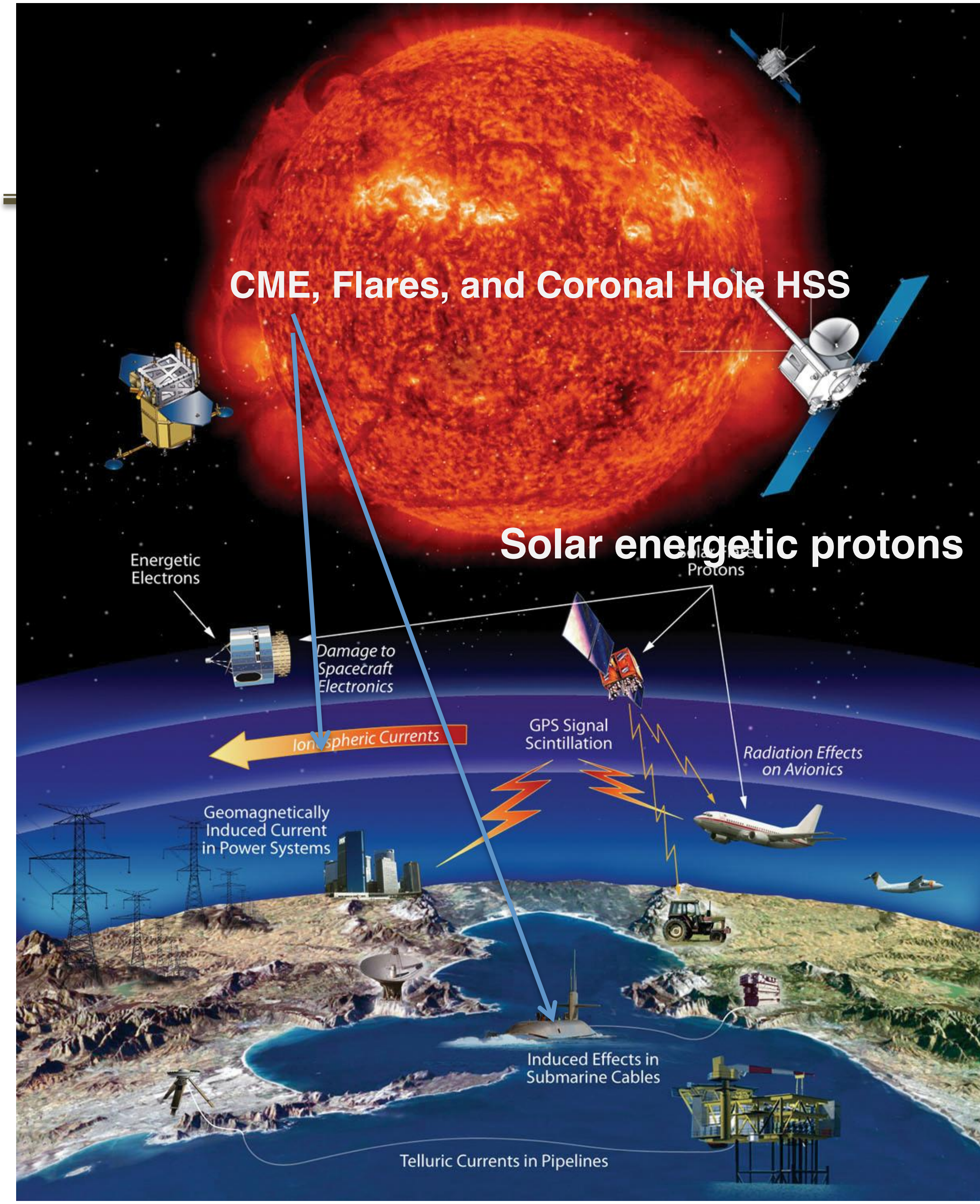
Recap and Space Weather In the Magnetosphere (II)

Yihua Zheng

SW REDI

June 5, 2013



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)**

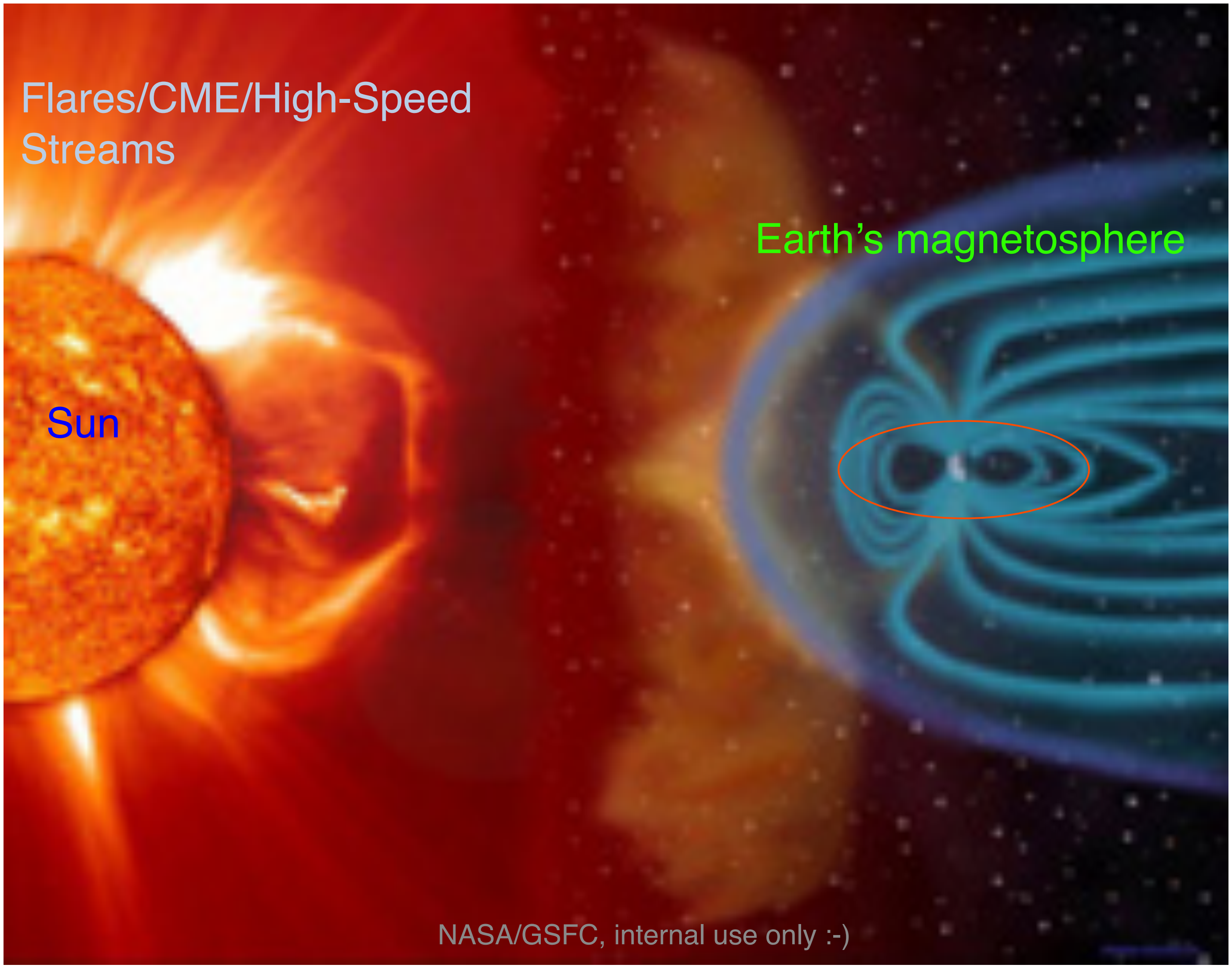
Outline

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

Geomagnetic storm

- **CME storm (can be severe)**
- **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

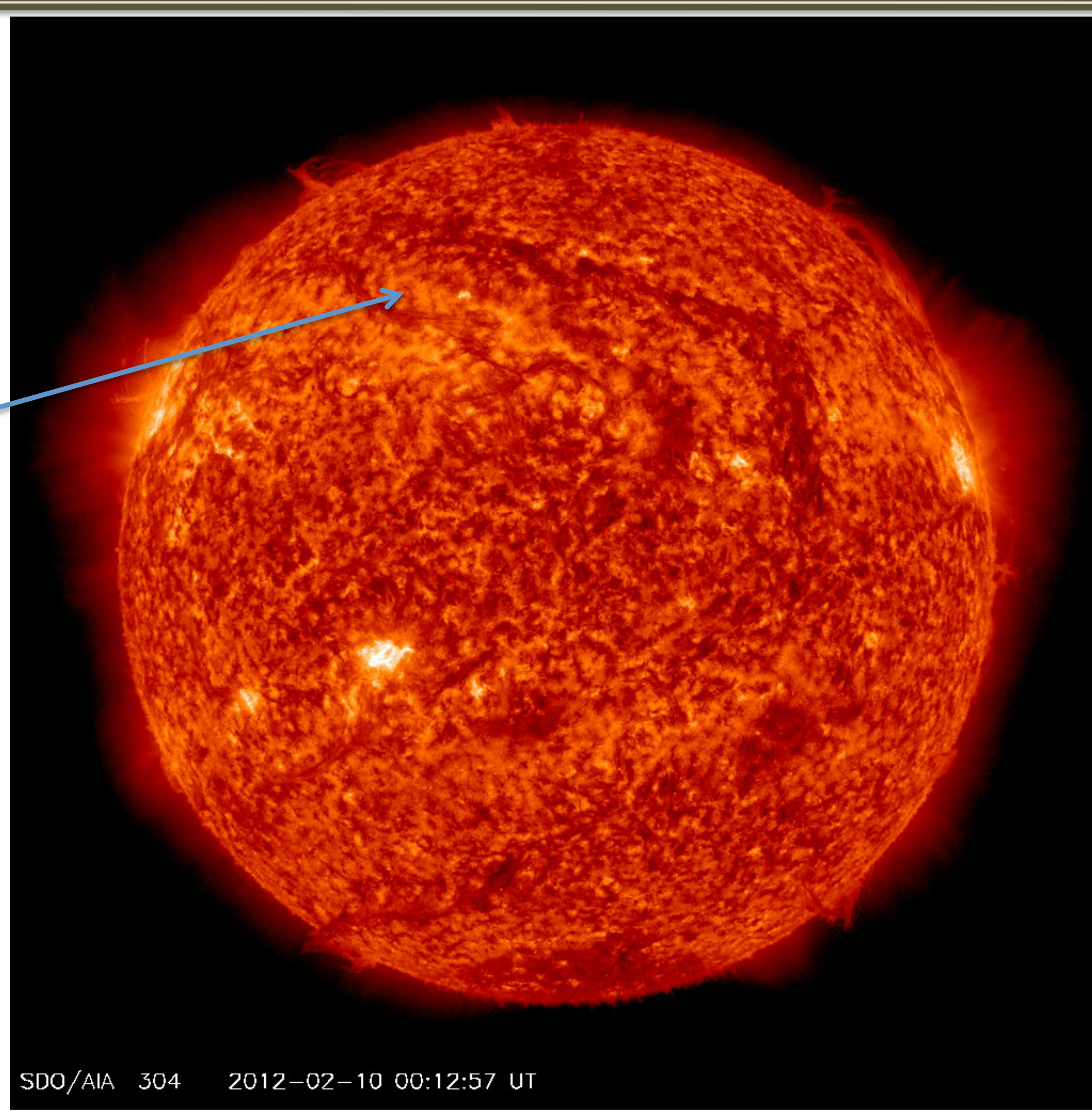
  iSWA layout

Associated with an Active Region

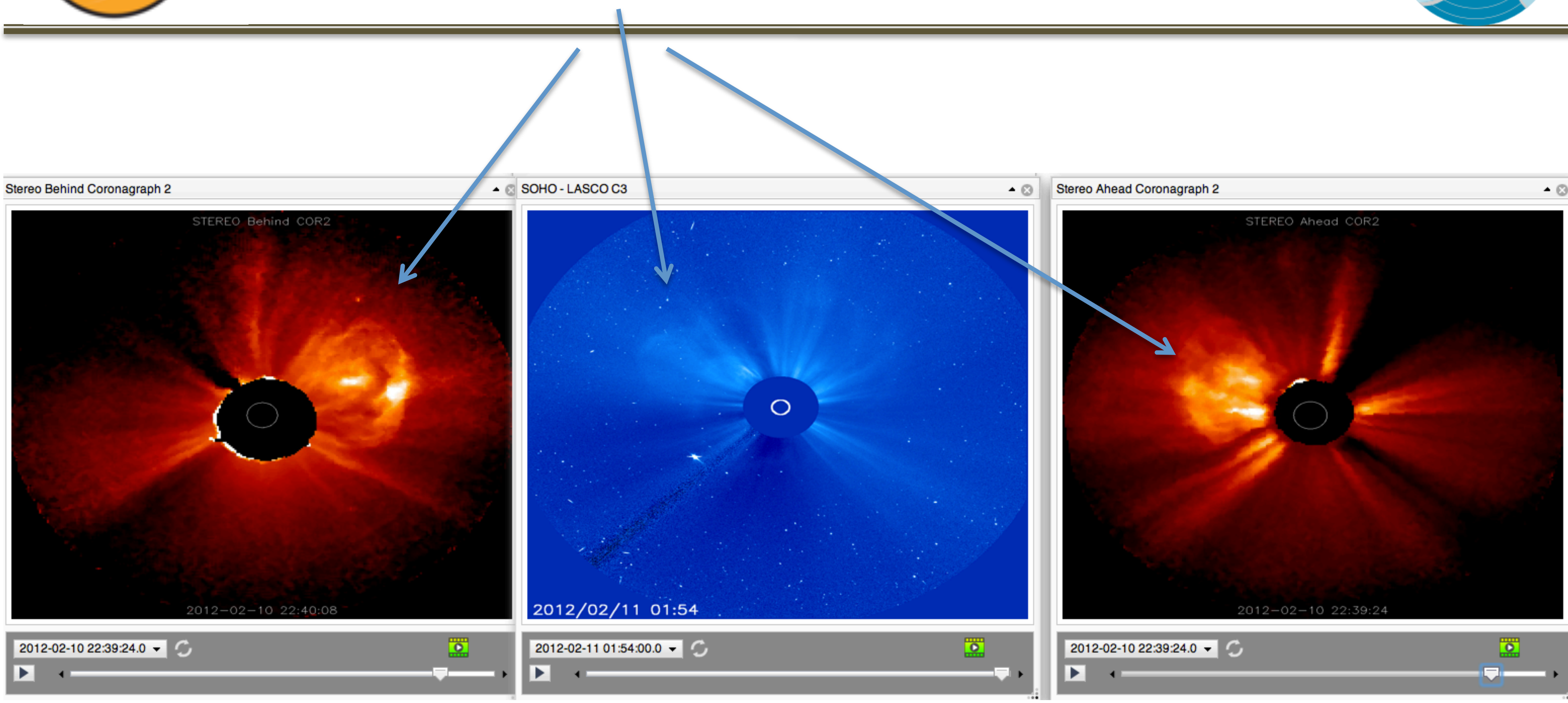
CME from Filament eruption

A movie

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



The associated CME



STEREO B SOHO STEREO A

Heart-shaped

Coronal Hole HSS

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)

CIR and HSS

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).

