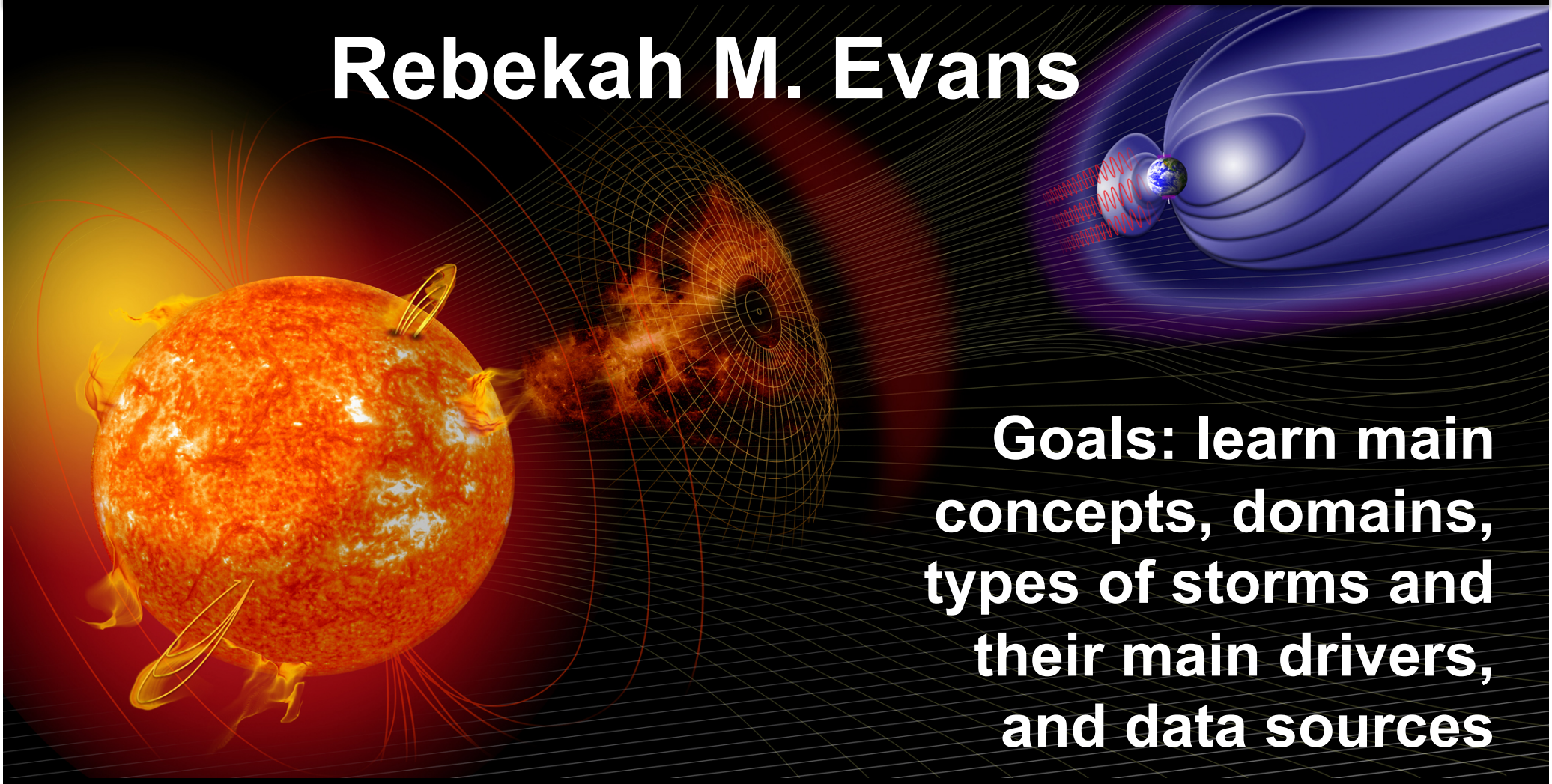
Introduction to Space Weather

Rebekah M. Evans



Goals: learn main concepts, domains, types of storms and their main drivers, and data sources

June 4, 2013

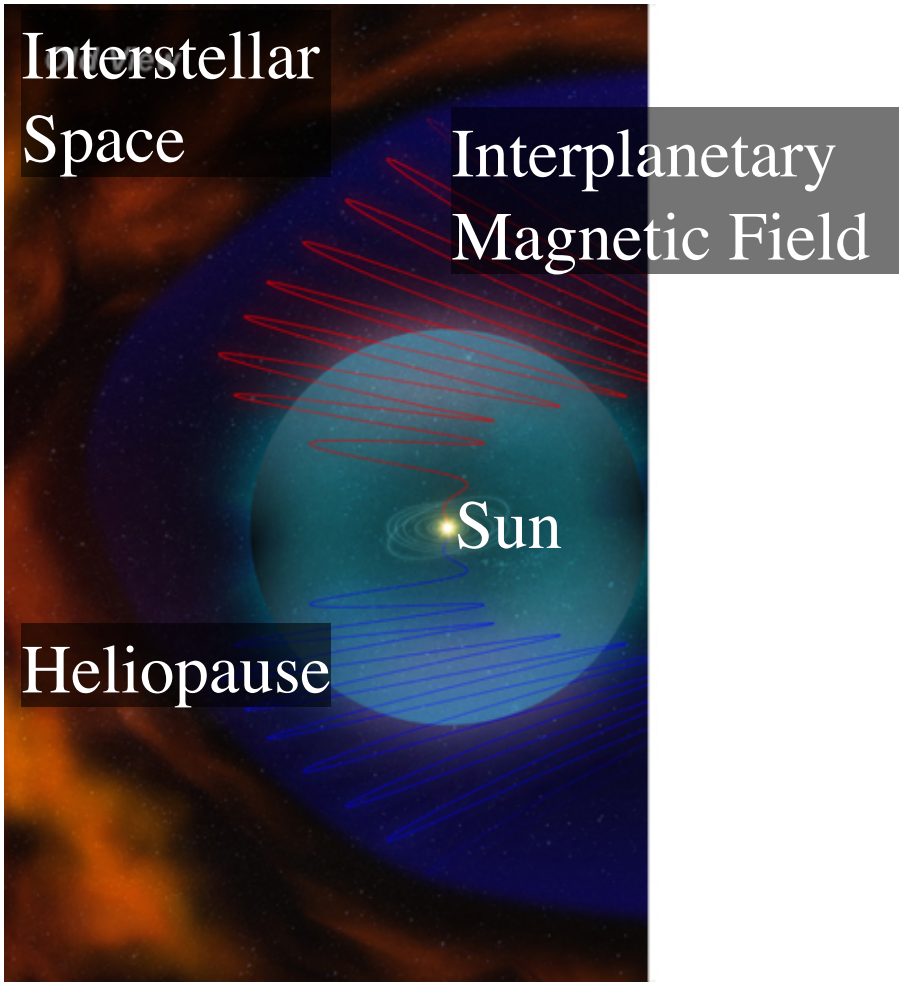
SW REDI Boot Camp

Main Concepts

Let's start with a movie!

- http://vimeo.com/31376715
- http://www.nasa.gov/mission_pages/sunearth/news/mystery-sun.html

Physical Domains



Heliosphere

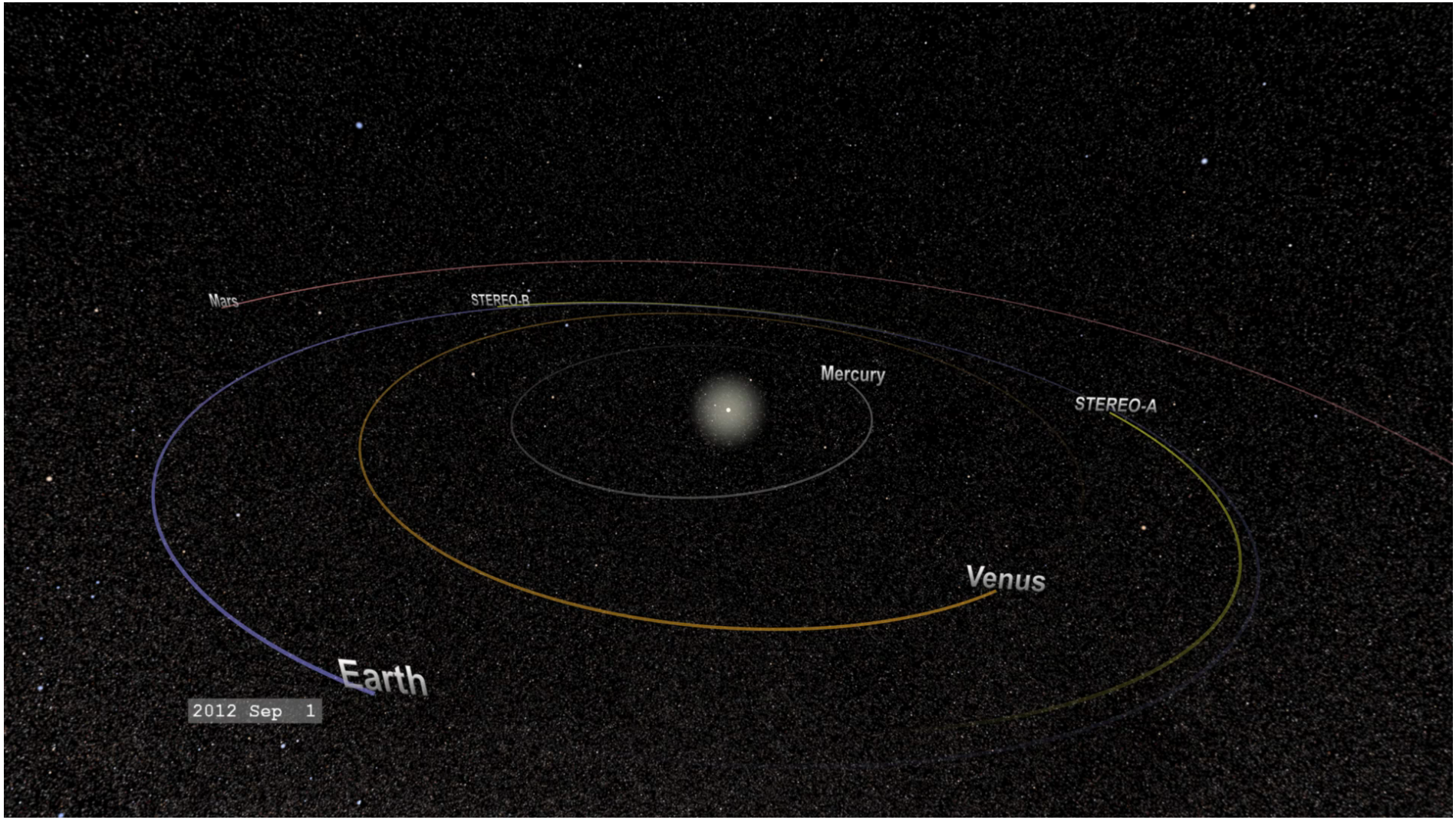
The region of space dominated by the Sun's expanding atmosphere.

