>declining phase</td>
</tr>
<tr>
<td>Occurrence pattern</td>
<td>irregular</td>
<td>27-day repeating</td>
</tr>
<tr>
<td>Calm before the storm</td>
<td>sometimes</td>
<td>usually</td>
</tr>
<tr>
<td>Solar energetic particles (SEP)</td>
<td>sometimes</td>
<td>none</td>
</tr>
<tr>
<td>Storm sudden commencement (SSC)</td>
<td>common</td>
<td>infrequent</td>
</tr>
<tr>
<td>Mach number of the bow shock</td>
<td>moderate</td>
<td>high</td>
</tr>
<tr>
<td>$\beta$ of magnetosheath flow</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Plasma-sheet density</td>
<td>very superdense</td>
<td>superdense</td>
</tr>
<tr>
<td>Plasma-sheet temperature</td>
<td>hot</td>
<td>hotter</td>
</tr>
<tr>
<td>Plasma-sheet $O^+/H^+$ ratio</td>
<td>extremely high</td>
<td>elevated</td>
</tr>
<tr>
<td>Spacecraft surface charging</td>
<td>less severe</td>
<td>more severe</td>
</tr>
<tr>
<td>Ring current (Dst)</td>
<td>stronger</td>
<td>weaker</td>
</tr>
<tr>
<td>Global sawtooth oscillations</td>
<td>sometimes</td>
<td>no</td>
</tr>
<tr>
<td>ULF pulsations</td>
<td>shorter duration</td>
<td>longer duration</td>
</tr>
<tr>
<td>Dipole distortion</td>
<td>very strong</td>
<td>strong</td>
</tr>
<tr>
<td>Saturation of polar-cap potential</td>
<td>sometimes</td>
<td>no</td>
</tr>
<tr>
<td>Fluxes of relativistic electrons</td>
<td>less severe</td>
<td>more severe</td>
</tr>
<tr>
<td>Formation of new radiation belts</td>
<td>sometimes</td>
<td>no</td>
</tr>
<tr>
<td>Convection interval</td>
<td>shorter</td>
<td>longer</td>
</tr>
<tr>
<td>Great aurora</td>
<td>sometimes</td>
<td>rare</td>
</tr>
<tr>
<td>Geomagnetically induced current (GIC)</td>
<td>sometimes</td>
<td>no</td>
</tr>
</tbody>
</table>

Two major types of solar wind-magnetosphere interactions

Southward IMF

Northward IMF
The Earth’s Magnetosphere
The Earth’s Magnetosphere

**Inner Magnetosphere:**
Up to ~ 10Re

- **Van Allen Belts:** 400 keV – 6 MeV
- **Plasmasphere:** 1-10 eV
- **Ring Current:** 1-400 keV

**Plasmasphere:**

**Van Allen Belts:**

**Magnetopause:**

**Magnetosheath:**

**Solar Wind:**

**Tail Lobe:**

**Current Sheet:**

**Plasma Mantle:**
Magnetic Storms

- Most intense solar wind-magnetosphere coupling
- Associated with solar coronal mass ejections (CME), coronal holes HSS
- IMF Bz southward, strong electric field in the tail
- Formation of ring current and other global effects

- Dst measures ring current development
  - Storm sudden commencement (SSC), main phase, and recovery phase
  - Duration: days
Substorms

- Instabilities that abruptly and explosively release solar wind energy stored within the Earth’s magnetotail.
- Manifested most visually by a characteristic global development of auroras
- Last ~ hours
Kp: measure of storm intensity

"planetarische Kennziffer" (= planetary index).

- Geomagnetic activity index
  - range from 0-9 disturbance levels of magnetic field on the ground - currents

1. Non-event - period of 12/01/2010 – 12/7/2010
2. Moderate event – April 5, 2010

Geomagnetic Storm classification

- [http://www.swpc.noaa.gov/NOAAscales/index.html#GeomagneticStorms](http://www.swpc.noaa.gov/NOAAscales/index.html#GeomagneticStorms)

- Operational world
Dst: Disturbance of Storm Time

Measure of Storm Intensity

CIR storm at most: Dstmin ~ -130 nT
CME storm: Dstmin ~ -600 nT

1989 March 14 Dstmin= -589 nT
Geomagnetic Storm Classification
Research

Example 30-Day Dst Plot for the 2003 Halloween Storm

Atmospheric and Environmental Research

Storm Classification by Shaded Regions

quiet to mild storm
moderate storm
intense storm
super storm

(nT)

5 7 10 13 16 19 22 25 28 31 1 3
Inner magnetosphere plasmas

- **Plasmasphere**
  - 1-10 eV ions
  - Ionospheric origin
- **Ring current**
  - 1-400 keV ions
  - Both ionospheric and solar wind origin
- **Outer radiation belt**
  - 0.4-10 MeV electrons
  - Magnetospheric origin

Inner magnetosphere: Gigantic Particle accelerator
RB: Current understanding

Electron acceleration in the outer radiation belt

1. Substorm injection and inward diffusion
   ~1–300 keV electrons

2. Gyro-resonant Wave acceleration

3. Inward diffusion

3. Outward diffusion
   ~MeV electrons

Horne et al., 2007, Nature Physics
2.1. Importance of waves in radiation belt dynamics

In the basically collisionless plasma of the magnetosphere, changes in the energetic electron and ion populations are mainly controlled by interactions with a variety of plasma waves, which lead to violation of one or more of the particle adiabatic invariants. Such interactions lead to various effects such as pitch-angle scattering and precipitation loss to the atmosphere, heating and acceleration of particles by the absorption of wave power, as well as radial transport across L-shells. Our ability to accurately model the dynamic variability of the radiation belts during geomagnetically active periods requires a very thorough and detailed description of the global power and polarization of all the important plasma waves in the magnetosphere, as well as their variability due to changes in either solar wind forcing or geomagnetic activity.