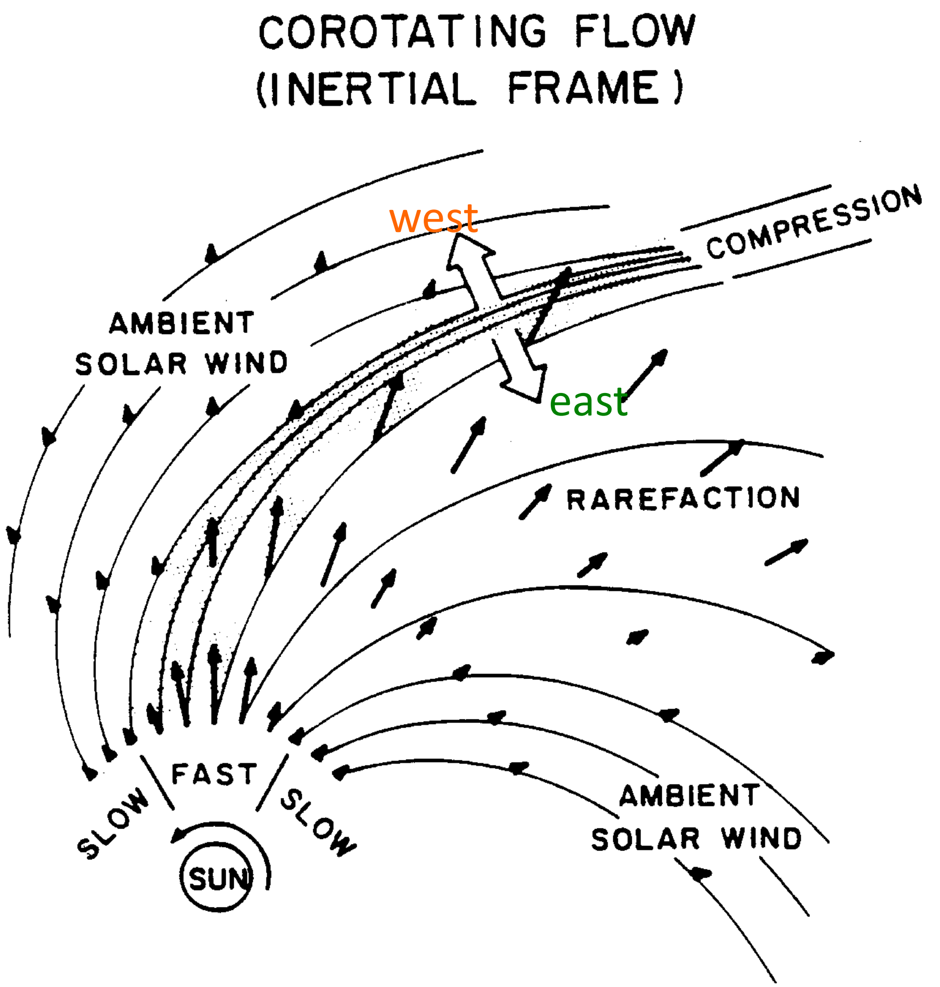
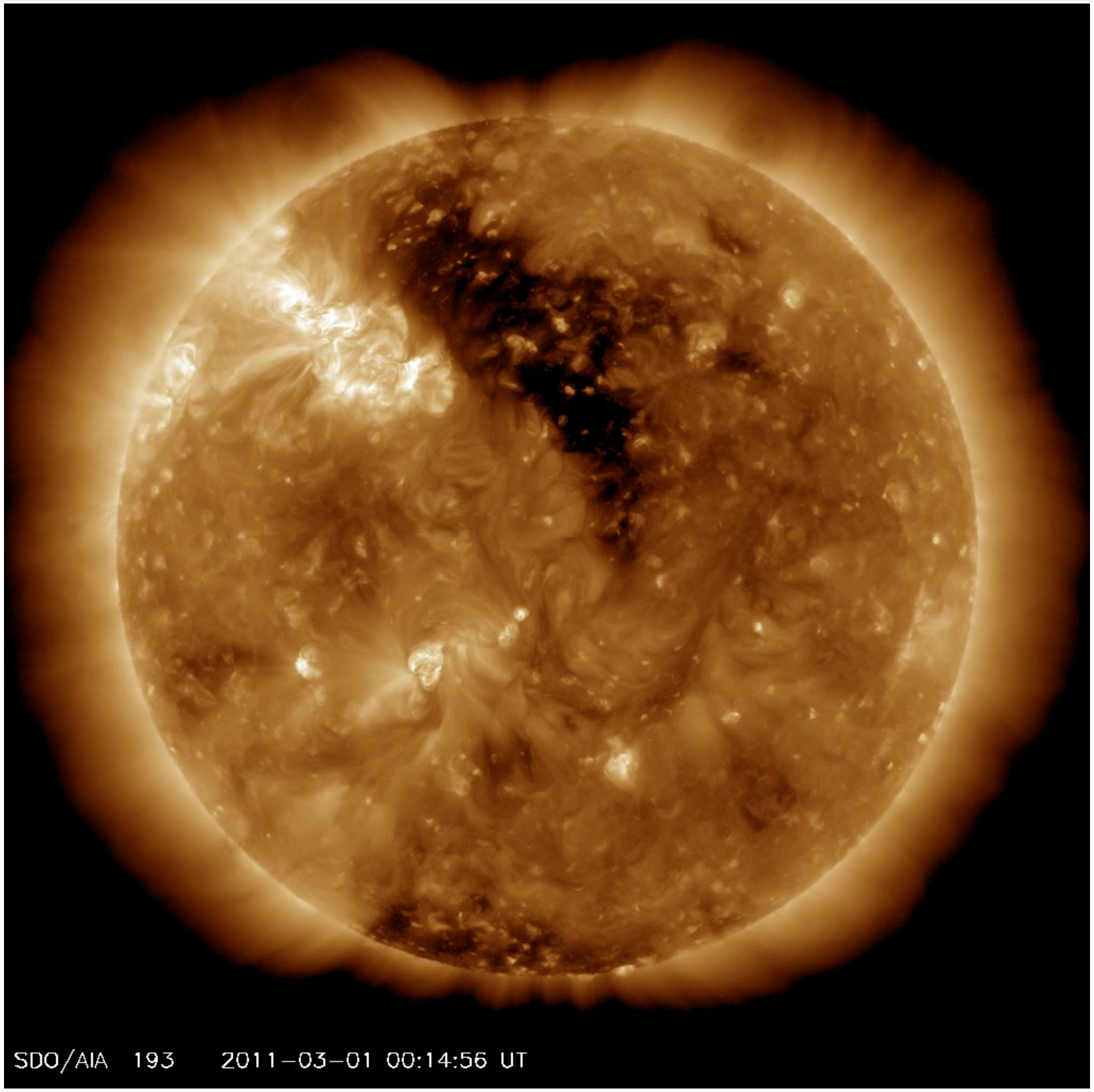


Figure 6. Schematic illustrating 2-D corotating stream structure in the solar equatorial plane in the inner heliosphere (from Pizzo, 1978).

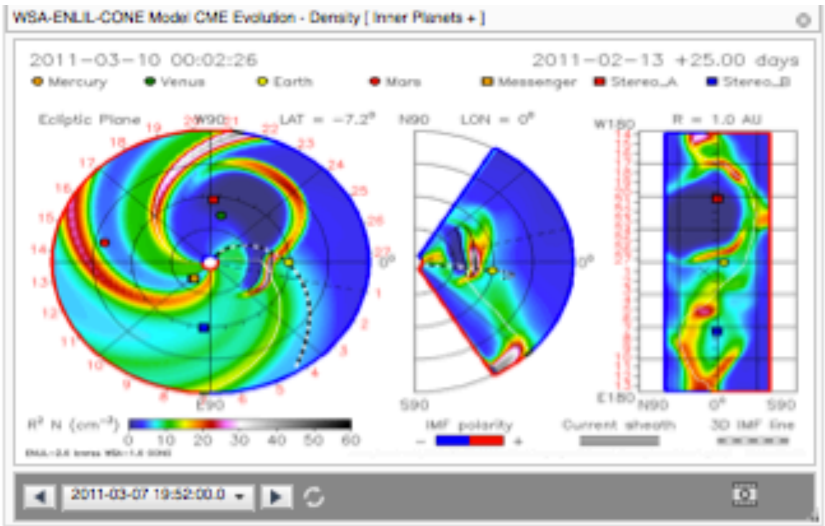
Coronal Hole HSS

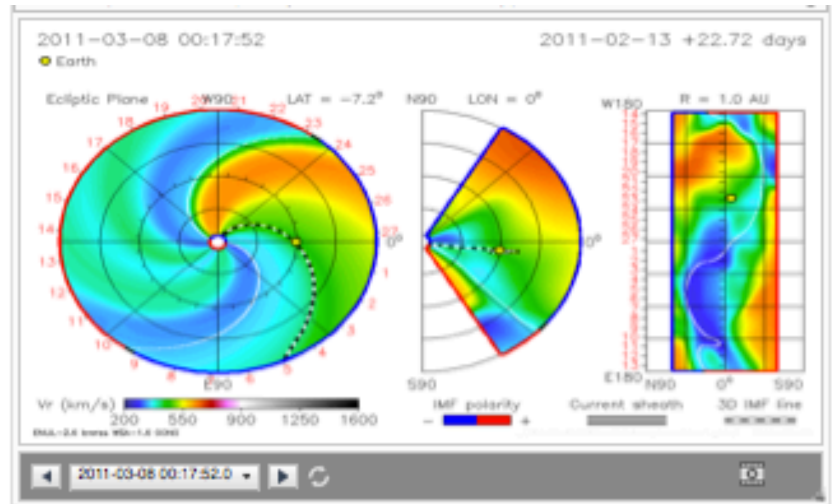


Mar 1, 2011

June 4, 2012

Forecasting capability enabled by ENLIL



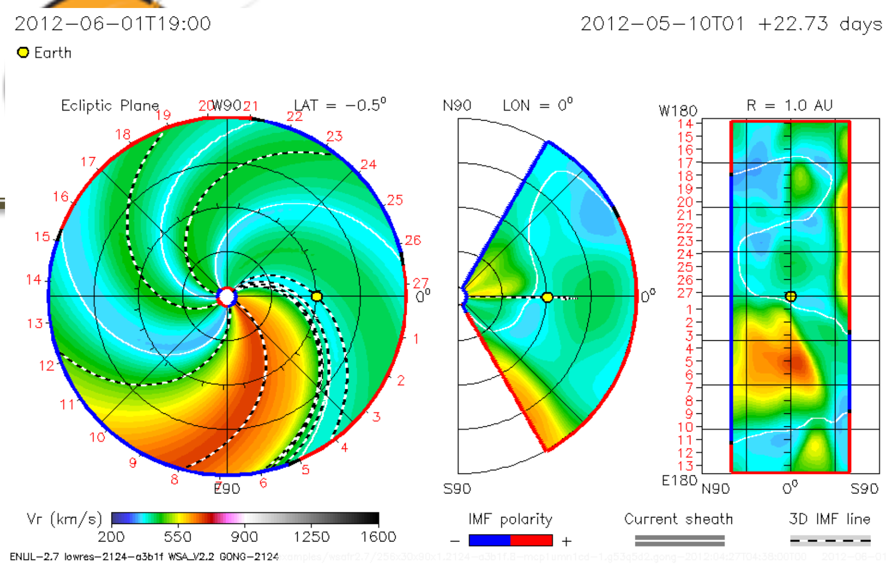


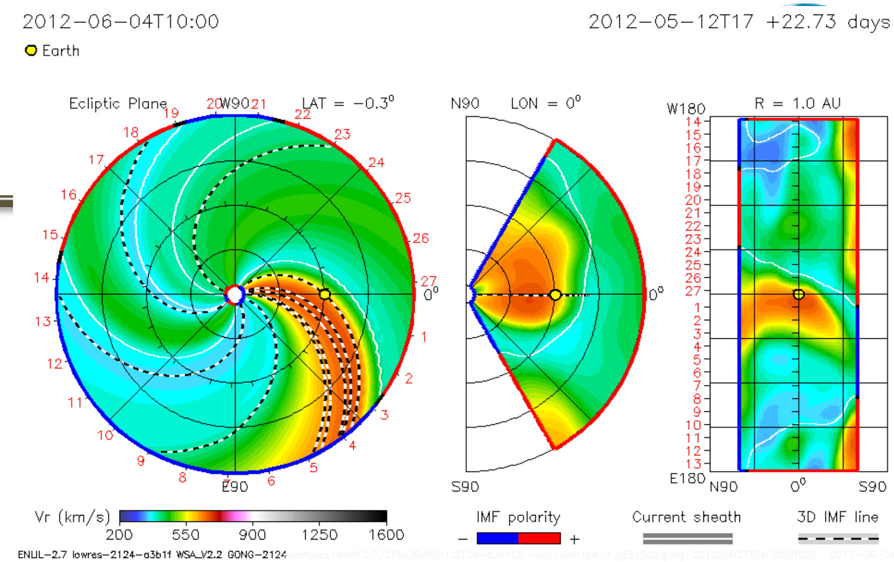
WSA+ENLIL+cone

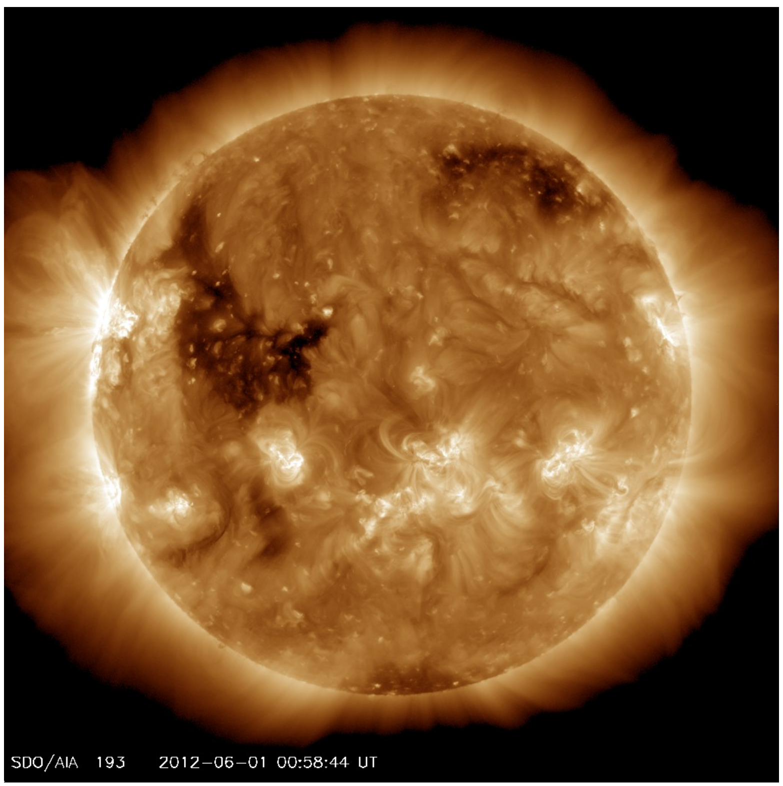
Predicting impacts of CMEs

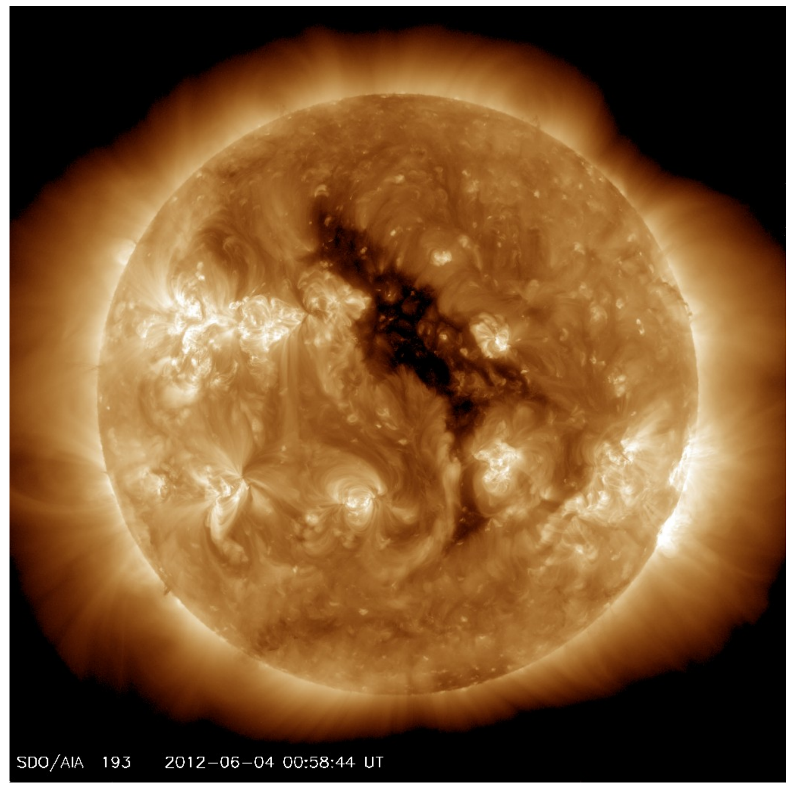
WSA+ENLIL

Modeling and predicting the ambient solar wind


2012-06-01T19:00
2012-05-10T01 +22.73 days
Earth
Ecliptic Plane
LAT = −0.5°
N90 LON = 0°
R = 1.0 AU
Vr (km/s)
200 550 900 1250 1600
IMF polarity
Current sheath
3D IMF line
ENLIL-2.7 lowres-2124-a3b1f WSA_V2.2 GONG-2124