Based on views of other stellar spheres, the heliosphere probably has a tear-drop shape due to its interaction with the interstellar wind

Physical Domains

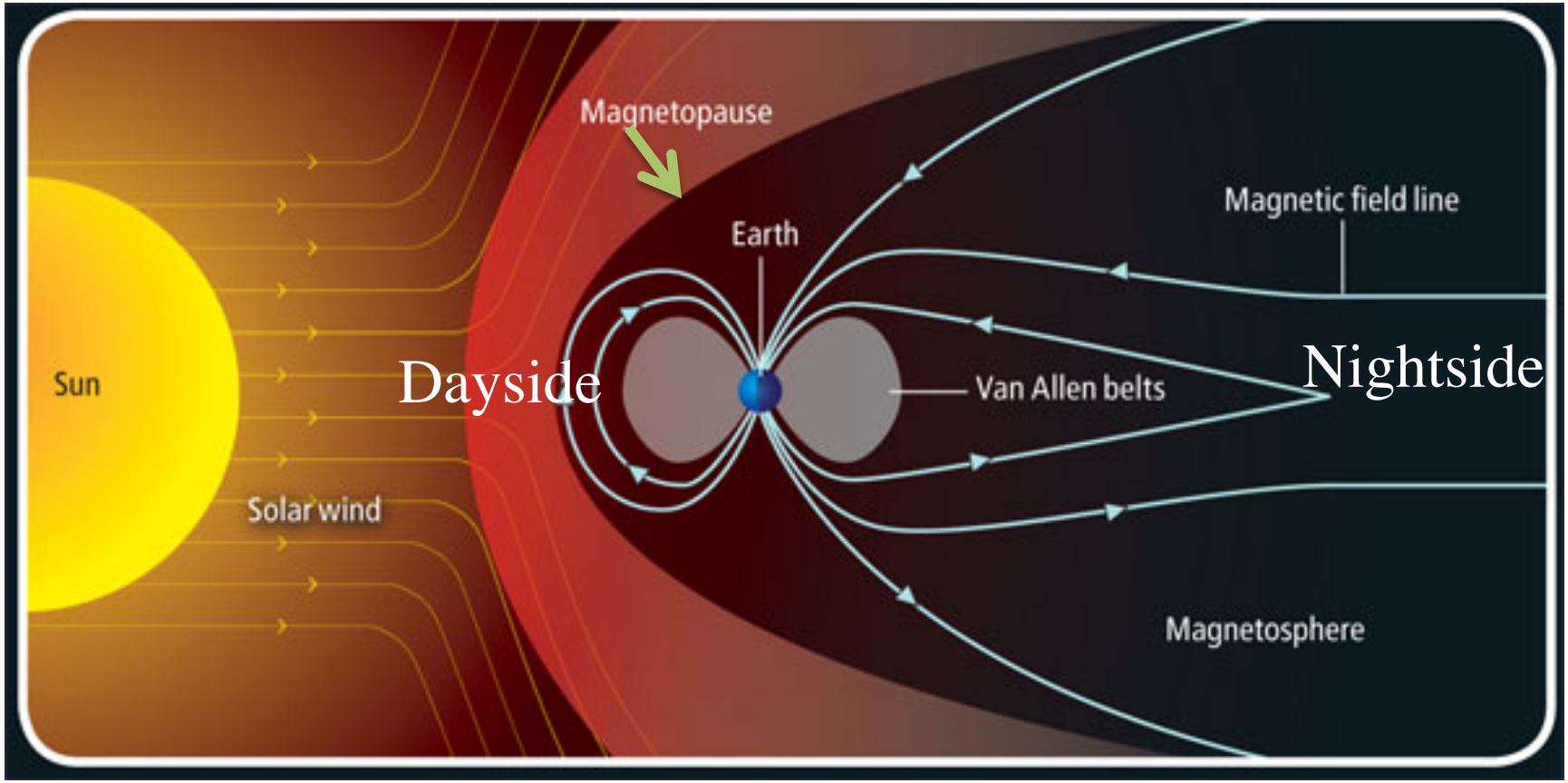
Heliosphere

Planets are mostly located in one plane
– called *ecliptic plane*



Physical Domains

Earth's Magnetosphere

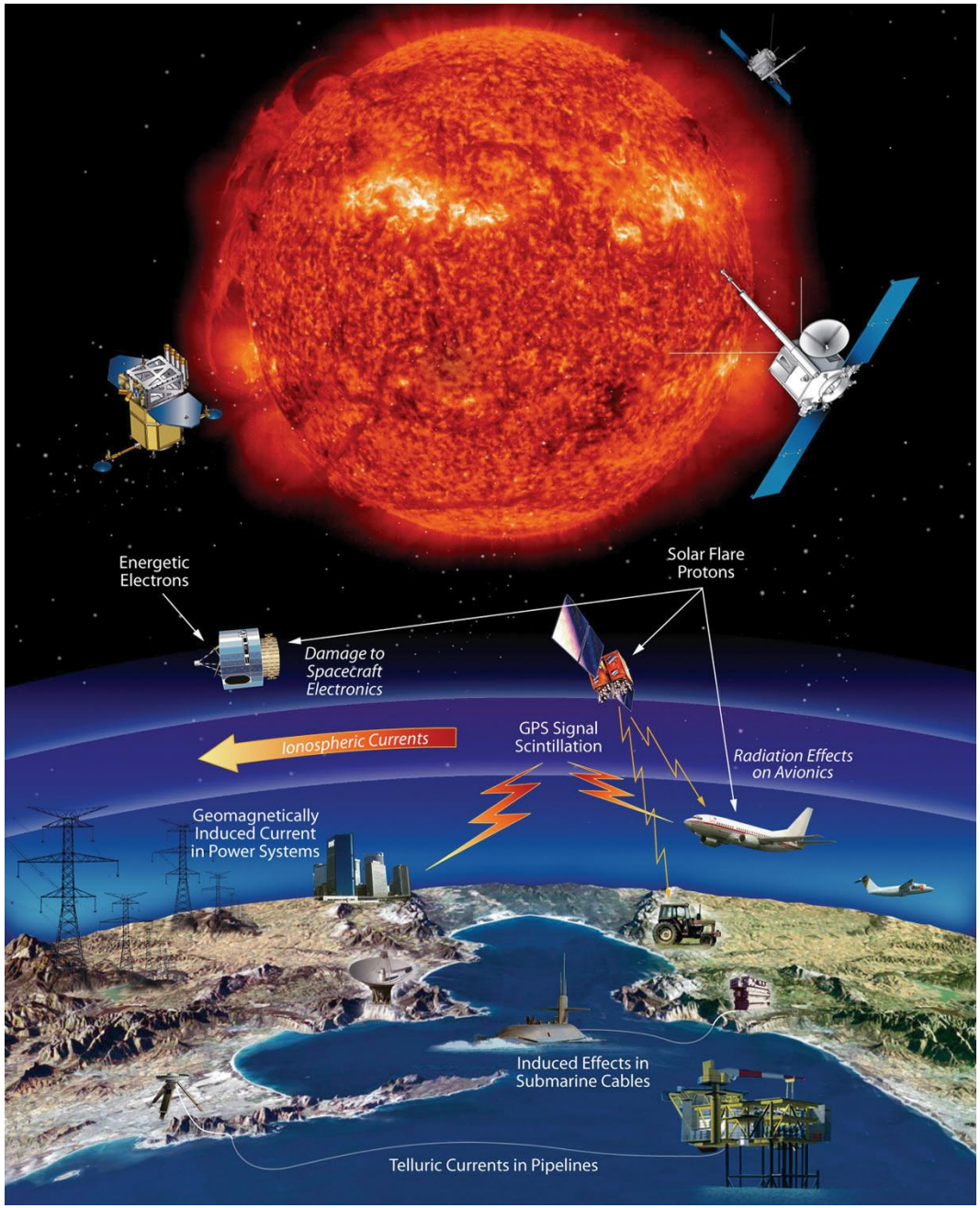


***Ionosphere* 85-100 km**

Geosynchronous Orbit 36,000 km = 6.6 RE

Magnetopause stand-off distance – quiet time ~ 12 RE

Space Weather



Is space weather something new?

No!

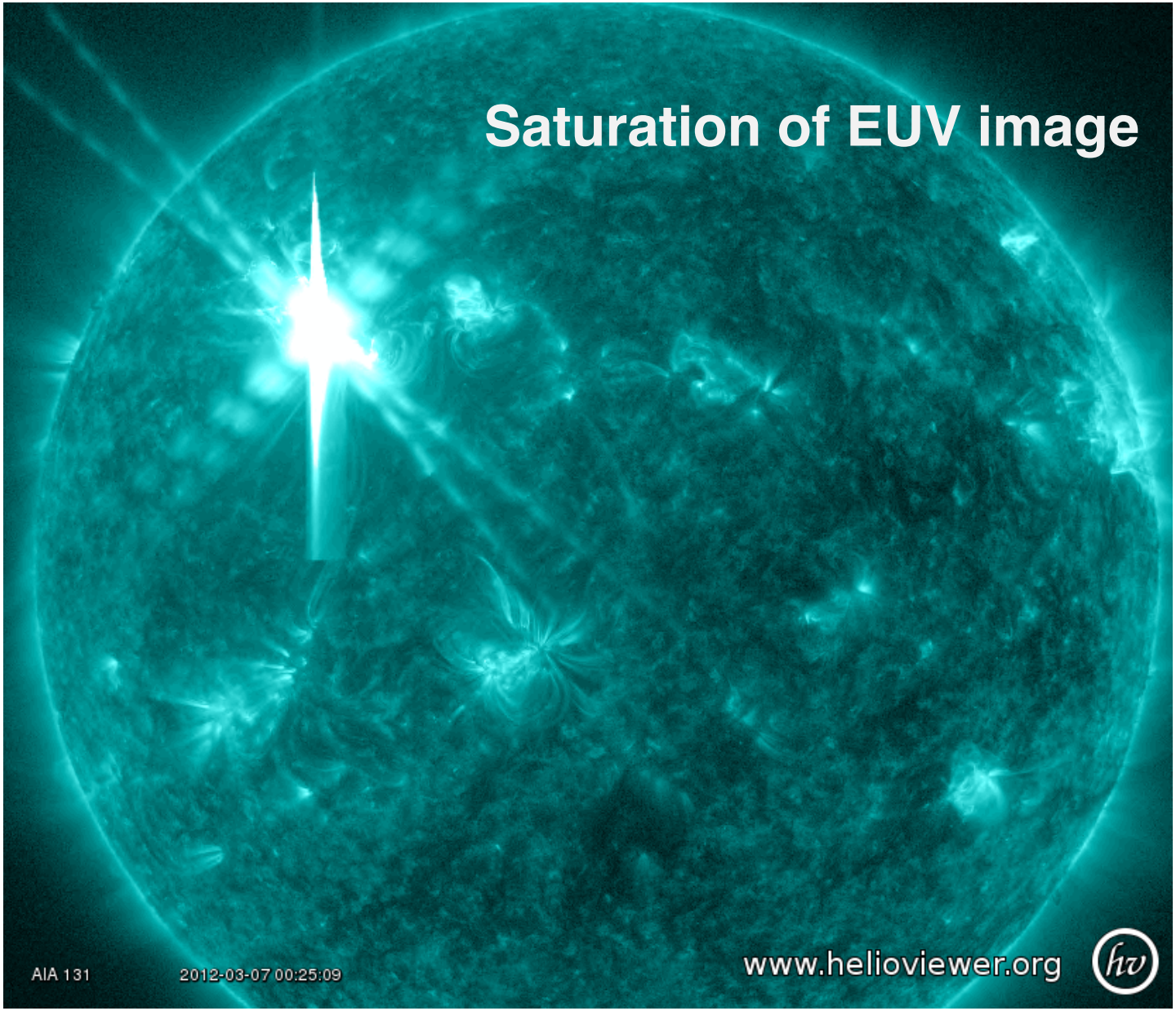
Why do we even care?

Technology-driven society

The Sun is the maker of space weather

The main DRIVERS of space weather…

What is a Flare?



Sudden, rapid variation in brightness indicating a conversion of magnetic energy into radiation and heat

Radiates across the whole electromagnetic spectrum

What is a CME?

