The Sun
maker of space weather

CME, Flares, and Coronal Hole HSS

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)
Flare: SWx impacts

• Cause radio blackout through changing the structures/composition of the ionosphere (sudden ionospheric disturbances) – x ray and EUV emissions, lasting minutes to hours and dayside

• Affect radio comm., GPS, directly by its radio noises at different wavelengths

• Contribute to SEP – proton radiation, lasting a couple of days
Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. The strength of the event was especially surprising since the solar radio bursts occurred near solar minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.

• Contribute to SEP (particle radiation): 20-30 minutes from the occurrence of the CME/flare
• Result in a geomagnetic storm: takes 1-2 days arriving at Earth
• Result in electron radiation enhancement in the near-Earth space (multiple CMEs): takes 1-3 days

Affecting spacecraft electronics – surfacing charging/internal charging, single event upsets
Radio communication, navigation
Power grid, pipelines, and so on
The Inner Heliosphere

This is the region between the Sun and Jupiter that is filled with outflowing, supersonic solar wind and frozen-in spiraling magnetic fields—the Parker Spiral. The streams of solar plasma evolve significantly as they pass through this region, where fast streams of solar wind plough into slower-moving streams, forming shocks. Transients, such as CMEs, reshape the ambient environment. Some CMEs move faster than the local solar wind, building up high-density fronts that form shocks where particles are accelerated to extremely high energies. CMEs can expand as they move outwards, leaving low-density regions behind the propagating front.

Electrons flow along the large-scale magnetic field lines, thus producing radio bursts of various types, showing which field lines remain connected back to the Sun and which ones have reconnected. Because of the spiral nature of the fields, Earth is better connected to the western hemisphere of the Sun; thus an event near the west limb of the Sun is more likely to be geoeffective than one in the eastern hemisphere. Photons take only eight minutes to arrive at Earth from the Sun, and high-energy protons can be detected a few minutes later, whereas material from a CME event seen on the Sun may take up to three days to arrive.

Geospace

Earth’s magnetic field acts as a barrier to most of the harmful particle fluxes originating from the Sun. Much of the solar wind is deflected around the magnetosphere, which forms a teardrop-shaped shield around Earth. The shape and size of the magnetosphere change as solar wind conditions vary. Earth’s magnetic field is compressed within about 10 Earth radii ($R_E$) on the sunward side of the planet and stretched out by many tens of $R_E$ on the anti-sunward side.
Outline

• Solar wind +magnetosphere interactions
• CIR and HSS impacts on Earth
• Importance of magnetosphere in space weather
• Importance of ionosphere in space weather
• **Mysteries of the Sun**
• Watch the video on ‘Earth’s magnetosphere’

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.
The Earth’s Magnetosphere

Inner Magnetosphere:
Up to ~ 10Re
"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


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Is one important space weather contributor too!
Particularly for its role in enhancing electron radiation levels in the near-Earth environment 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.
Figure 6. Schematic illustrating 2-D corotating stream structure in the solar equatorial plane in the inner heliosphere (from Pizzo, 1978).
Coronal Hole HSS

Mar 1, 2011

June 4, 2012
Forecasting capability enabled by ENLIL

WSA+ENLIL+cone
Predicting impacts of CMEs

WSA+ENLIL
Modeling and predicting the ambient solar wind
Dense (20-30 cc), HSS

IMFBz: -18 nT

Clean HSS

may be more hazardous to Earth-orbiting satellites than ICME-related magnetic storm particles and solar energetic particles

Electron radiation
Click the check boxes to toggle series visibility

 GOES data of energetic electron fluxes

ACE measurements of Solar Wind Speed

HSS and radiation belt electron flux enhancement
Various types of waves that are important to RB dynamics.
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>

Solar Cycle

Timeline of Solar Cycles over 400 Years

23+ Solar Cycles

high and low sunspot activity that repeats about every 11 years

Sunspots have been observed and recorded since Galileo's time in 1610. But it wasn't until 1849 that the Zurich Observatory started a continuous daily record. From these early observations scientists have been able to construct a timeline of solar cycles that spans more than 400 years.

While early observations were not as extensive, well-documented records show a period of very few sunspots (a prolonged sunspot minimum) from 1645 to 1715, which is called the Maunder Minimum. This period corresponds to the "Little Ice Age," when temperatures across the Northern Hemisphere plunged and alpine glaciers extended over farmland, sea ice extended from the Arctic, and even canals in the Netherlands froze.

NASA scientists are continuing to study the links between solar activity and climate, and understanding the Sun's natural variations is key to these ongoing climate studies. NASA missions continue to collect data about the Sun's activity and variability to help us better understand the extent to which solar activity is influencing present-day climate change.

The Solar & Heliospheric Observatory (SOHO)

The Solar & Heliospheric Observatory (SOHO), launched in 1995, captures images of the Sun every 12 minutes. Scientists can now view images of the Sun through an entire solar cycle.

The graph on the slide shows the smoothed sunspot number prediction from 2010 to 2019, with observed data through April 2012. The graph indicates two types of storms: CME storms and CIR storms.
SWx consequences of CIR HSS

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!
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?

June 4, 2012 HSS

You can do the homework using this iSWA layout for HSS
The importance of magnetosphere and ionosphere in SWx
Magnetosphere and magnetospheric products
The Earth’s Magnetosphere
"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


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Click the check boxes to toggle series visibility

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

HSS and RBE flux enhancement

Bulk Speed Zoom: In Out full Pan: left right
Energetic proton flux

• >10 MeV flux by GOES spacecraft

Threshold: 10 pfu
  – Non–event Dec 1 – 7, 2010
  – Event: Aug 14 – 18, 2010

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• r0 <= 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
Videos

• **Mysteries of the Sun**

• Watch the video on ‘Earth’s upper atmosphere’
Ionosphere-Thermosphere

- Aurora – hemispheric power
- Satellite drag due to neutrals
- Equatorial bubbles/irregularities – scintillation, communication problems


Products demo

Auroral power
Auroral oval
TEC map
CTI Pe products
HF absorption map

Scintillation index S4

An iSWA layout for ionosphere products

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• plasma bubbles: typical east–west dimensions of several hundred kilometers
  – contain irregularities with scale-lengths ranging from tens of kilometers to tens of centimeters (Woodman and Tsunoda). Basu et al. (1978) showed that between sunset and midnight, 3-m scale irregularities that cause radar backscatter at 50 MHz, co-exist with sub-kilometer scale irregularities that cause VHF and L-band scintillations. After midnight, however, the radar backscatter and L-band scintillations decay but VHF scintillations caused by km-scale irregularities persist for several hours.