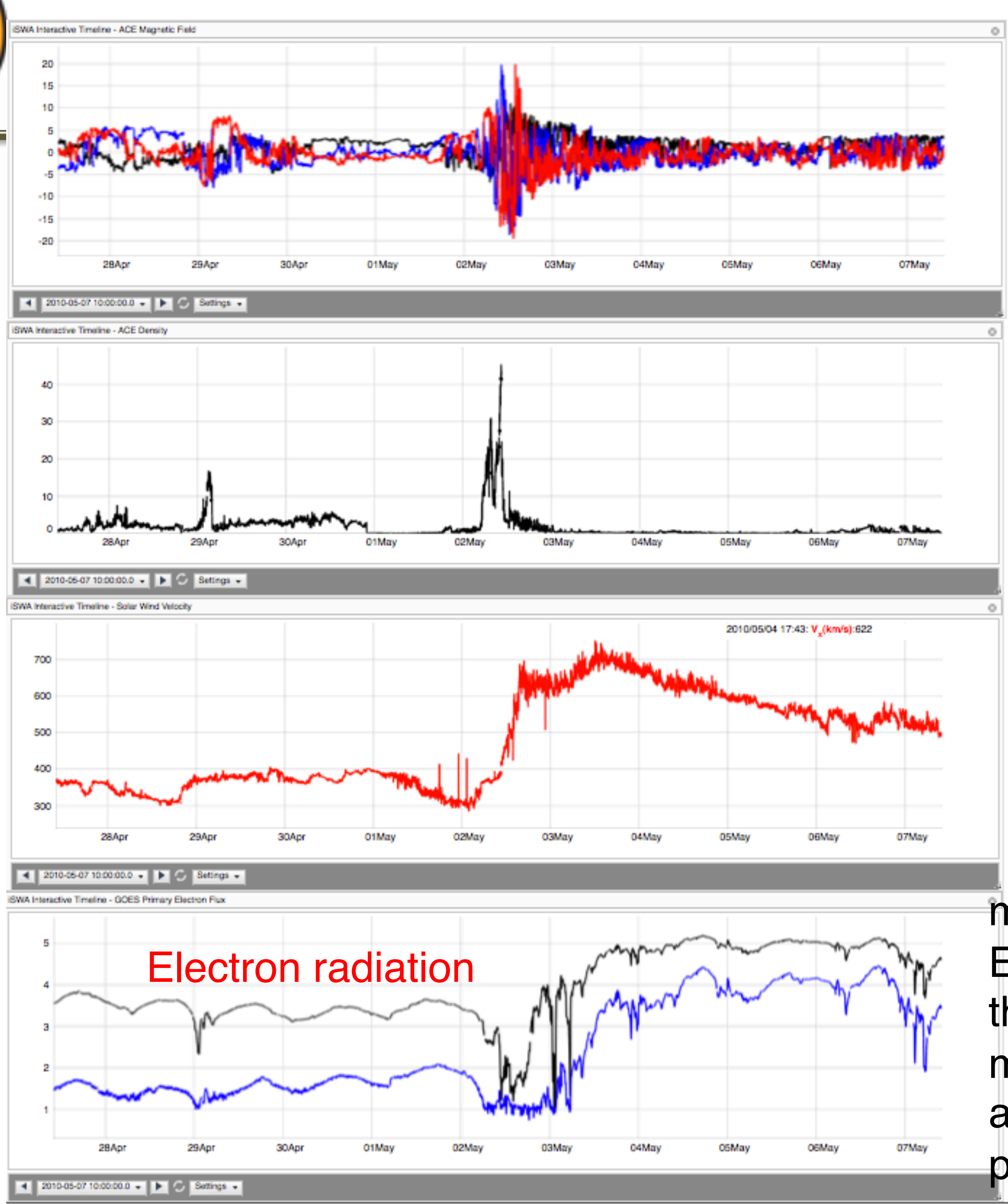

2012-06-04T10:00
2012-05-12T17 +22.73 days
Earth
Ecliptic Plane
LAT = −0.3°
N90 LON = 0°
R = 1.0 AU
Vr (km/s)
200 550 900 1250 1600
IMF polarity
Current sheath
3D IMF line
ENLIL-2.7 lowres-2124-a3b1f WSA_V2.2 GONG-2124


SDO/AIA 193 2012-06-01 00:58:44 UT


SDO/AIA 193 2012-06-04 00:58:44 UT

In-situ signatures of CME and CIR HSS at L1

ACE and WIND



Clean HSS

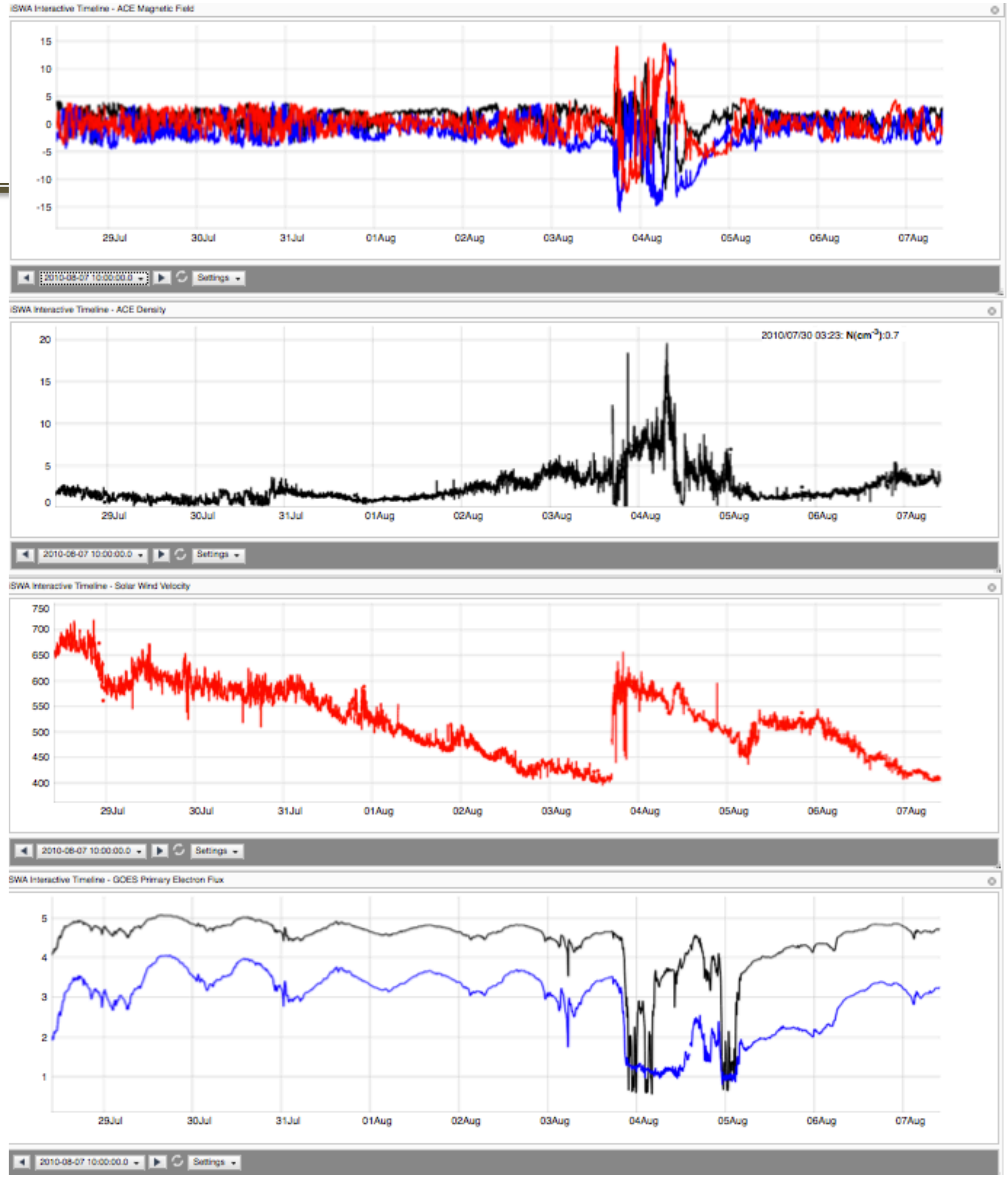
May 2, 2010

Dense (20-30 cc), HSS

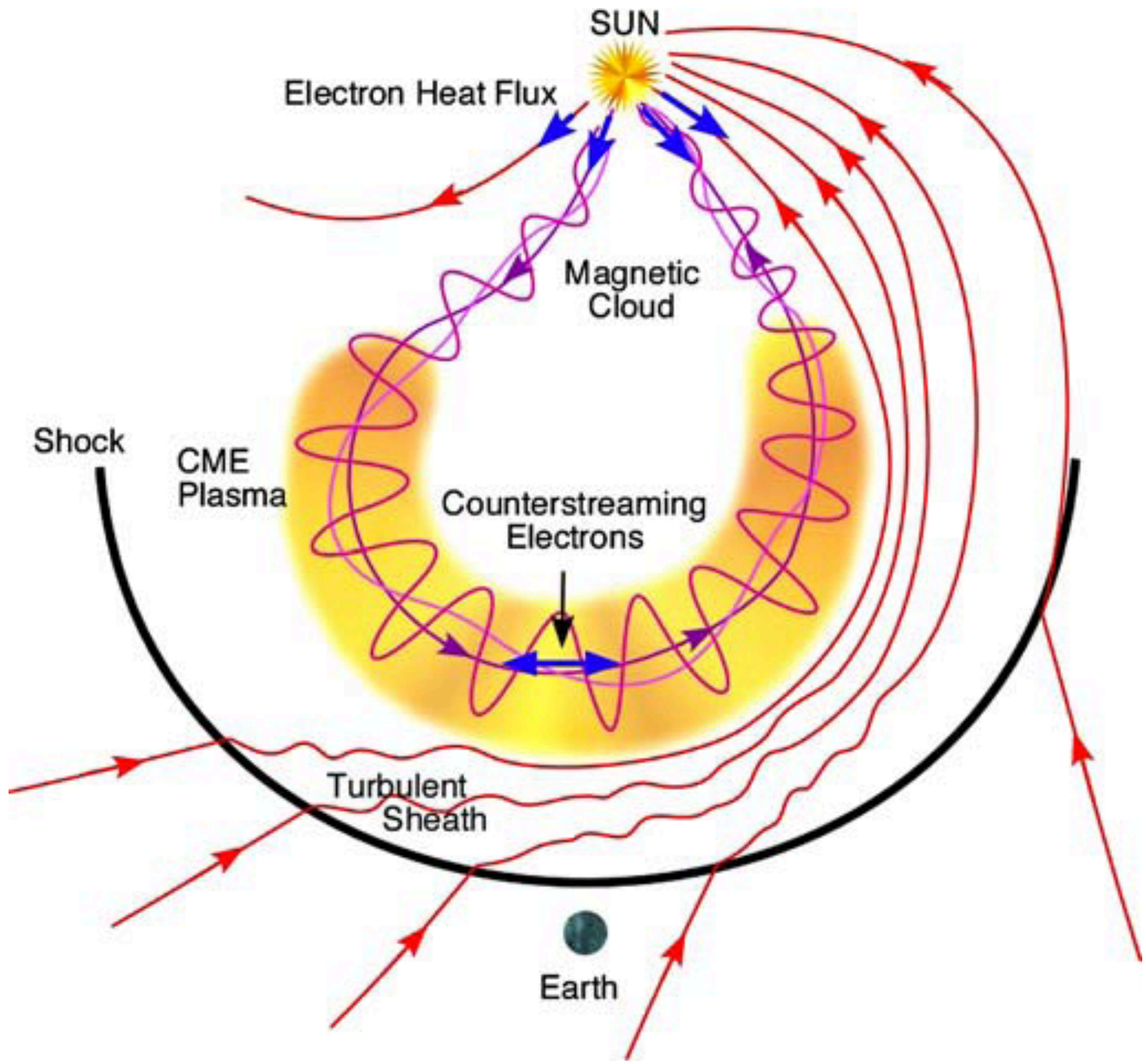
IMFBz: -18 nT

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

Aug 3, 2010


iSWA Interactive Timeline - ACE Magnetic Field
15
10
5
0
-5
-10
-15
29Jul 30Jul 31Jul 01Aug 02Aug 03Aug 04Aug 05Aug 06Aug 07Aug
2010-08-07 10:00:00.0
Settings
iSWA Interactive Timeline - ACE Density
2010/07/30 03:23: N(cm-3):0.7
20
15
10
5
0
29Jul 30Jul 31Jul 01Aug 02Aug 03Aug 04Aug 05Aug 06Aug 07Aug
2010-08-07 10:00:00.0
Settings
iSWA Interactive Timeline - Solar Wind Velocity
750
700
650
600
550
500
450
400
29Jul 30Jul 31Jul 01Aug 02Aug 03Aug 04Aug 05Aug 06Aug 07Aug
2010-08-07 10:00:00.0
Settings
iSWA Interactive Timeline - GOES Primary Electron Flux
5
4
3
2
1
29Jul 30Jul 31Jul 01Aug 02Aug 03Aug 04Aug 05Aug 06Aug 07Aug
2010-08-07 10:00:00.0
Settings