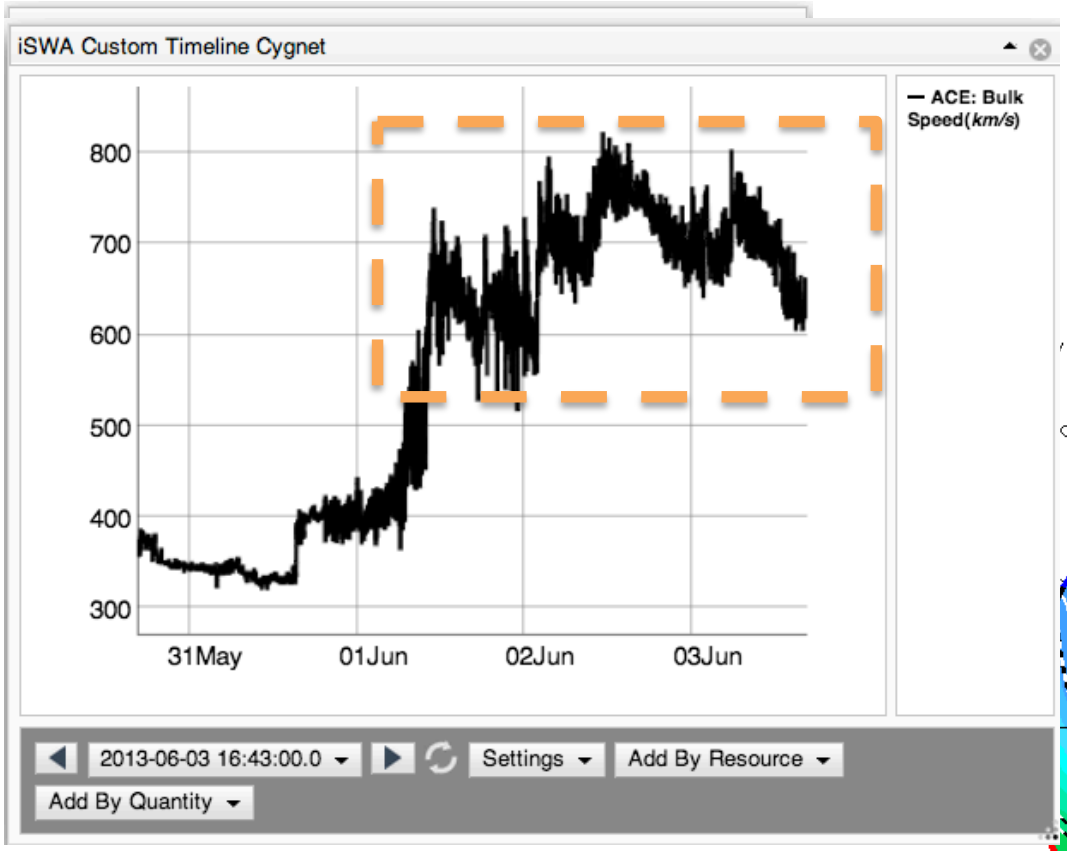
Eruption of 10^{15} grams of plasma

Speeds 100-1000s km/s

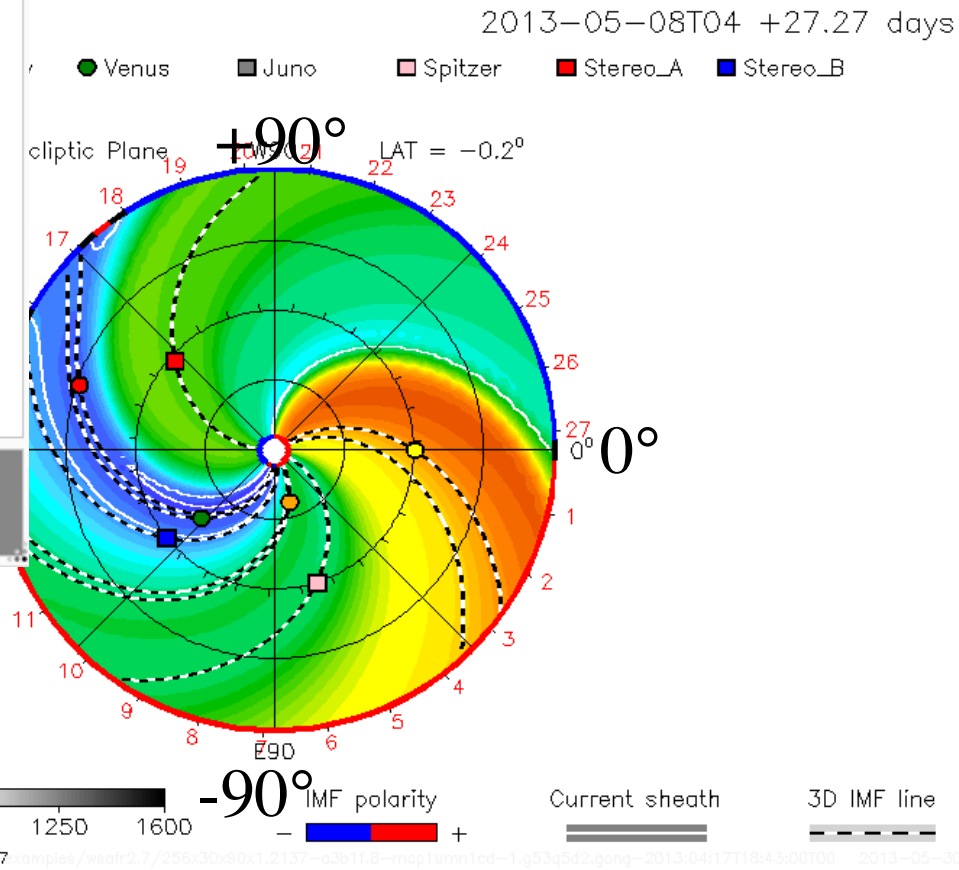
Internal magnetic field

Most are associated with flares, but the relationship is complicated…

What is a high speed stream (HSS)?