The distribution of plasma waves that control ring current and radiation belt dynamics is mainly determined by a combination of the hot and cold plasma motion and distributions, and is shown schematically in Figure 1. These include chorus, plasmaspheric hiss, magnetosonic, and EMIC waves, each of which impacts the dynamics of the radiation belts in a different way, and since the distributions and spectral characteristics of each of these waves evolve during the course of a geomagnetic storm, the net balance of their various effects varies accordingly.

Figure 1: Schematic diagram showing the spatial distribution of important waves in the inner magnetosphere, in relation to the plasmasphere and the drift-paths of ring-current (10–100 keV) electrons and ions and relativistic (>0.5 MeV) electrons.
Van Allen Probes: current mission on radiation belt dynamics

Courtesy: Baker et al.
Three-Belt Structure

Quiet-time phenomenon

Energetic electron data from the Relativistic Electron-Proton Telescopes (REPT) on the Van Allen Probes
Different impacts on RB

CME vs CIR storms

• CME geomagnetic storms: RB flux peak inside geosynchronous orbit. The peak locations moves inward as storm intensity increases

• CIR geomagnetic storms: More responsible for the electron radiation level enhancement at GEO orbit
Click the check boxes to toggle series visibility

HSS and radiation belt electron flux enhancement

GOES data of energetic electron fluxes

ACE measurements of Solar Wind Speed

Bulk Speed

Zoom: In Out full Pan: left right

E > 0.8 MeV  E > 2.0 MeV
CME (superstorm condition) impact on RB

Halloween storm

Carrington-like superstorm
CME (superstorm condition) impact on RB

Shprits et al., 2011, Space Weather
CIR HSS: usually long-duration (3-4 days)
- Radiation belt electron flux enhancement
- Surface charging
- Geomagnetic disturbances (moderate at most)
- Heating of upper atmosphere: satellite drag

Energetic electron radiation: (the >0.8 MeV electron flux exceeding $10^5$ pfu alert threshold): takes 2-3 days from the CIR interface

Although geomagnetic activity (due to CIR HSS) during the declining and minimum phases of the solar cycle appears to be relatively benign (especially in comparison to the dramatic and very intense magnetic storms caused by interplanetary coronal mass ejections (ICMEs) that predominate during solar maximum), this is misleading. Research has shown that the time-averaged, accumulated energy input into the magnetosphere and ionosphere due to high speed streams can be greater during these solar phases than due to ICMEs during solar maximum!
Homework

March 1, 2011 high speed streams, find out the time of arrival and examine its behavior in terms of speed and density profile, IMF characteristics, when the >0.8 MeV energetic electron flux at GOES started to exceed $10^5$ pfu?

Do the same for the June 4, 2012 HSS

You can do the homework using this iSWA layout for HSS
Homework

Find all Kp >= 6 times for the year 2013

(Challenging one - optional: and the potential cause of Kp >= 6 – CME, CIR HSS or combination, or others)

Has the magnetopause stand-off distance been smaller than 6.6 Re (Re: Earth radii), i.e., magnetopause been pushed inside geosynchronous orbit? when? (year 2013)

The periods when GOES > 0.8 MeV electron flux exceeding 10^5 pfu (year 2013)

Iswa layout for homework
http://1.usa.gov/191s6AU
1. Find when GOES > 10 MeV proton flux exceeding 10 pfu in 2013

Those who like challenges
2. Find when 13-100 MeV proton flux at STEREO A exceeding 0.1pfu/MeV in 2013
3. Do the same for STEREO B

Iswa layout to help you with the homework questions
http://1.usa.gov/15Eov7s
magnetospheric products
"planetarische Kennziffer" ( = planetary index).

- Geomagnetic activity index
  range from 0-9 disturbance levels of magnetic field on the ground - currents

1. Non-event - period of 12/01/2010 – 12/7/2010
2. Moderate event – April 5, 2010


NASA/GSFC, internal use only :-(
Click the check boxes to toggle series visibility

HSS and RBE flux enhancement

E > 0.8 MeV  E > 2.0 MeV  Zoom: In Out  Pan: left right

Bulk Speed  Zoom: In Out  Pan: left right
Magnetopause stand-off distance
delineating the boundary between SW and Earth’s magnetosphere

- $r_0 \leq 6.6$ Re – model product
  - **Events:** Dec 28, 2010
  - Jan 7, 2010 $kp=5$ at 22:30 UT on 1/6/2011
  - **Non-event:** Dec 1 – 7, 2010

Degree of compression of MP
Due to $P_{dyn}$ of solar wind
(interplanetary shock /HSS)
An iSWA layout for magnetospheric products