Schematic of the three-dimensional structure of an ICME and upstream shock

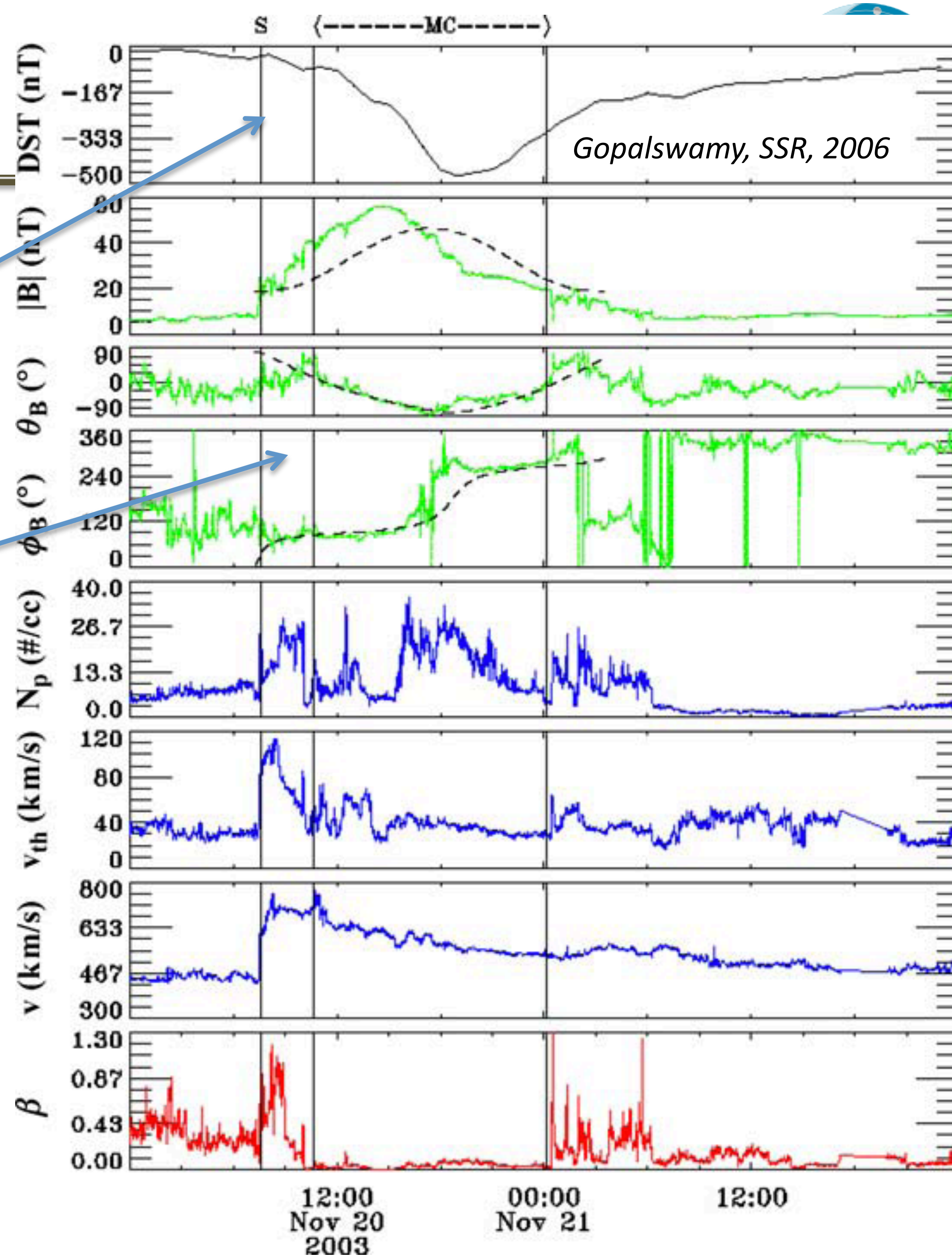


Textbook example of ICME in-situ signature

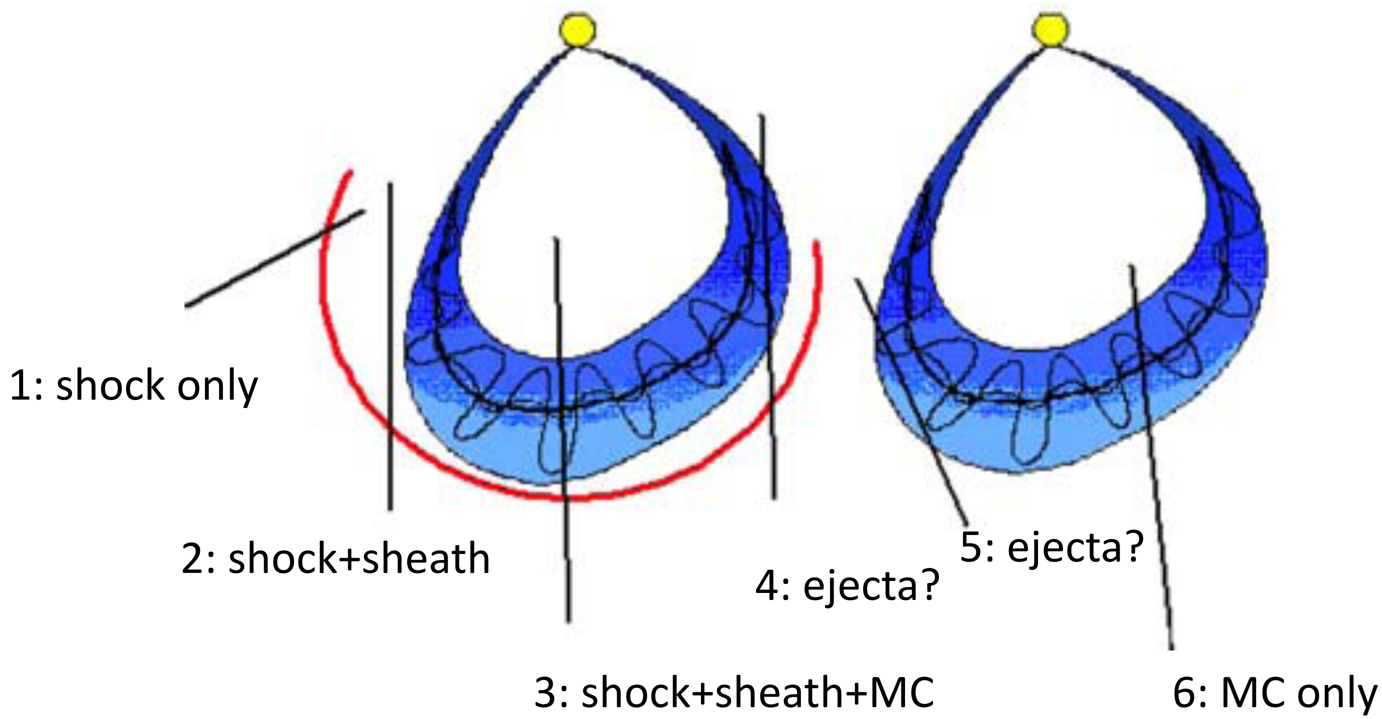
shock

sheath

Magnetic cloud



In-Situ signature can be quite complex



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

Typical behavior of CIRs

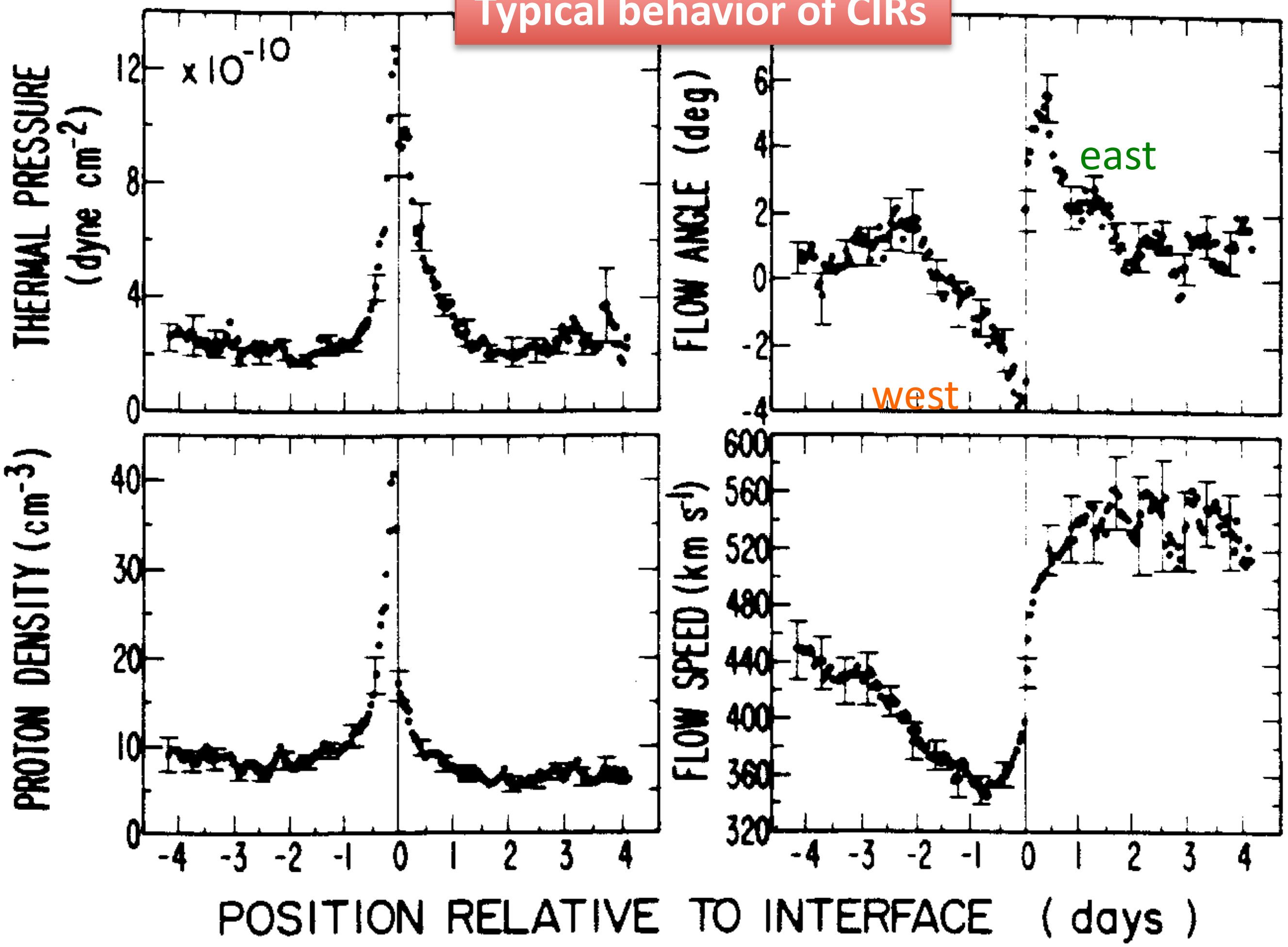


Figure 3. Superposed epoch plots of selected 1-hour averaged solar wind parameters for 23 CIRs containing abrupt stream interfaces. The flow angle is the azimuthal (east-west) flow angle and the sign convention is that negative flow angles correspond to flow in the direction of planetary motion about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

Another example

394 stream interfaces in the interval 1995–2006

McPherron, R. L., D. N. Baker, and N. U. Crooker (2009), Role of the Russell-McPherron effect in the acceleration of relativistic electrons, J. Atmos. Sol. Terr. Phys., 71(10–11), 1032–1044

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

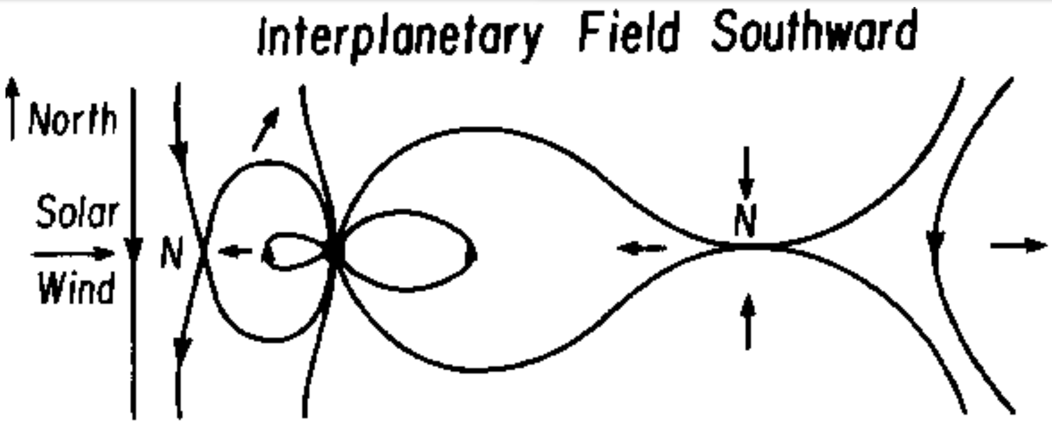
Table 1. A Summary of Some of the Important Differences Between CME-Driven Storms (Shock, Sheath, Ejecta, Cloud) and CIR-Driven Storms (CIR, High-Speed Stream)

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

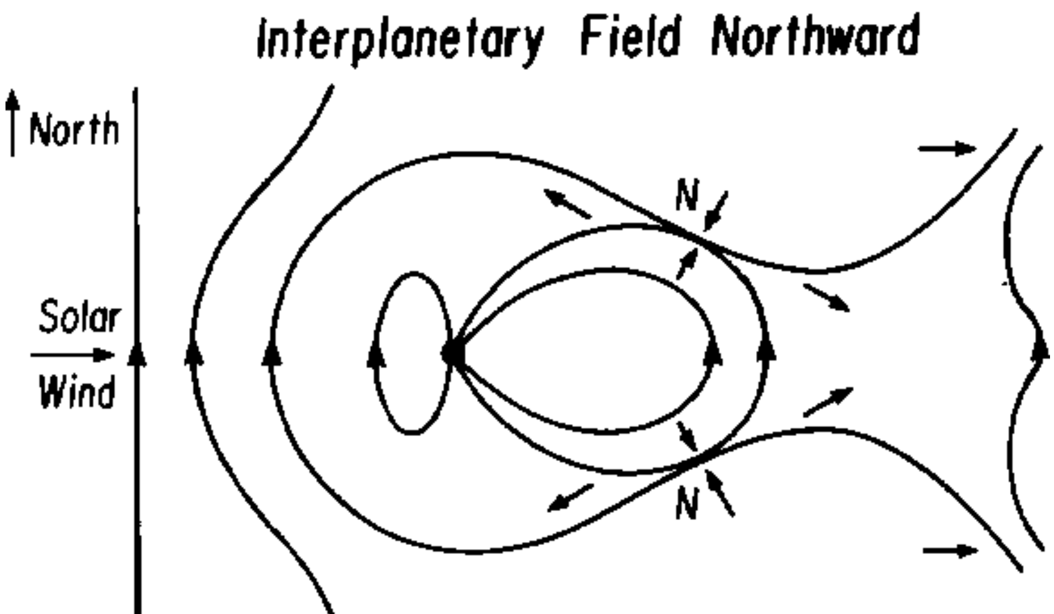
Borovsky, J. E. and M. H. Denton (2006), Differences between CME-driven storms and CIR-driven storms , *J. Geophys. Res.* , 111 , A07S08, doi:10.1029/2005JA011447.