Seen as dark signature in EUV lines with T~>1.5 MK (but



Types of Storms: Minor to Extreme

1. Geomagnetic Storm: G1-G5

2. Solar Radiation Storm: S1-S5

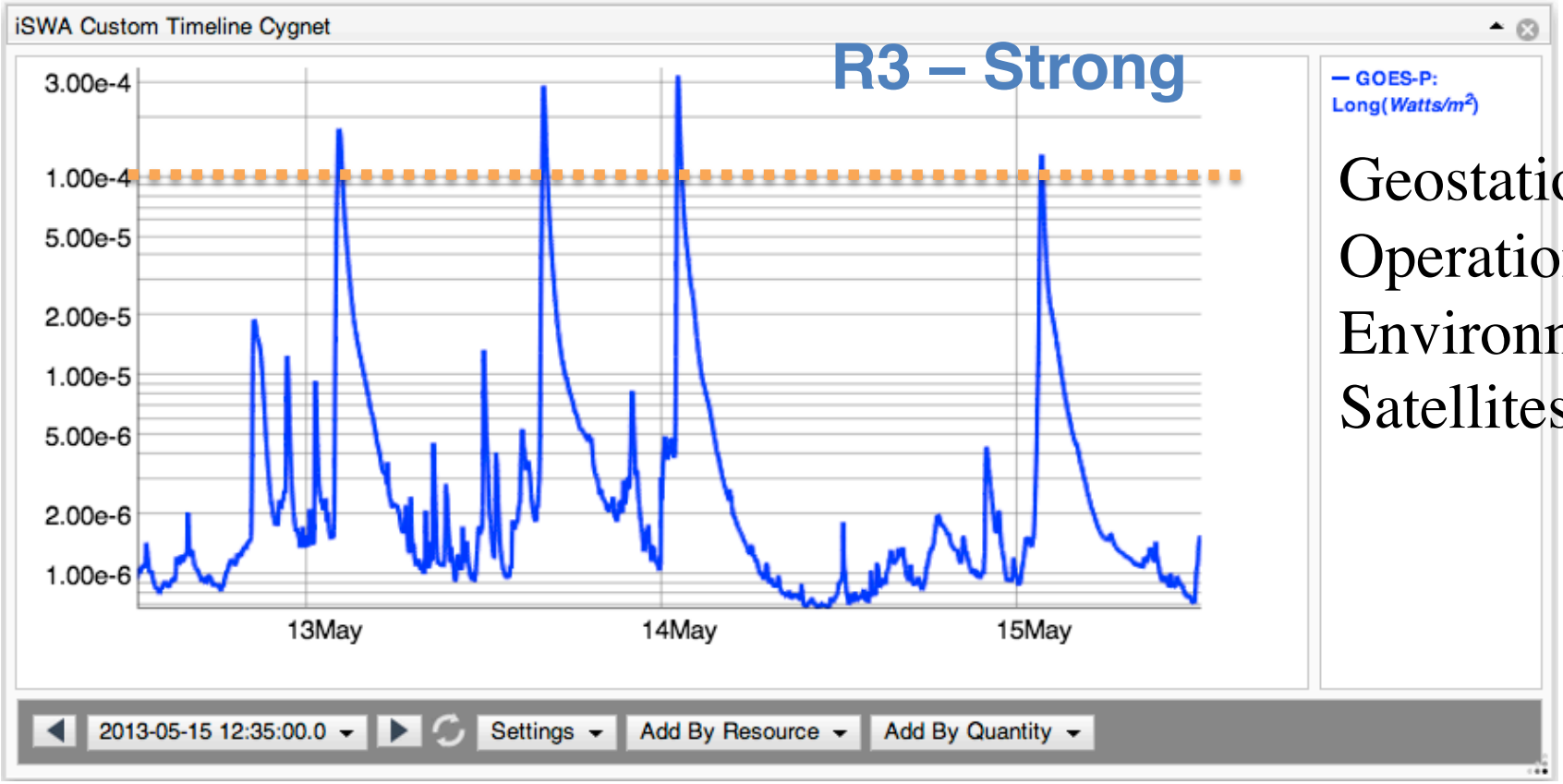
3. Radio Blackout: R1-R5

http://www.swpc.noaa.gov/NOAAscales/#SolarRadiationStorms

Types of Storms

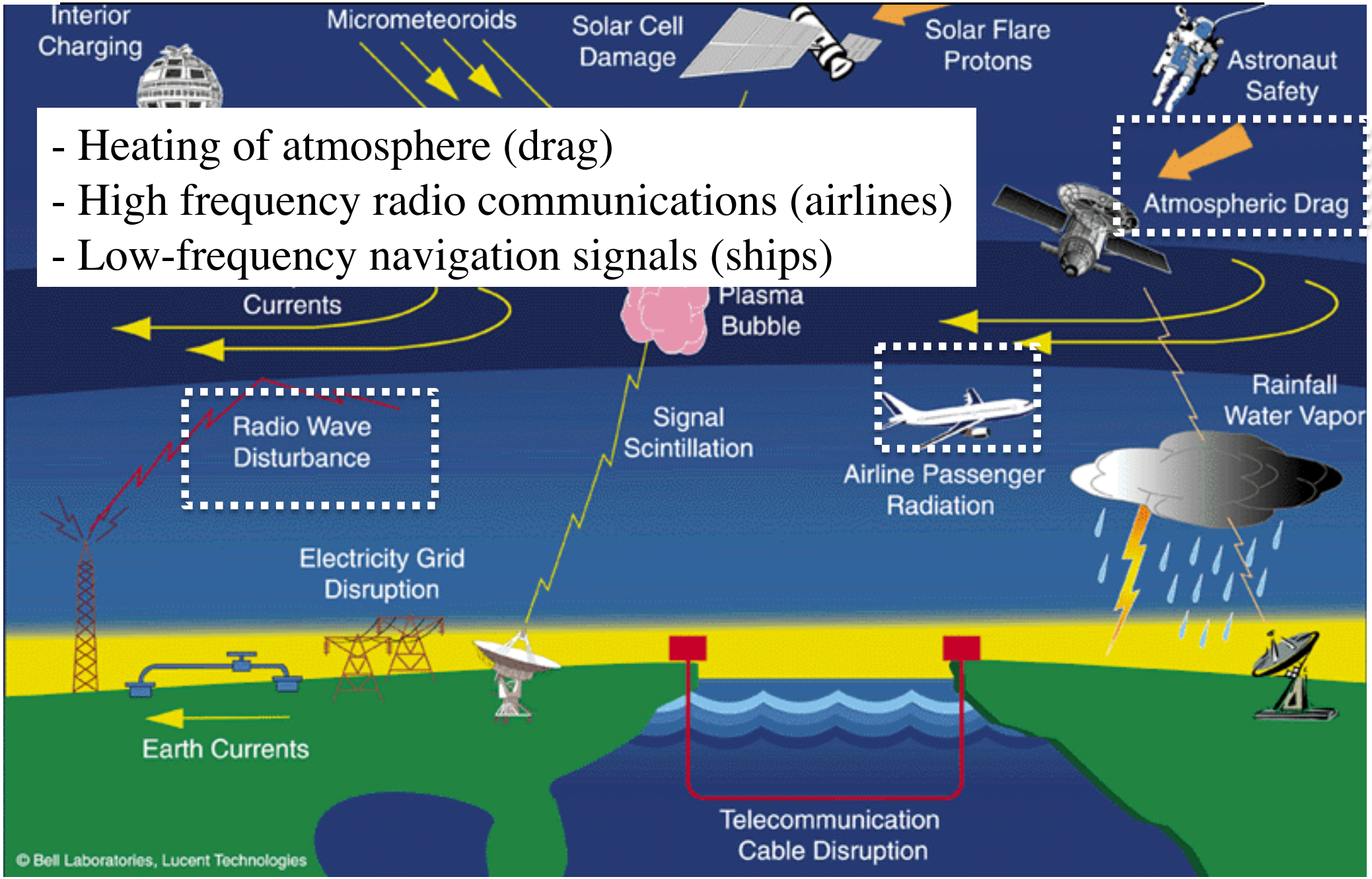
Radio Blackout: R1-R5

- *Source: Flare*
- *Measured quantity: X-ray flux*
- *Effect: heat the atmosphere*



Geostationary Operational Environmental Satellites

Radio Blackout Storm Effects

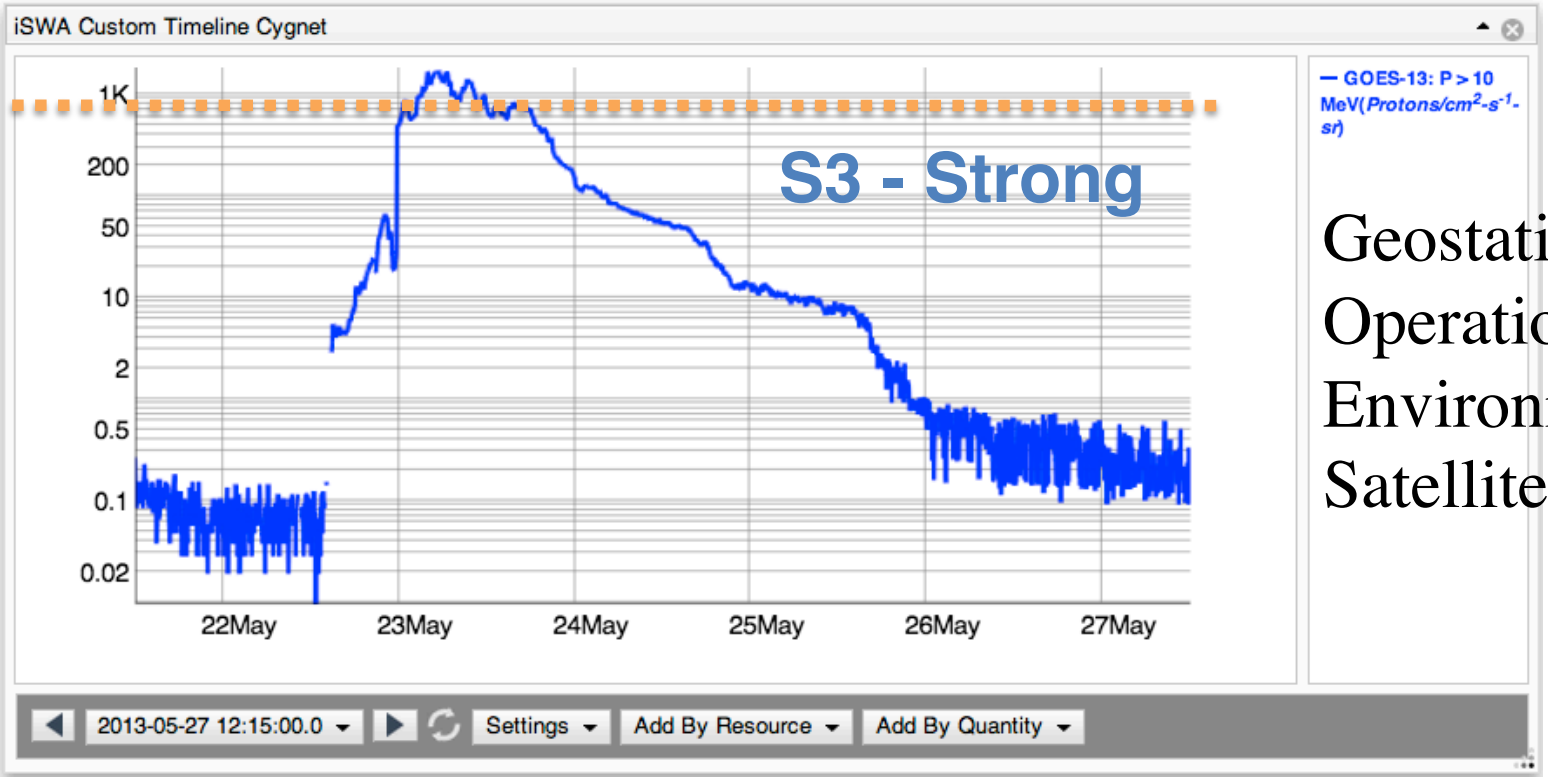


- Heating of atmosphere (drag)
- High frequency radio communications (airlines)
- Low-frequency navigation signals (ships)

Types of Storms

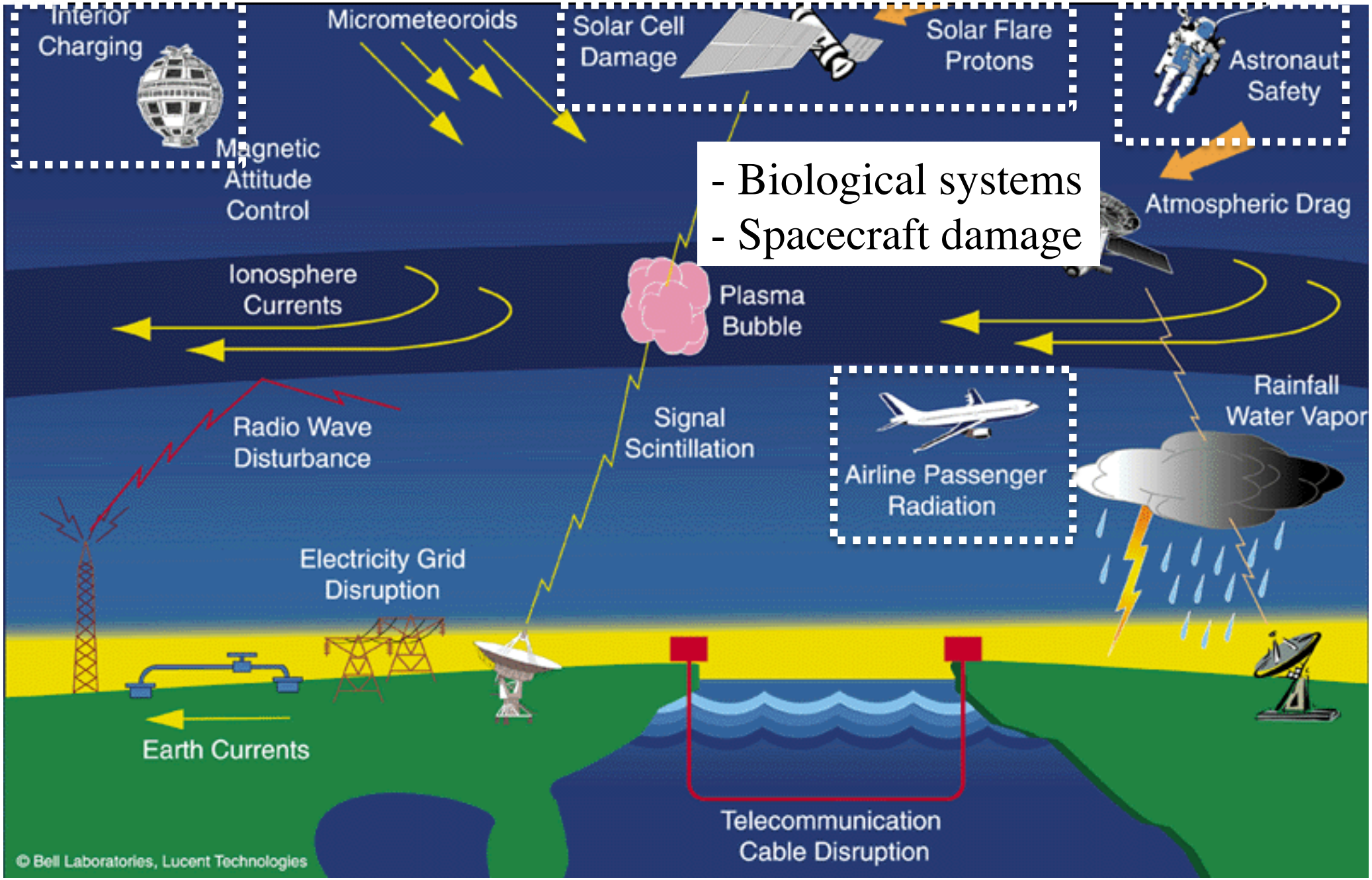
Solar Radiation Storm: S1-S5

- *Source can be: Flare, CME, and HSS*
- *Measured quantity: flux of energetic (>10 MeV) charged particles*