Two major types of solar wind-magnetosphere interactions

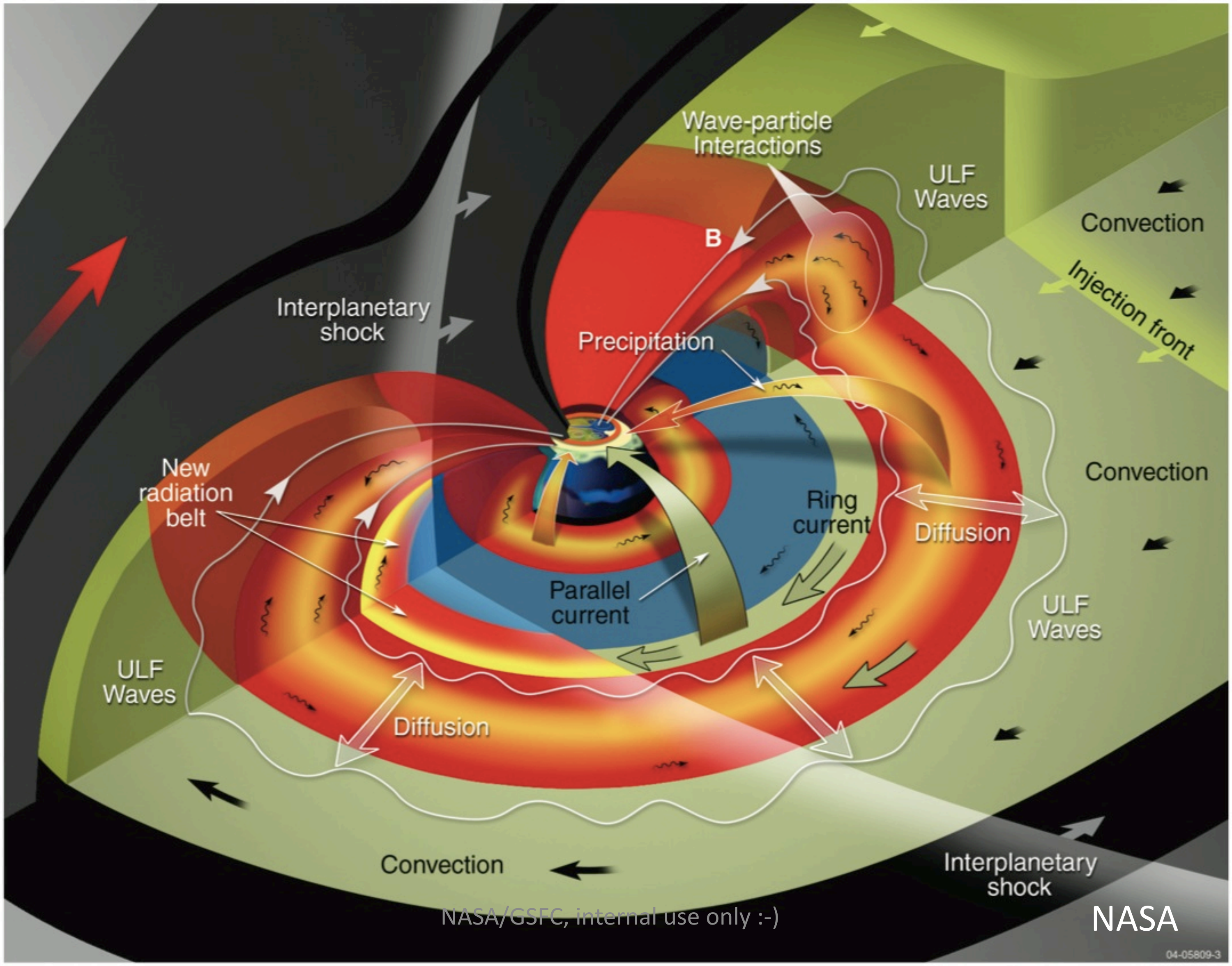
Southward IMF



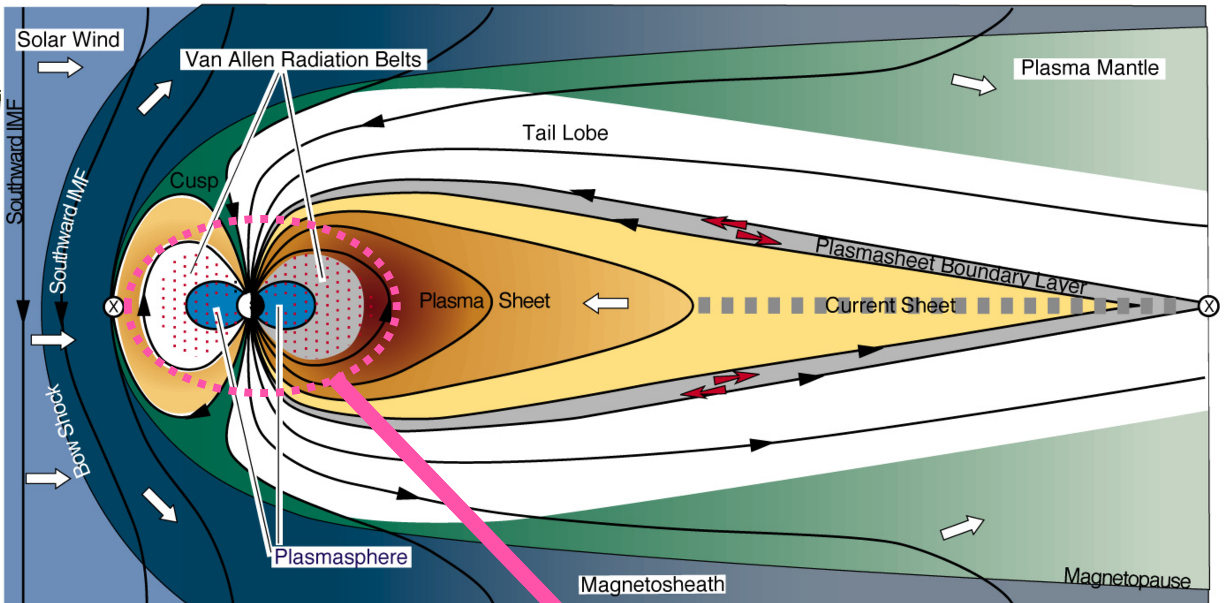
Northward IMF



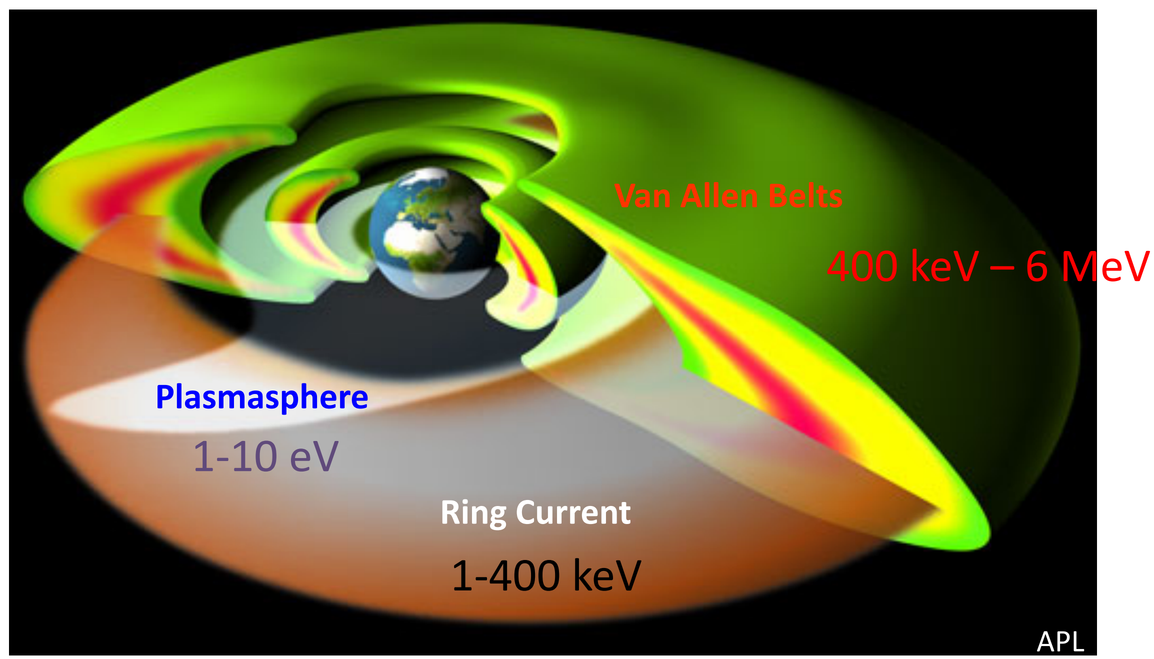
The Earth's Magnetosphere



The Earth's Magnetosphere



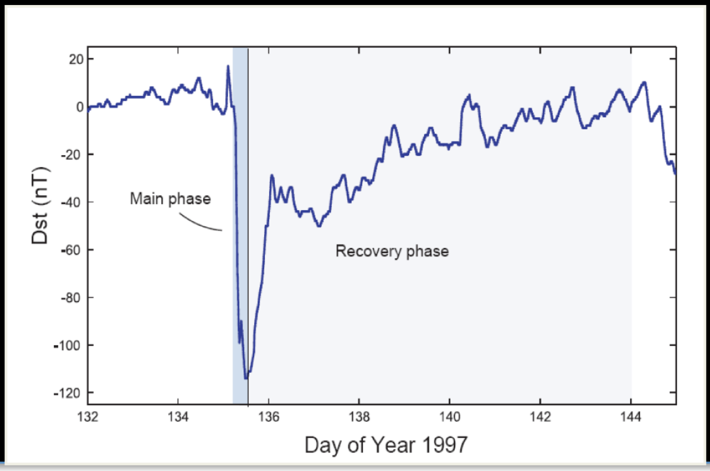
Inner Magnetosphere:
Up to ~ 10Re



Magnetic Storms

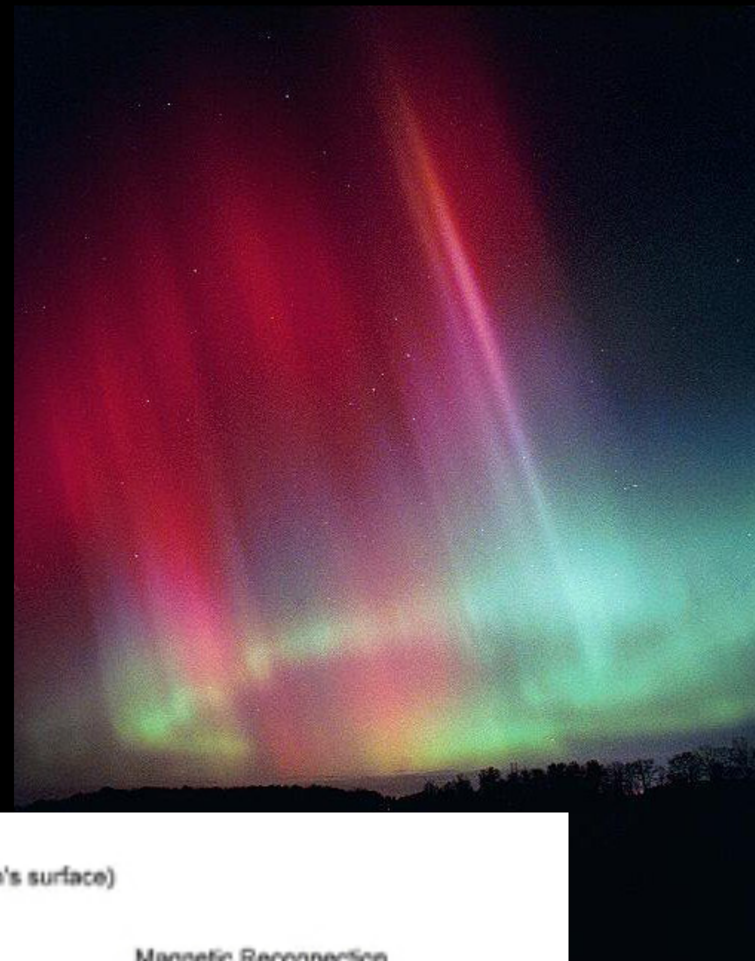
- Most intense solar wind-magnetosphere coupling
- Associated with solar coronal mass ejections (CME), coronal holes HSS
- IMF Bz southward, strong electric field in the tail
- Formation of ring current and other global effects

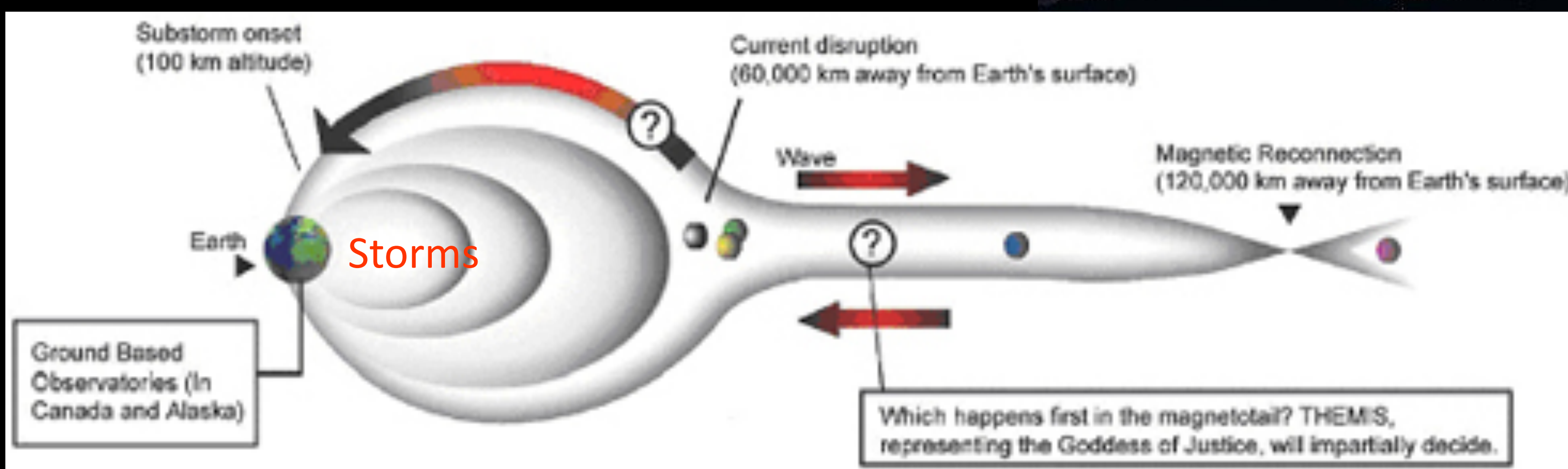
- Dst measures ring current development
  - Storm sudden commencement (SSC), main phase, and recovery phase
  - Duration: days



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

"*p*lanetarische *K*ennziffer" (= 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
3. Extreme event - Oct 29 – Oct 31, 2003