Geostationary Operational Environmental Satellites

Solar Radiation Storm Effects

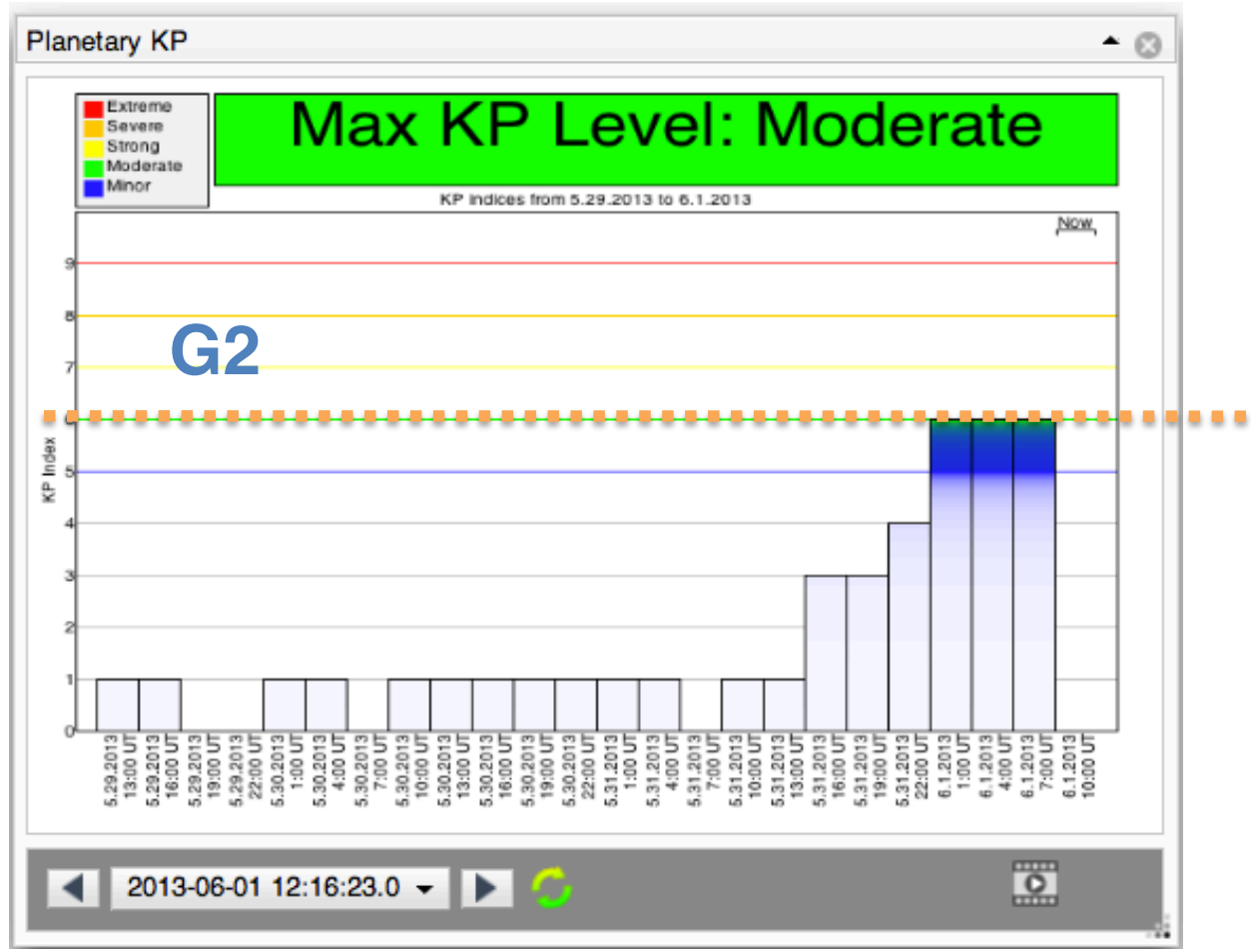


- Biological systems
- Spacecraft damage

Types of Storms

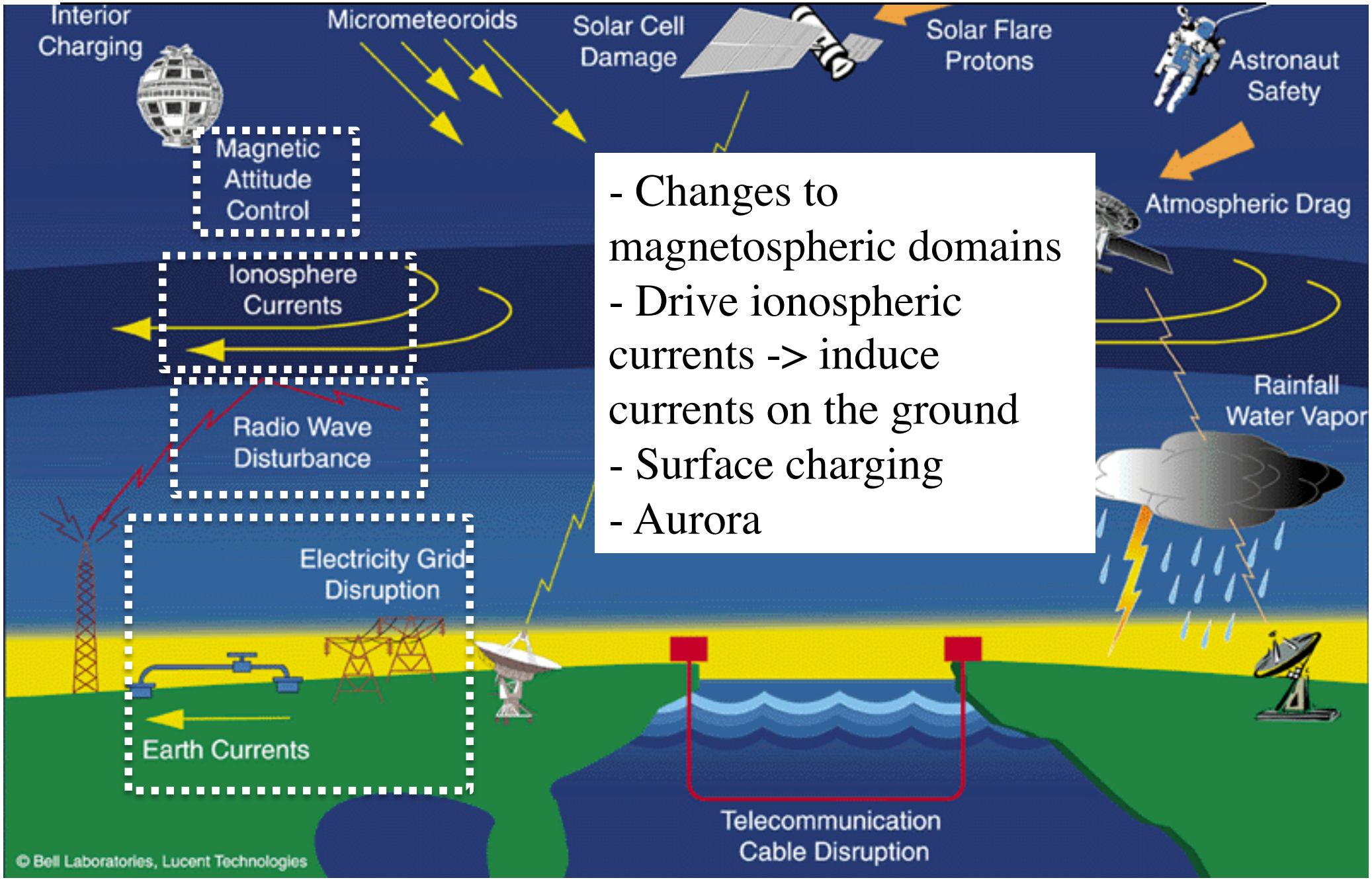
Geomagnetic Storm: G1-G5

- *Source can be:*
  - *Arrival of CME (can be severe)*
  - *Arrival of HSS (moderate)*
- *Measured quantity: Kp – index from 0-9 that describes fluctuations in the Earth's magnetic field*



http://www.swpc.noaa.gov/NOAAscales/#SolarRadiationStorms

Geomagnetic Storm Effects



- Changes to magnetospheric domains
- Drive ionospheric currents -> induce currents on the ground
- Surface charging
- Aurora

What is the Space Weather Research Center?

Space Weather Research Center at NASA/GSFC

Group that leverages resources of the CCMC (Community Coordinated Modeling Center)

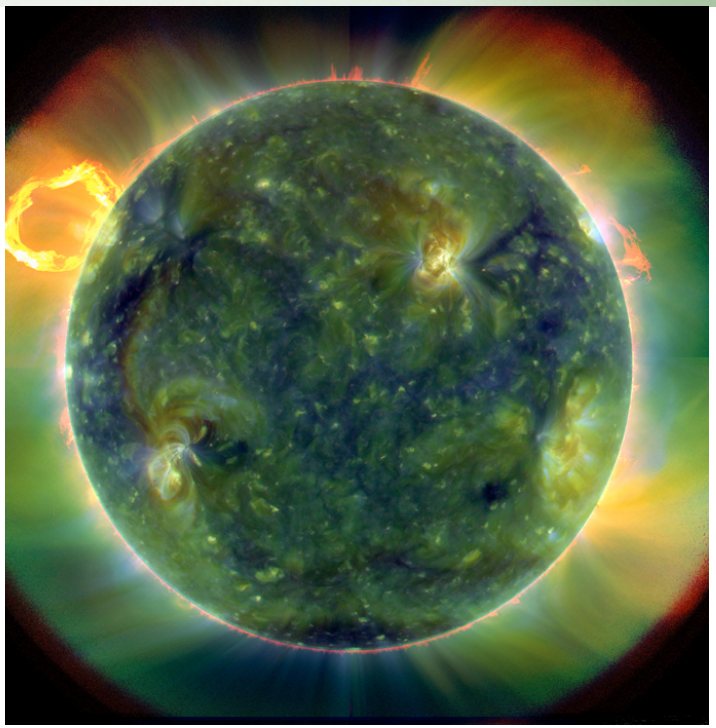
Objective:

Provide the latest space weather information to NASA robotic mission operators.

since March 2010

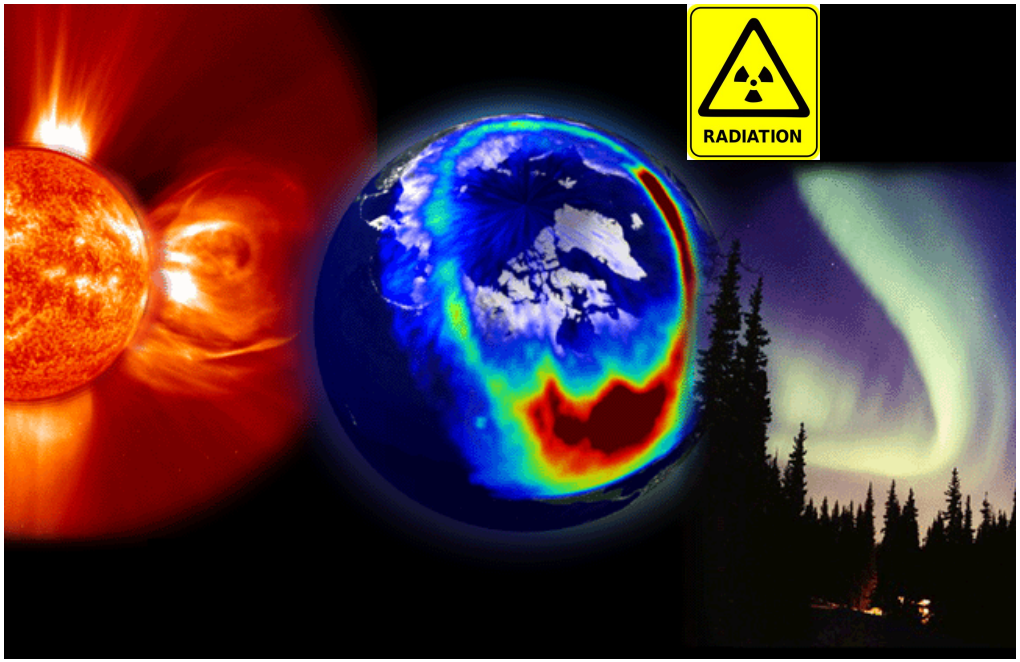
Types of Space Weather Services

1. Providing assistance in spacecraft anomaly resolution by assessing whether space weather has any role in causing the observed anomaly/ anomalies.
2. Sending out weekly space weather reports/ summaries to NASA mission operators, NASA officials and involved personnel.



Types of Space Weather Services

3. Disseminate timely space weather notifications regarding adverse conditions throughout the solar system, such as significant CME events, elevated radiation levels, etc.