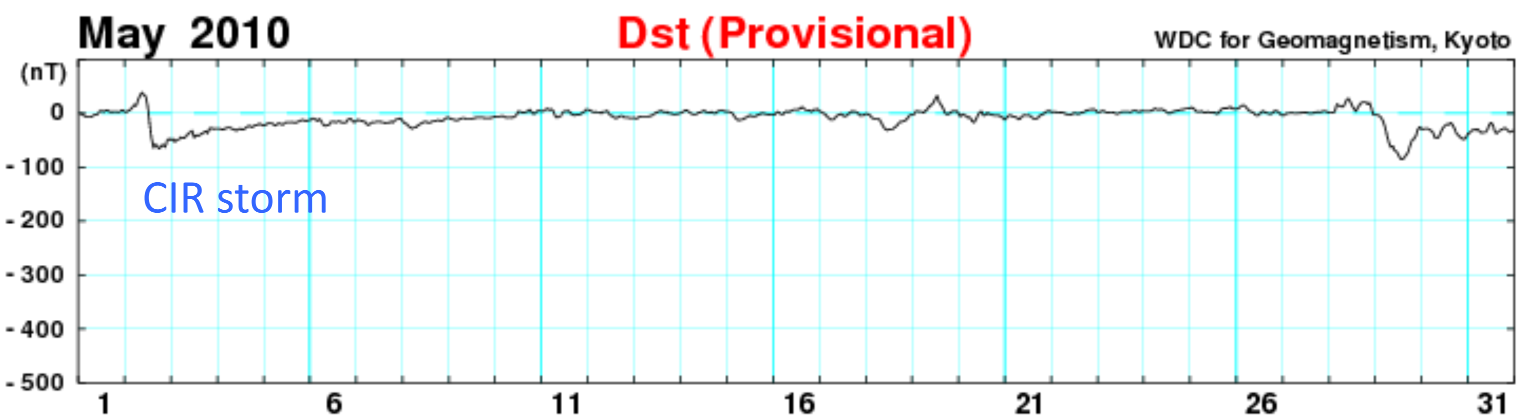
http://bit.ly/Kp_layout Threshold Kp>=6

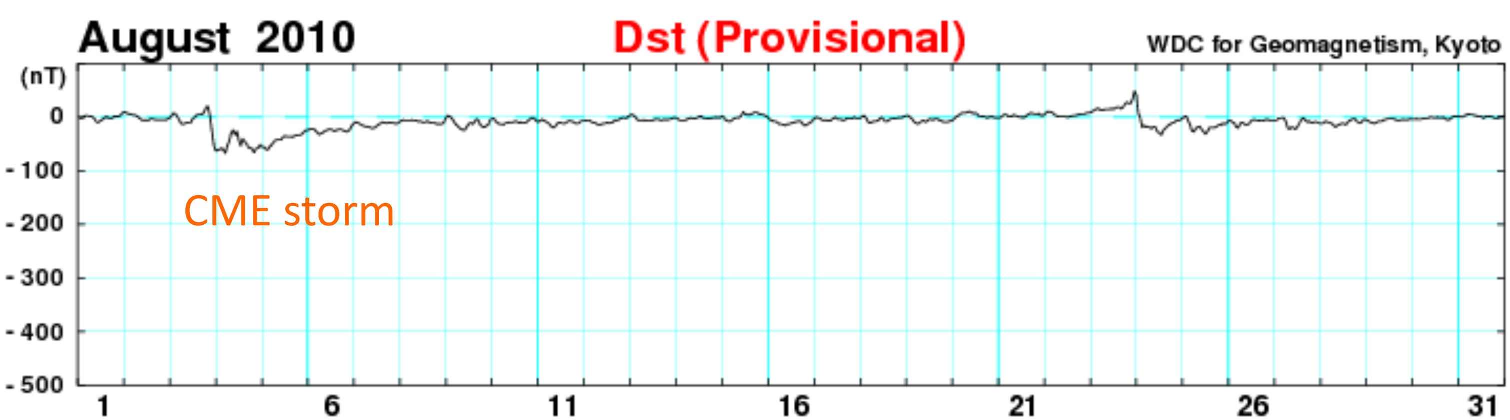
Geomagnetic Storm classification

- http://www.swpc.noaa.gov/NOAAscales/index.html#GeomagneticStorms
- Operational world

Dst: Disturbance of Storm Time

Measure of Storm Intensity





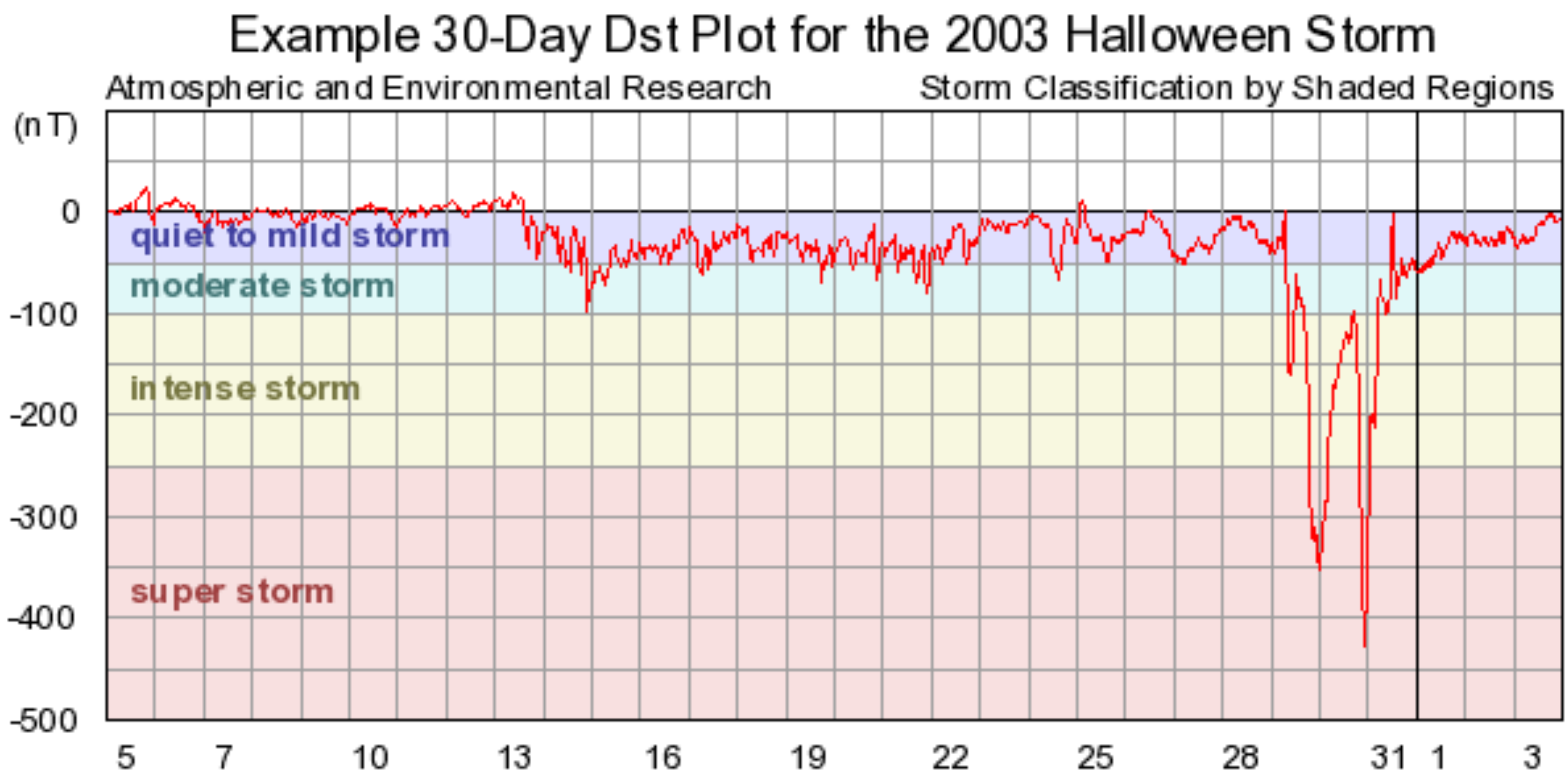
CIR storm at most: Dstmin ~ -130 nT

CME storm: Dstmin ~ -600 nT

1989 March 14 Dstmin= -589 nT

Geomagnetic Storm Classification

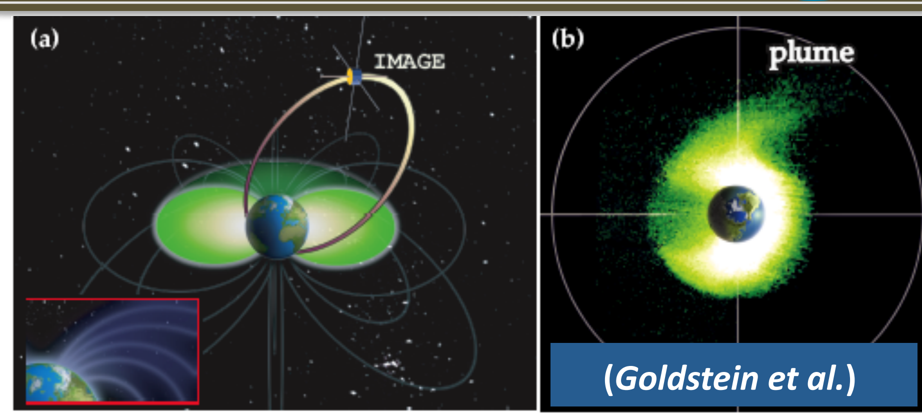
Research



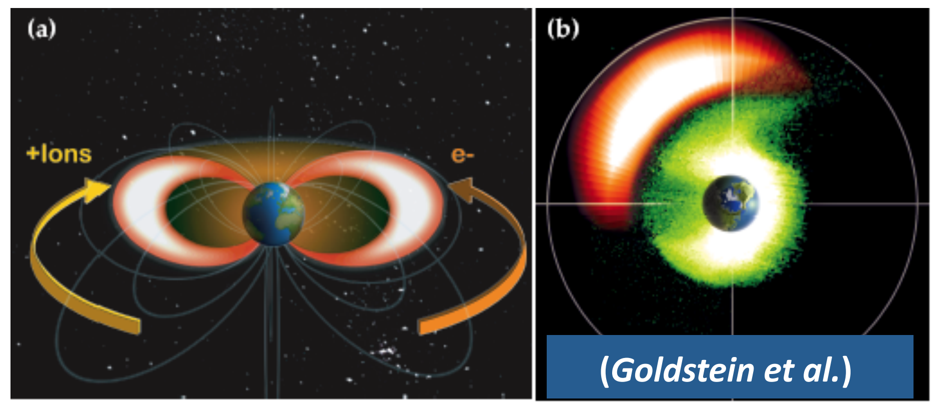
Inner magnetosphere plasmas

- 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

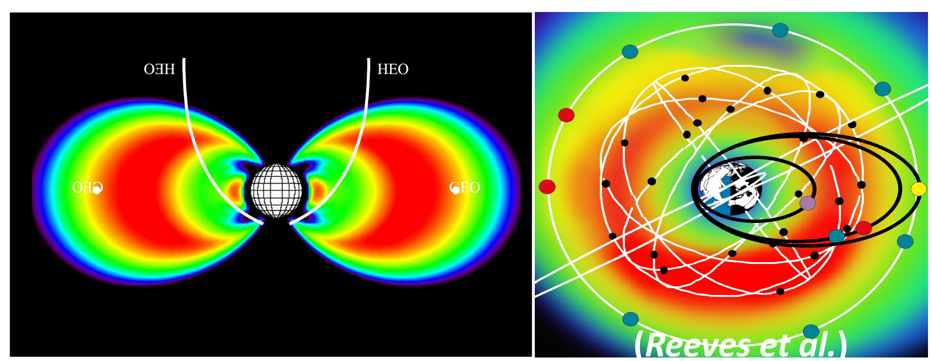
Inner magnetosphere: Gigantic Particle accelerator



(*Goldstein et al.*)

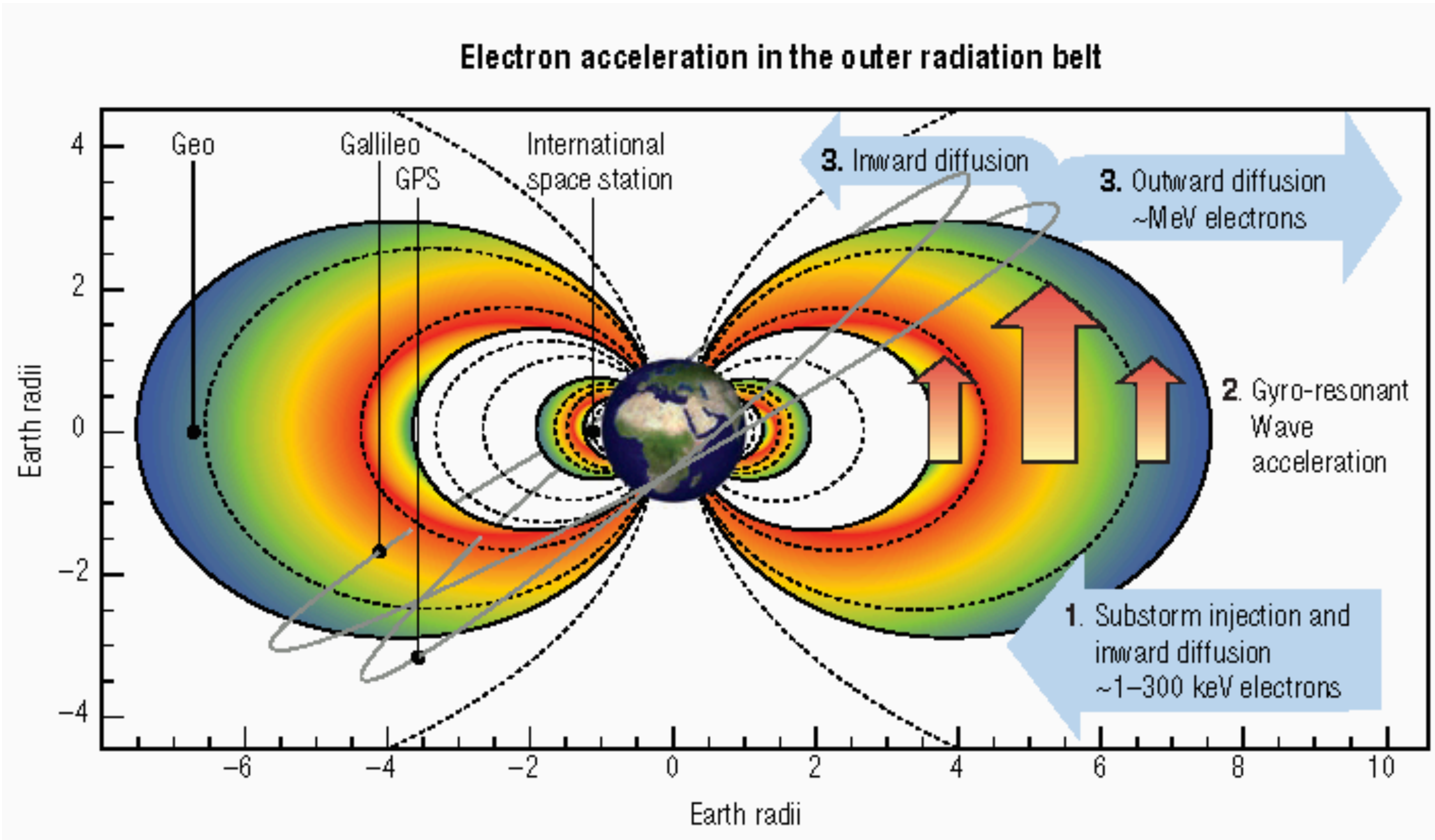


(*Goldstein et al.*)



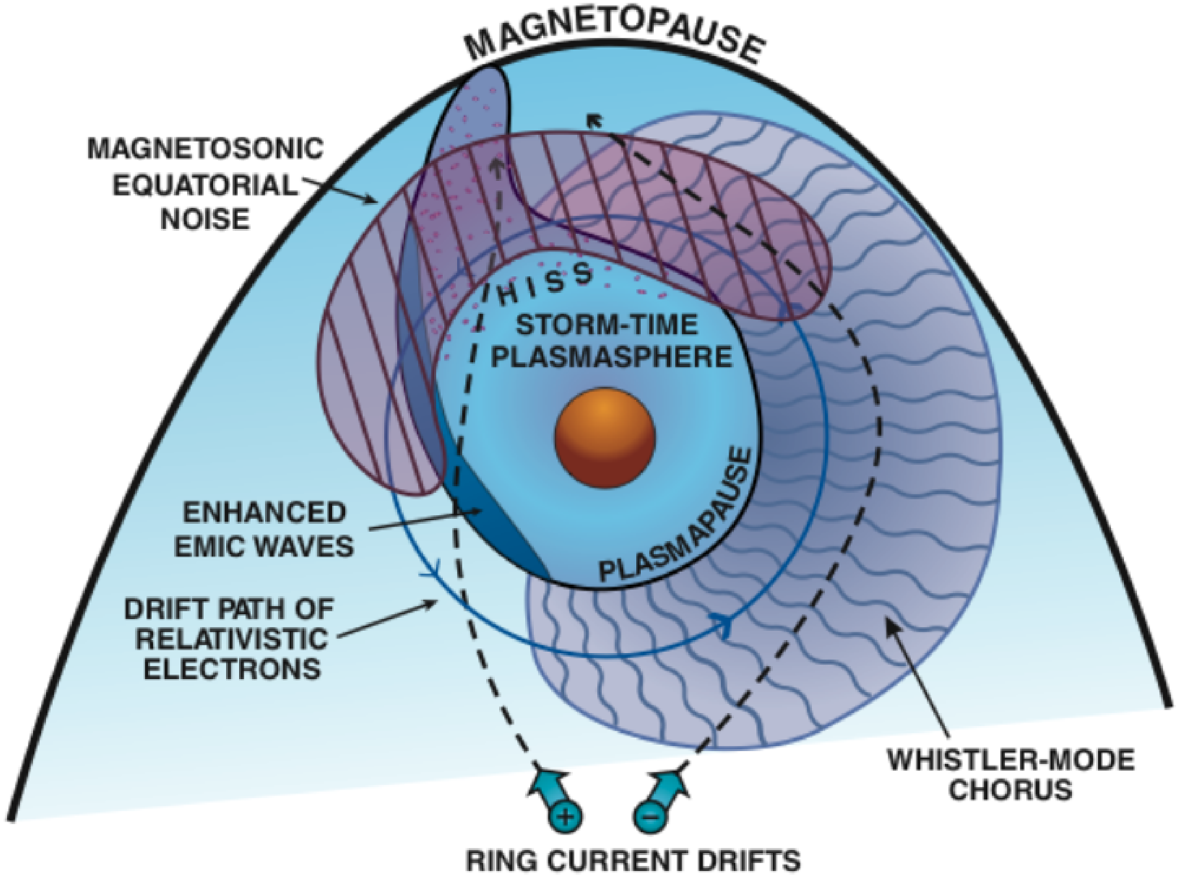
(*Reeves et al.*)