4. Providing general space weather support for NASA customers.

http://swrc.gsfc.nasa.gov

Search

NASA Goddard Space Weather Research Center

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Home / Notifications & Analysis / Notifications

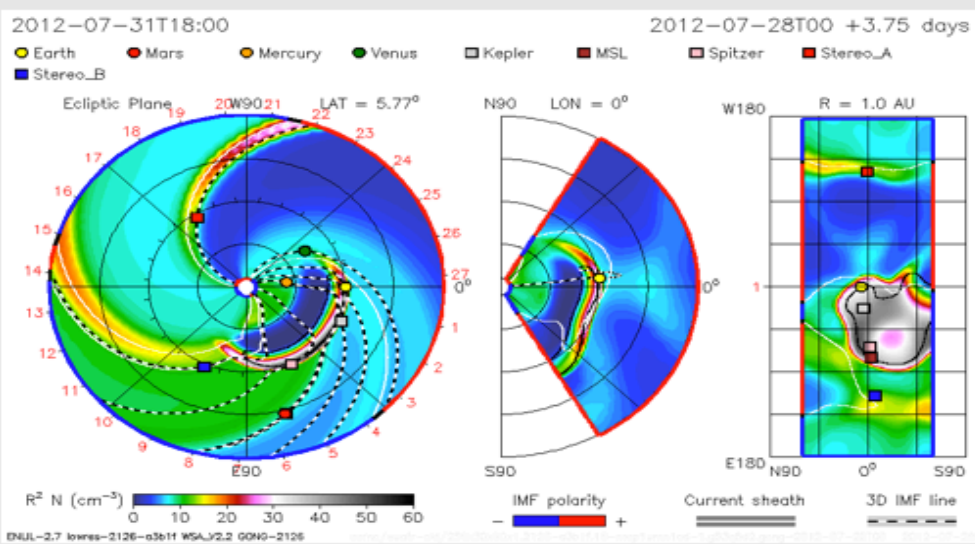
Important Disclaimer Notice

NOAA's Space Weather Prediction Center (http://swpc.noaa.gov) is the United States Government official source for space weather forecasts. This "Experimental Research Information" consists of preliminary NASA research products and should be interpreted and used accordingly.

Notifications

CME could impact Messenger, Spitzer, Earth, MSL, and Mars

SUBMITTED BY LMAYS ON SUN, 07/29/2012 - 03:28



How to monitor Space Weather

What are the sources of information?

- Directly measure quantities at a single point
- Remote sensing (images)
- Empirical models
- Physics-based models (driven by observations)
- Analysis tools

Access with iSWA (integrated Space Weather Analysis System)

To get a better understanding of these sources, let's track an event from the Sun to the Earth, comparing the 'Active' to 'Quiet' time data

First Driver: Flare

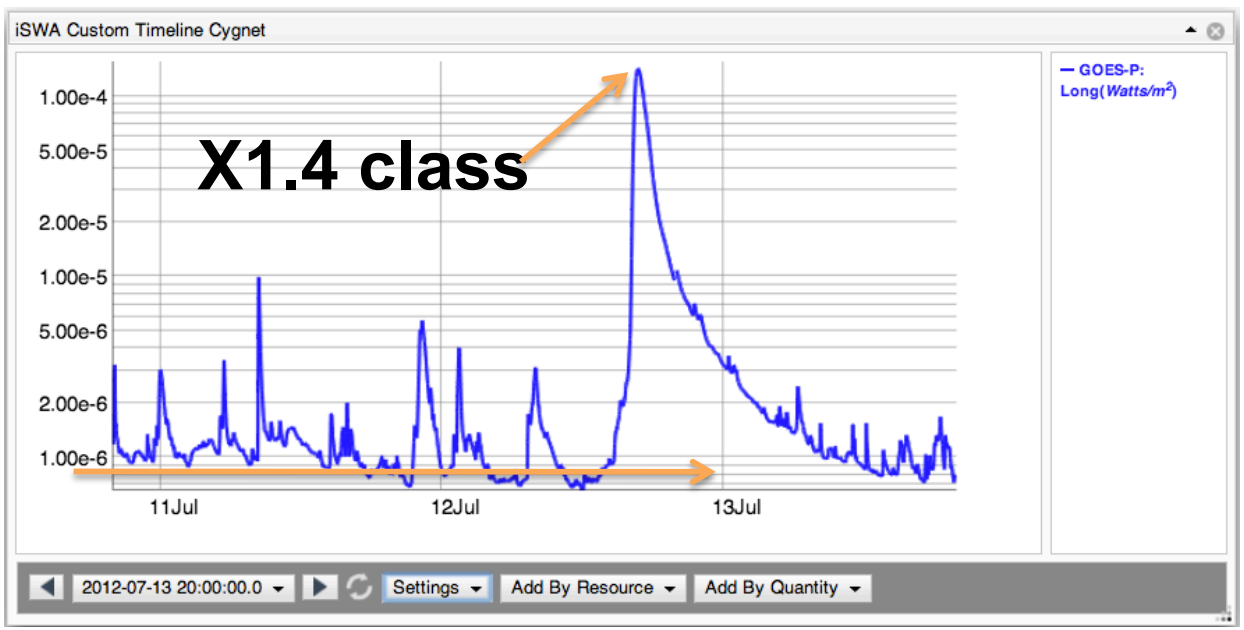
- **Increase in the flux of long wavelength X-rays 0.1-0.8 nm; [W/m^2]**
- **Geostationary Operational Environmental Satellites**

July 12, 2012 16:11 UT

How to monitor:

- ***GOES X-Ray Flux***
- ***SDO EVE***
- ***SDO AIA***

GOES-P (X-ray): Magnitude and Timing



First Driver: Flare

- **Brightening in the X-ray flux 0.1-0.7 nm**
- **Solar Dynamics Observatory/ Extreme Ultraviolet Variability Experiment**

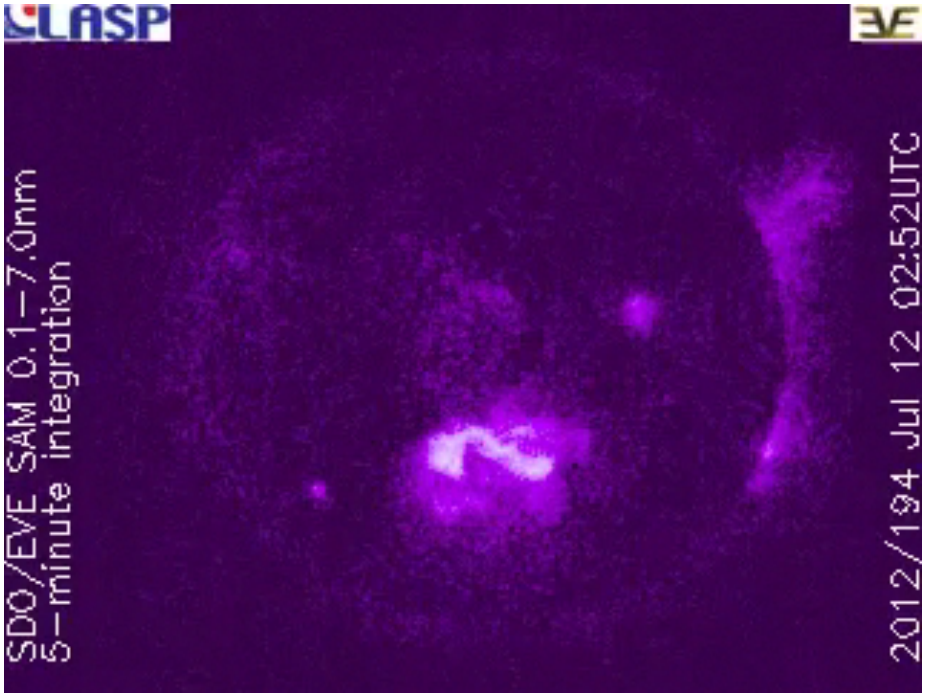
July 12, 2012 16:11 UT

How to monitor:

- ***GOES X Ray Flux***
- ***SDO EVE***
- ***SDO AIA***

SDO EVE (X-ray): Location

Quiet



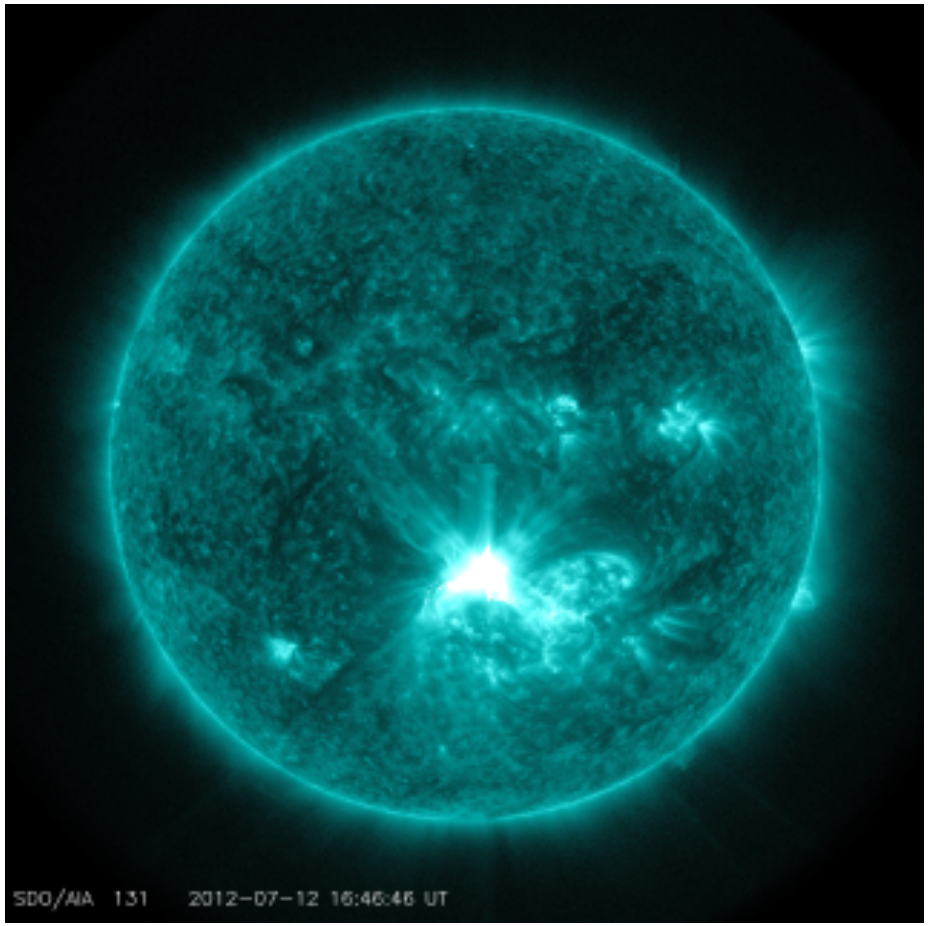
Active

First Driver: Flare

- Brightening in the EUV
- SDO/ Atmospheric Imaging Assembly (AIA), 131, 193 A
- Solar Terrestrial Relations Observatory (STEREO) / Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) / Extreme UV Imager (EUVI), 195 A

July 12, 2012 16:11 UT

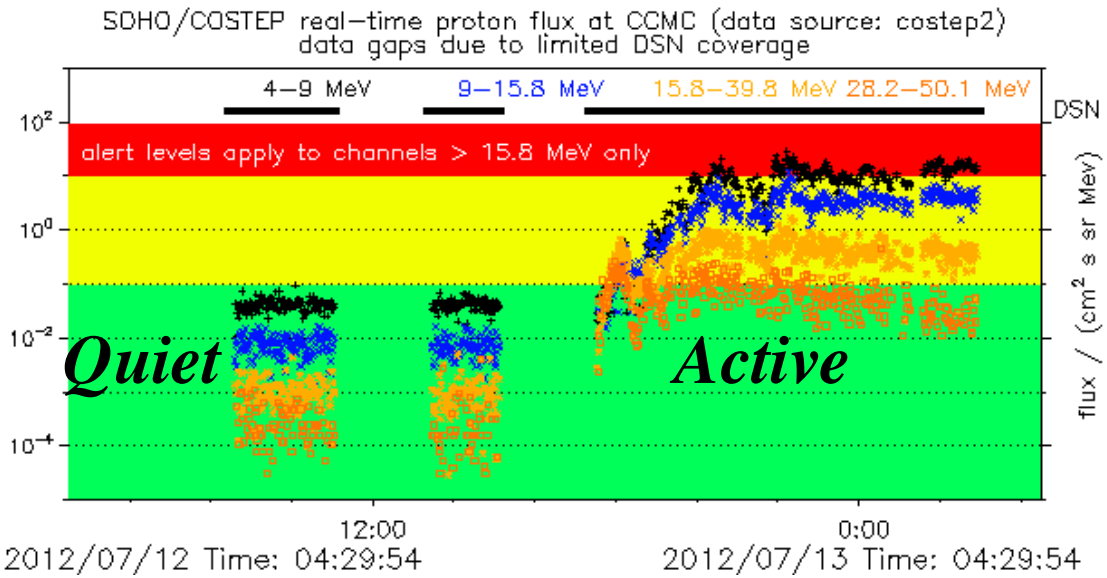
SDO AIA (EUV): Location

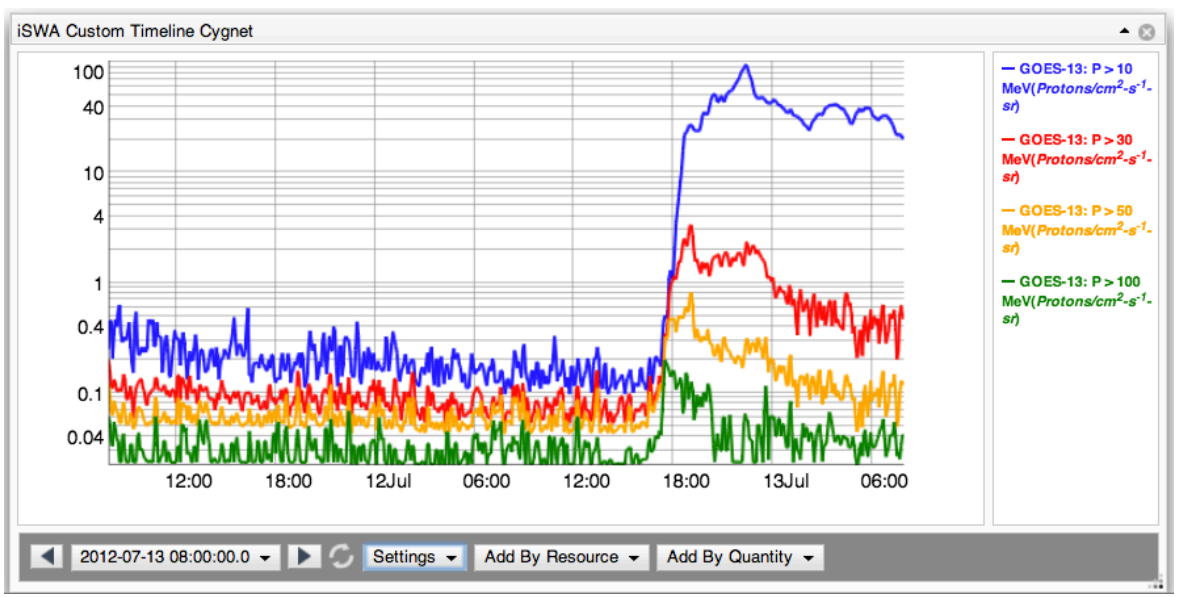


First Storm: SEP Radiation

July 12, 2012 17:50 UT

+ 1 hour 39 min



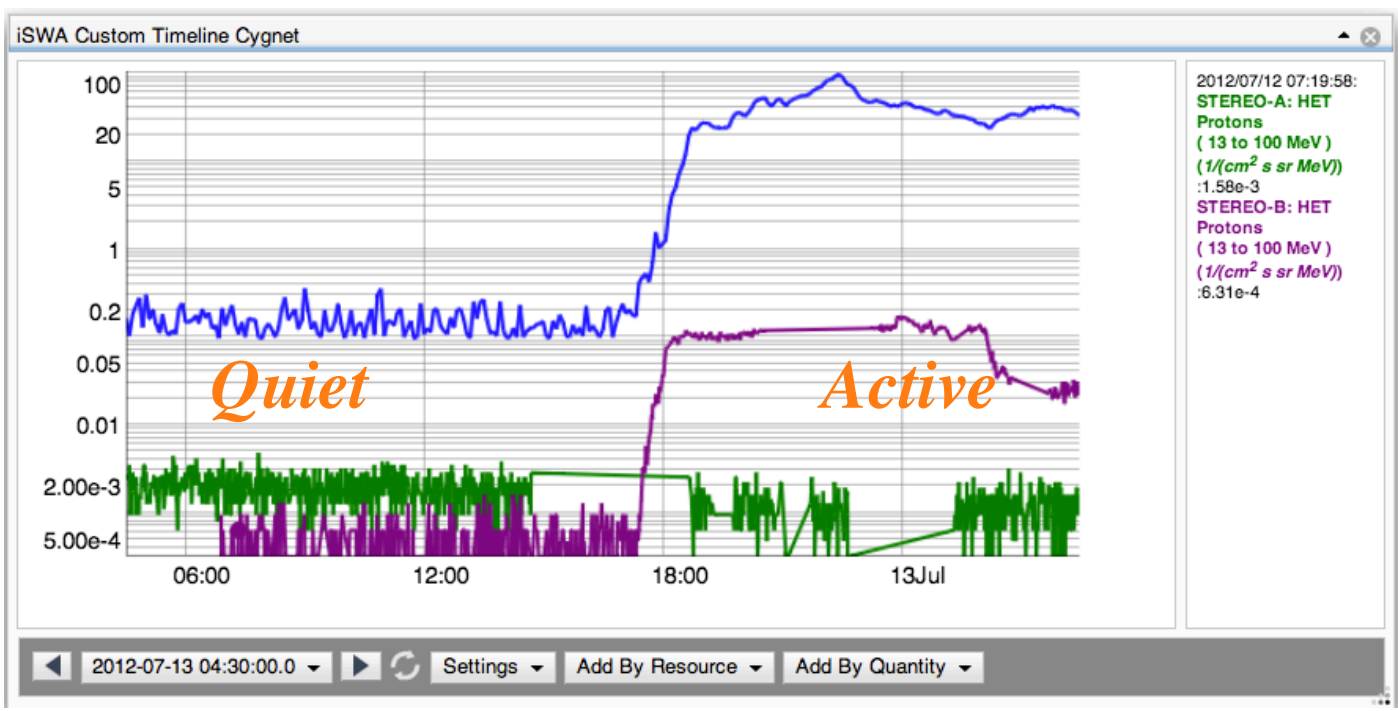


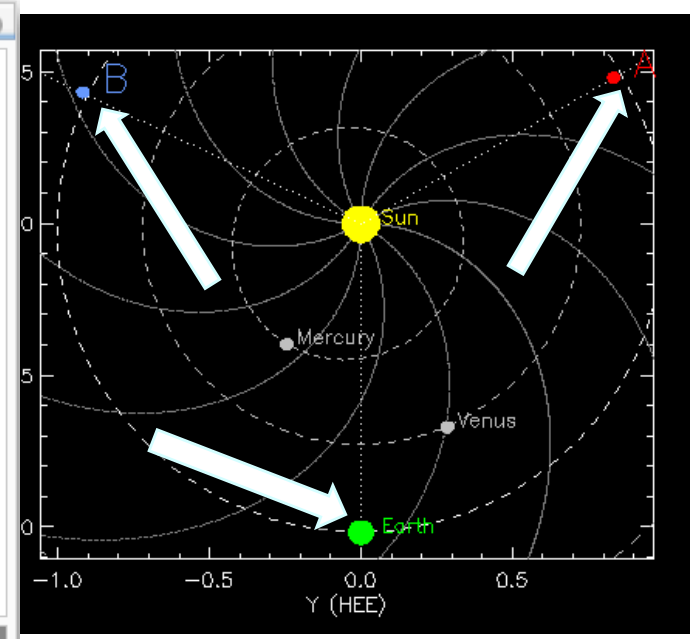
- **Upstream of Earth: Solar and Heliospheric Observatory (SOHO) / Comprehensive SupraThermal and Energetic Particle analyzer collaboration (COSTEP)**
- **In the magnetosphere: GOES**

First Storm: SEP Radiation

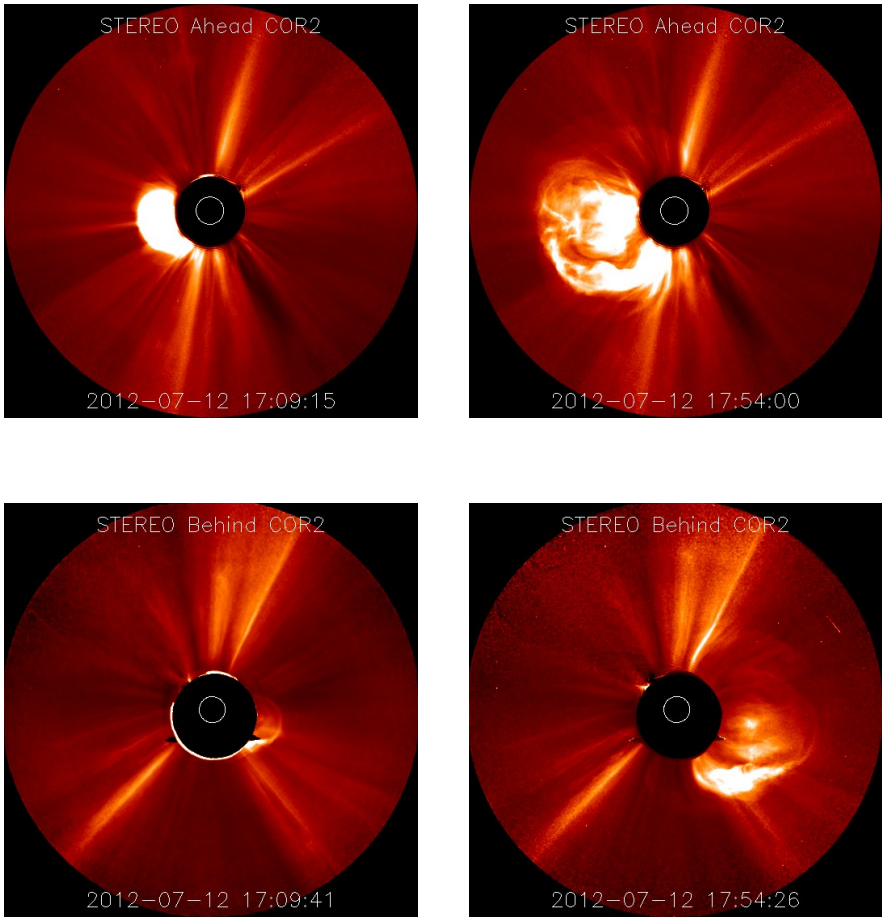
July 12, 2012 18:18 UT
+ 2 hours 7 min

In the heliosphere: STEREO In-situ Measurements of Particles and CME Transients (IMPACT) and Plasma and SupraThermal Ion Composition (PLASTIC)