RB: Current understanding

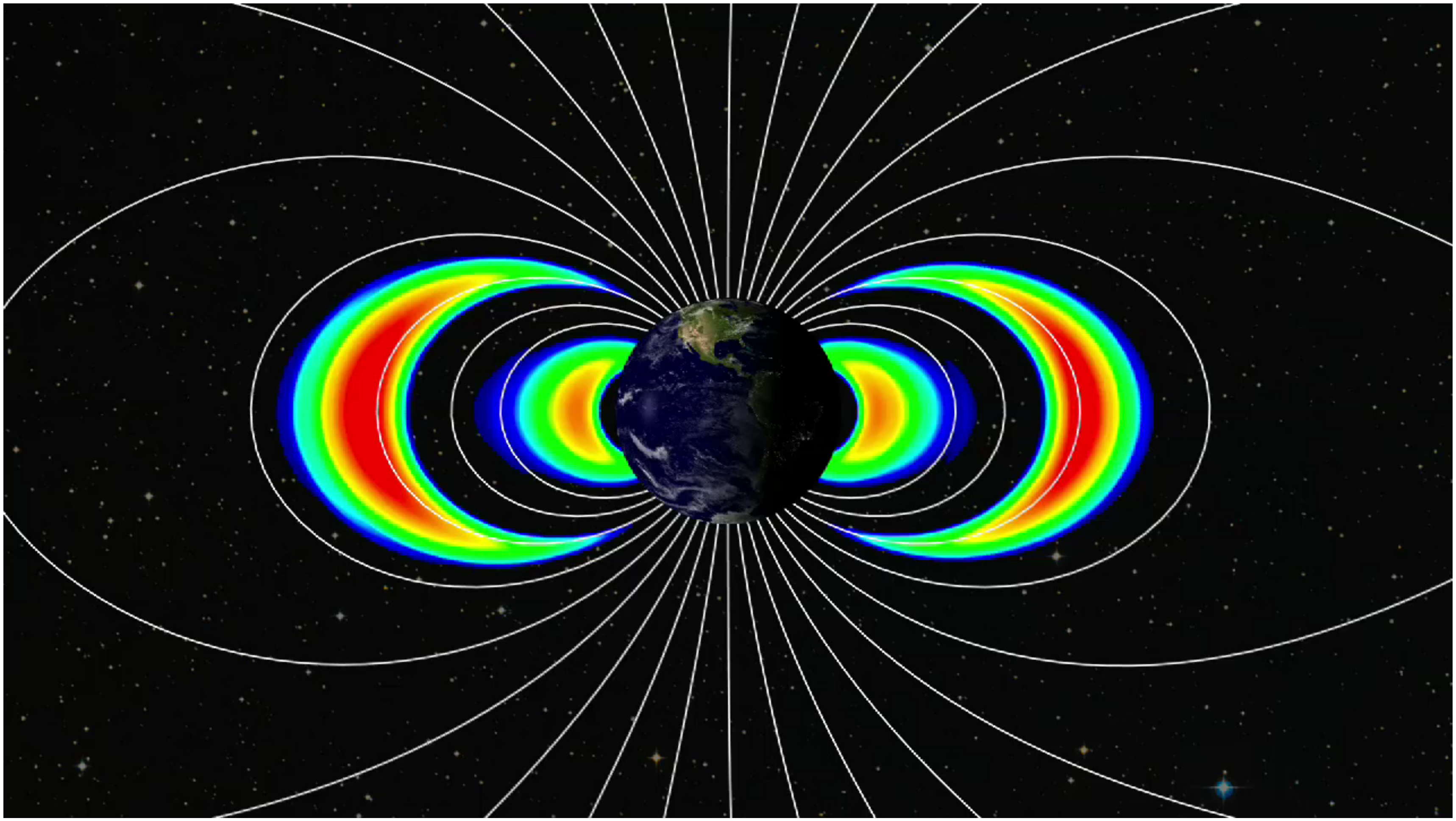


Horne et al., 2007, Nature Physics

Various types of waves that are important to RB dynamics

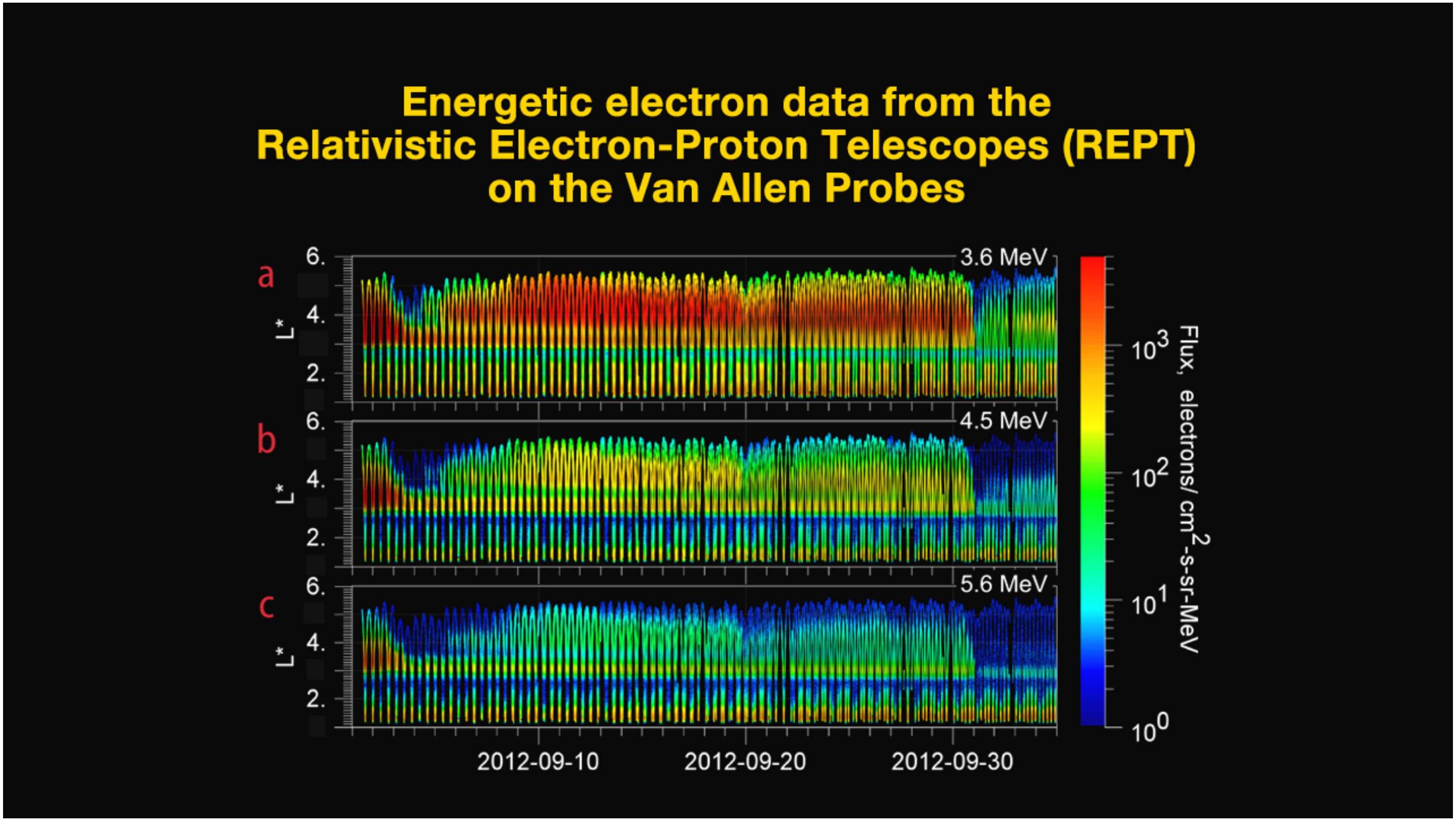


Van Allen Probes: current mission on radiation belt dynamics



Three-Belt Structure

Quiet-time phenomenon

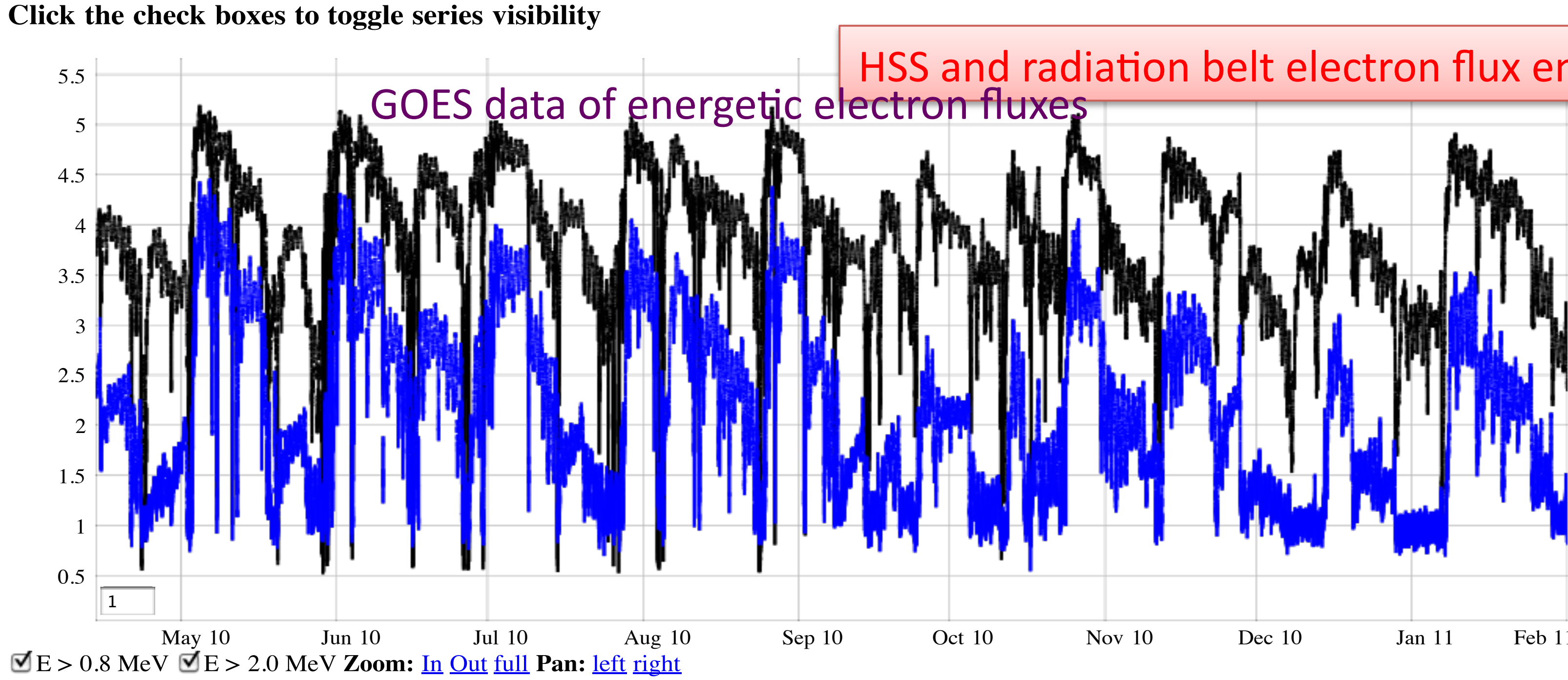


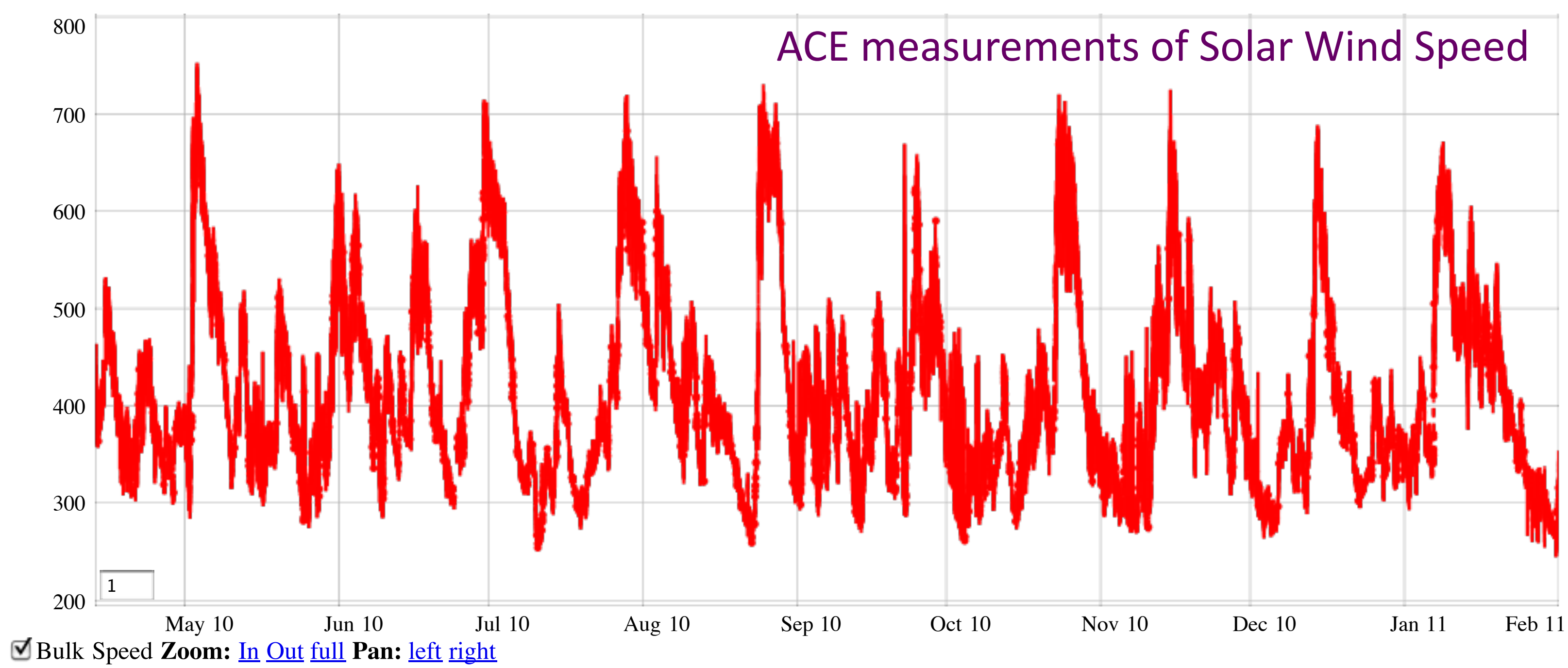
Different impacts on RB

CME vs CIR storms

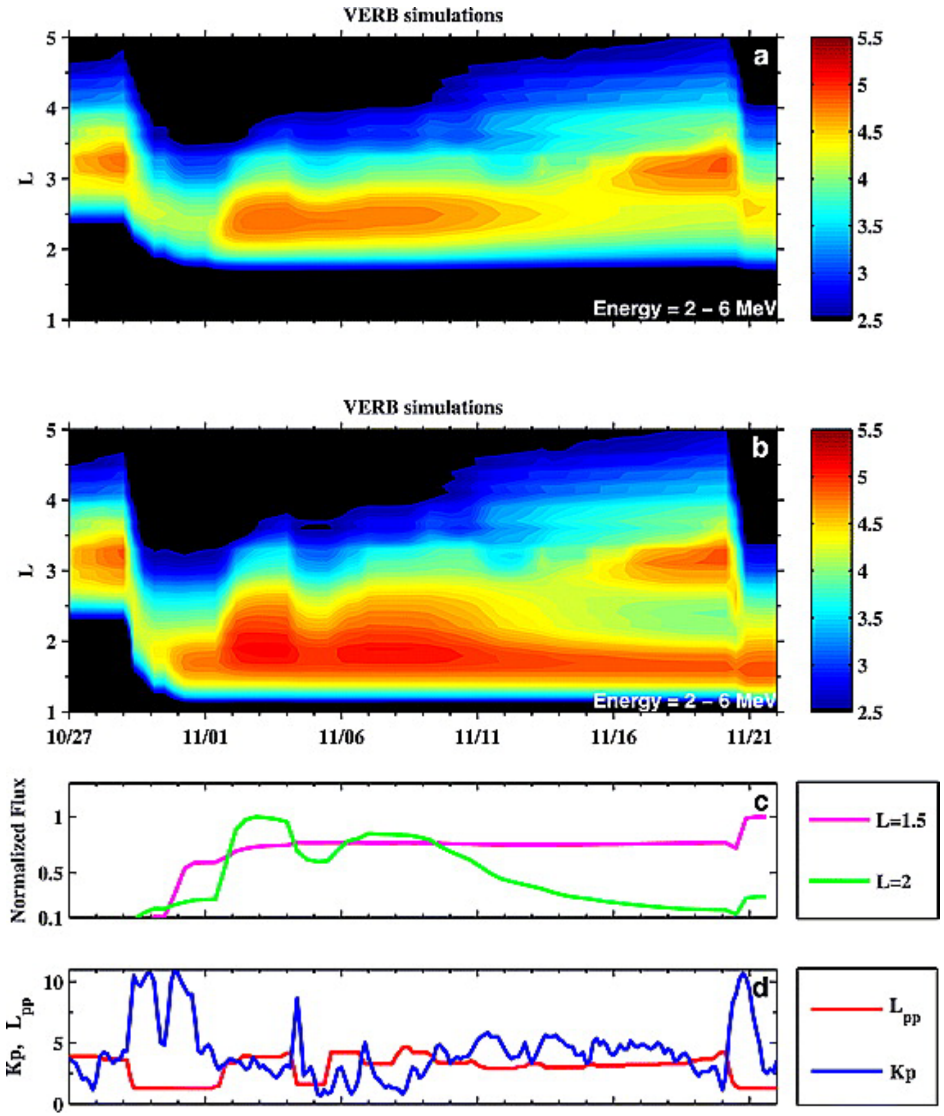
- CME geomagnetic storms: RB flux peak inside geosynchronous orbit. The peak locations moves inward as storm intensity increases
- CIR geomagnetic storms: More responsible for the electron radiation level enhancement at GEO orbit

HSS and radiation belt electron flux enhancement





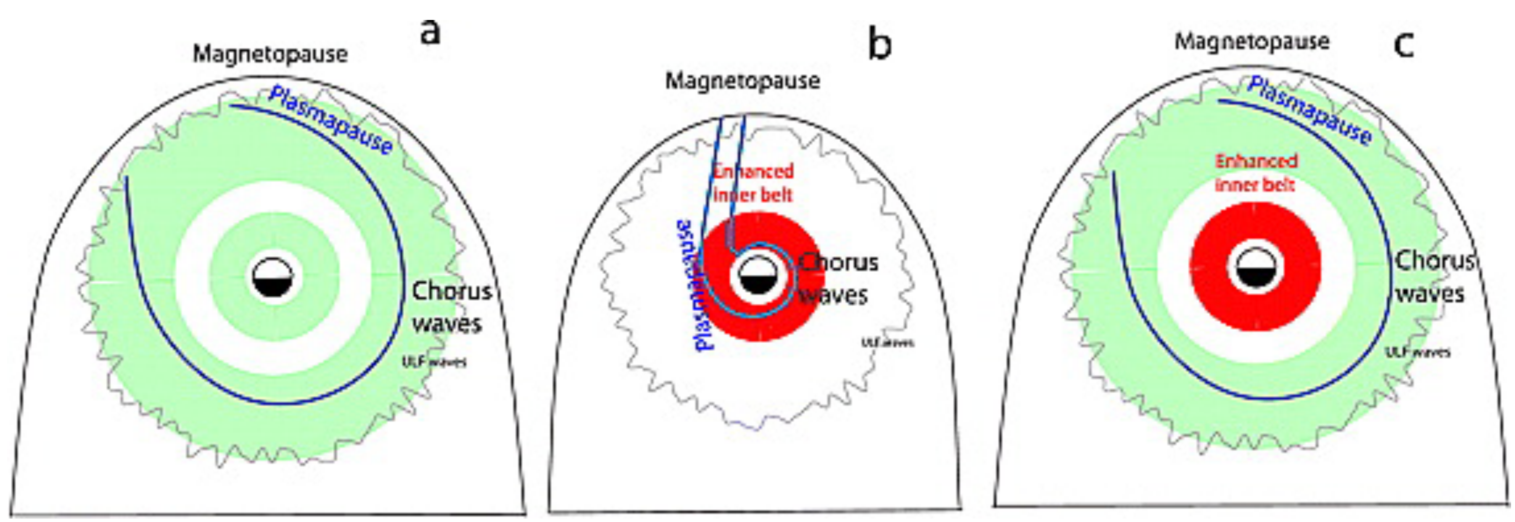
CME (superstorm condition) impact on RB



Halloween storm

Carrington-like superstorm

CME (superstorm condition) impact on RB



Shprits et al., 2011, Space Weather

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!

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
http://bit.ly/HSS_layout_20110301

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

Homework on SEP radiation storms

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

magnetospsheric products

Kp

"*p*lanetarische *K*ennziffer" (= planetary index).

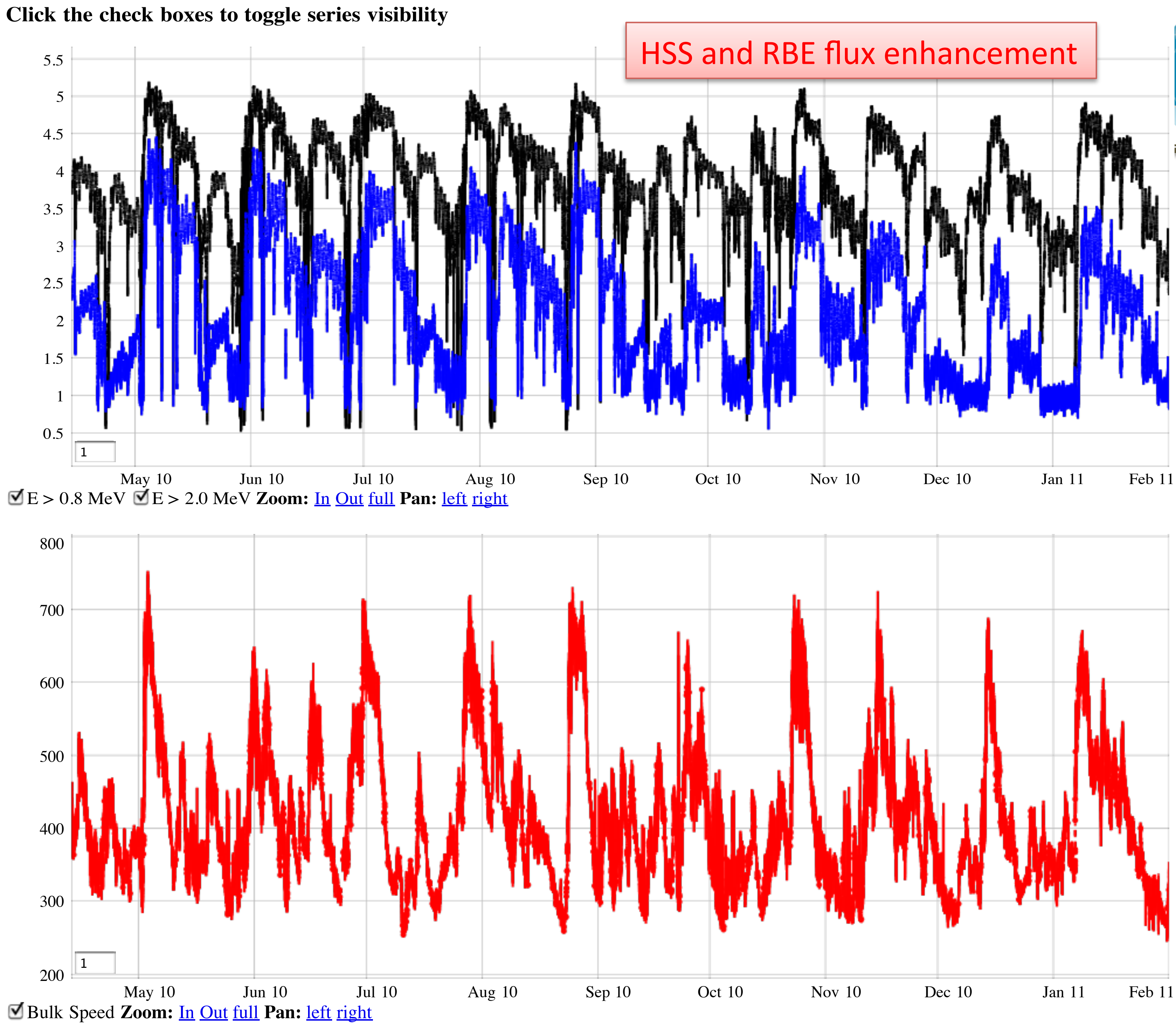
- Geomagnetic activity index

  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
3. Extreme event - Oct 29 – Oct 31, 2003

http://bit.ly/Kp_layout   Threshold Kp>=6

HSS and RBE flux enhancement

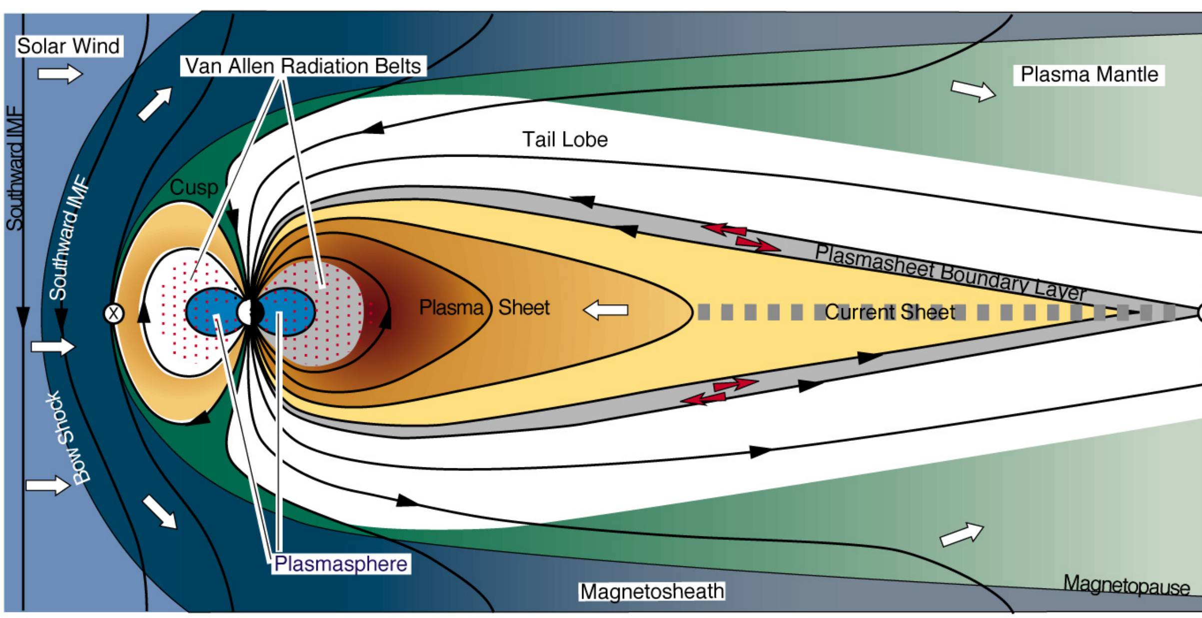


Magnetopause stand-off distance

delineating the boundary between SW and Earth's magnetosphere

- 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 Pdyn of solar wind
(interplanetary shock /HSS)



An iSWA layout for magnetospheric products

http://bit.ly/iswa_mag