Second Driver: CME



Speed, Width and Direction with Images and Analysis Tool

July 12, 2012 19:00 UT

+ 3 hours

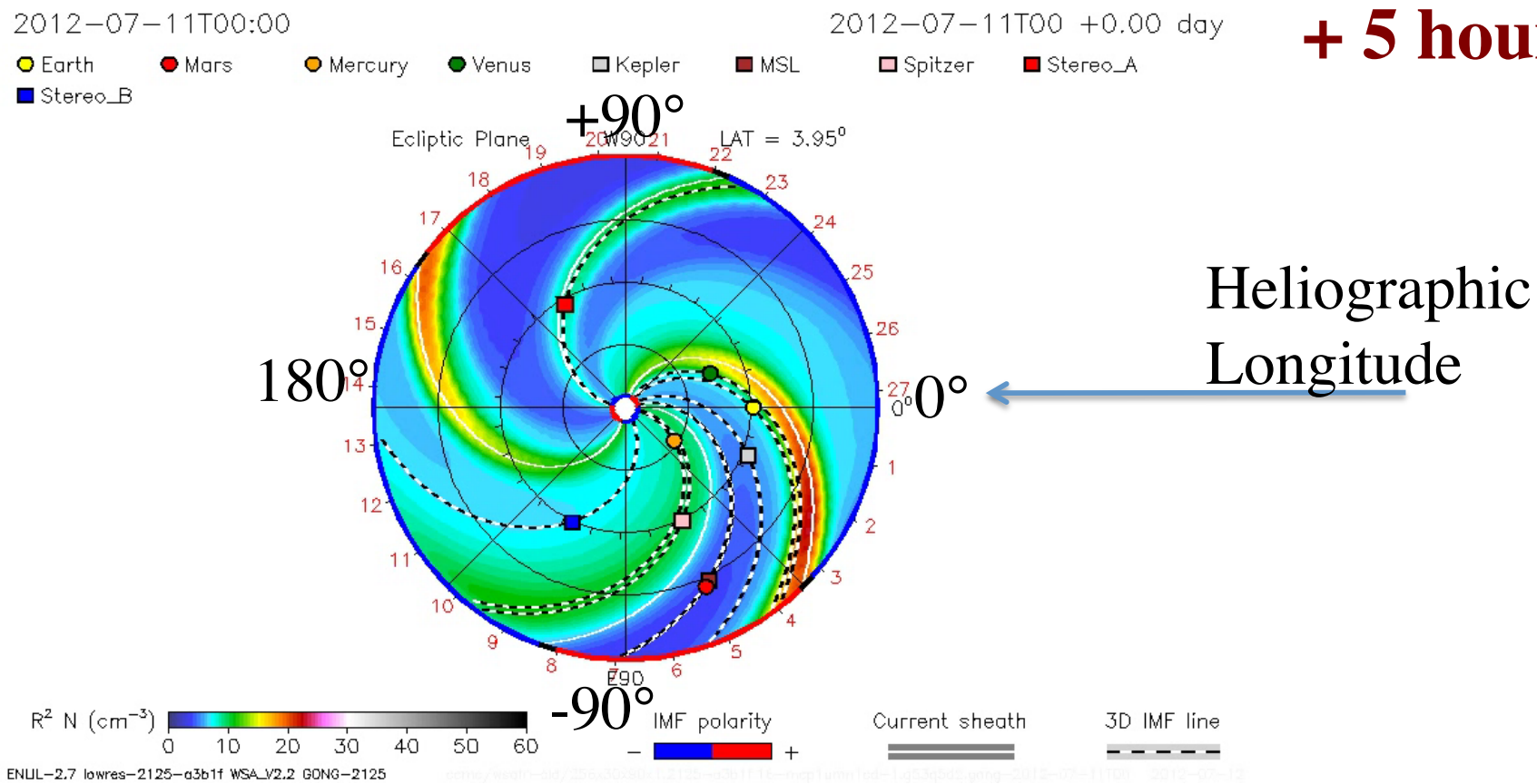
How to monitor:

- ***SDO/AIA 304 A***
- ***SOHO Large Angle and Spectrometric Coronagraph (LASCO) C2, C3***
- ***STEREO/SECCHI COR2A, COR2B***
- ***CME Analysis Tool***
- ***WSA-ENLIL+ cone model***

Second Driver: CME

July 12, 2012 21:00 UT

+ 5 hours



The estimated speed, width and position were in a coupled coronal-heliospheric model to determine the path of the CME. WSA, an empirical model driven by photospheric magnetic field measurements, is used to drive 3D time dependent MagnetoHydroDynamic (MHD) model ENLIL. Simulations are performed at the CCMC.

CME Arrival

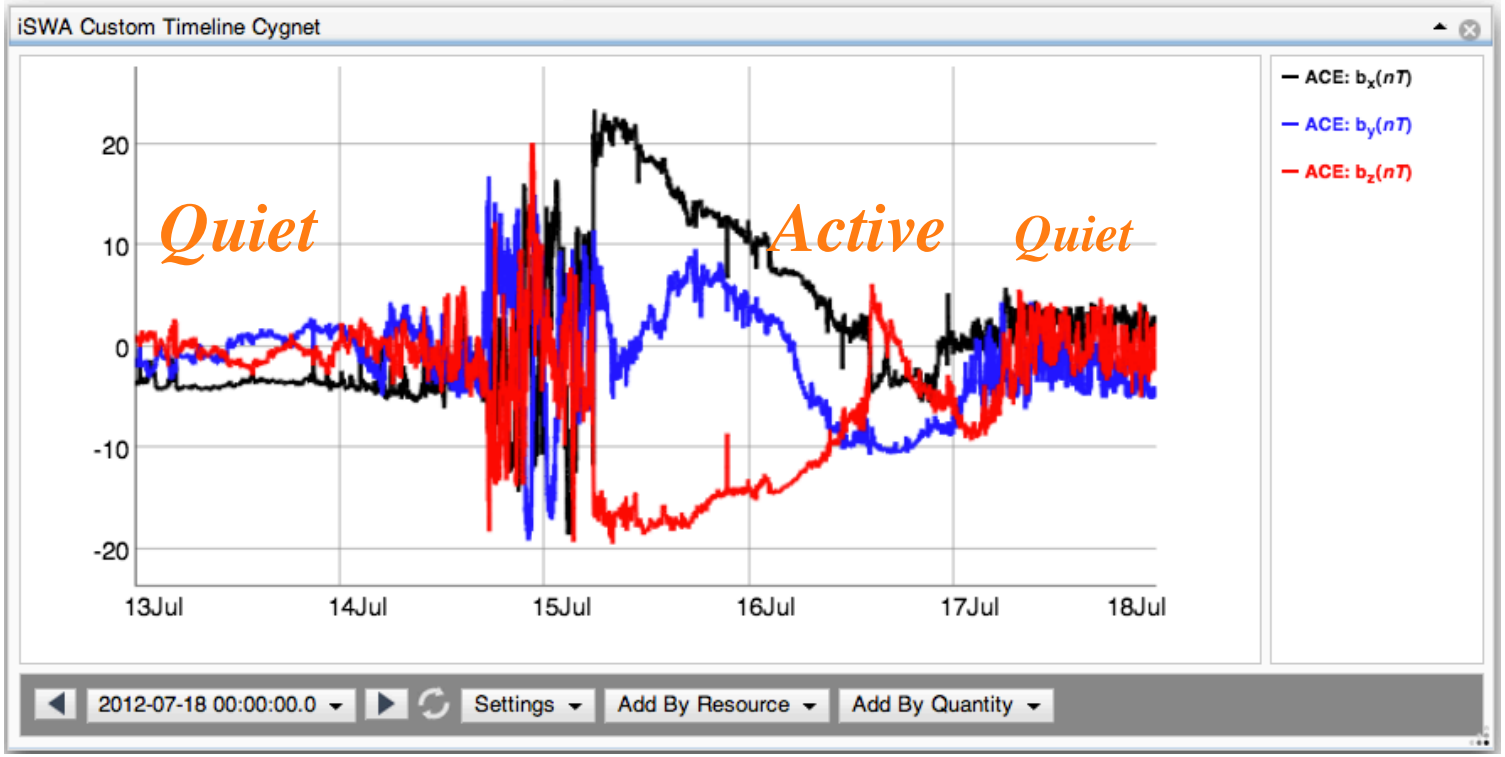
- **Upstream of Earth: Magnetic Field, Solar Wind Speed, Density and Temperature from Advanced Composition Explorer (ACE) and Wind**

July 14, 2012 17:26 UT

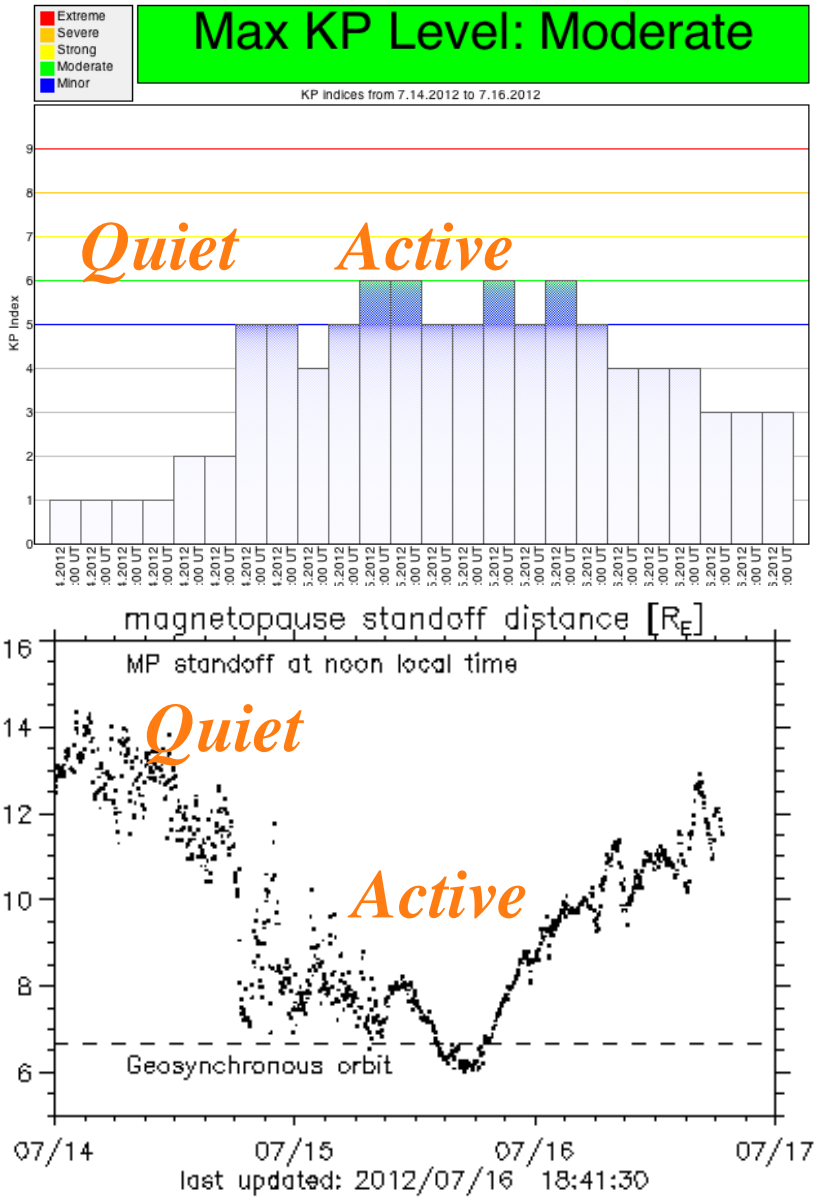
+ 2 days

Also monitor:

- ***Energetic protons***
- ***Radiation belt electrons***



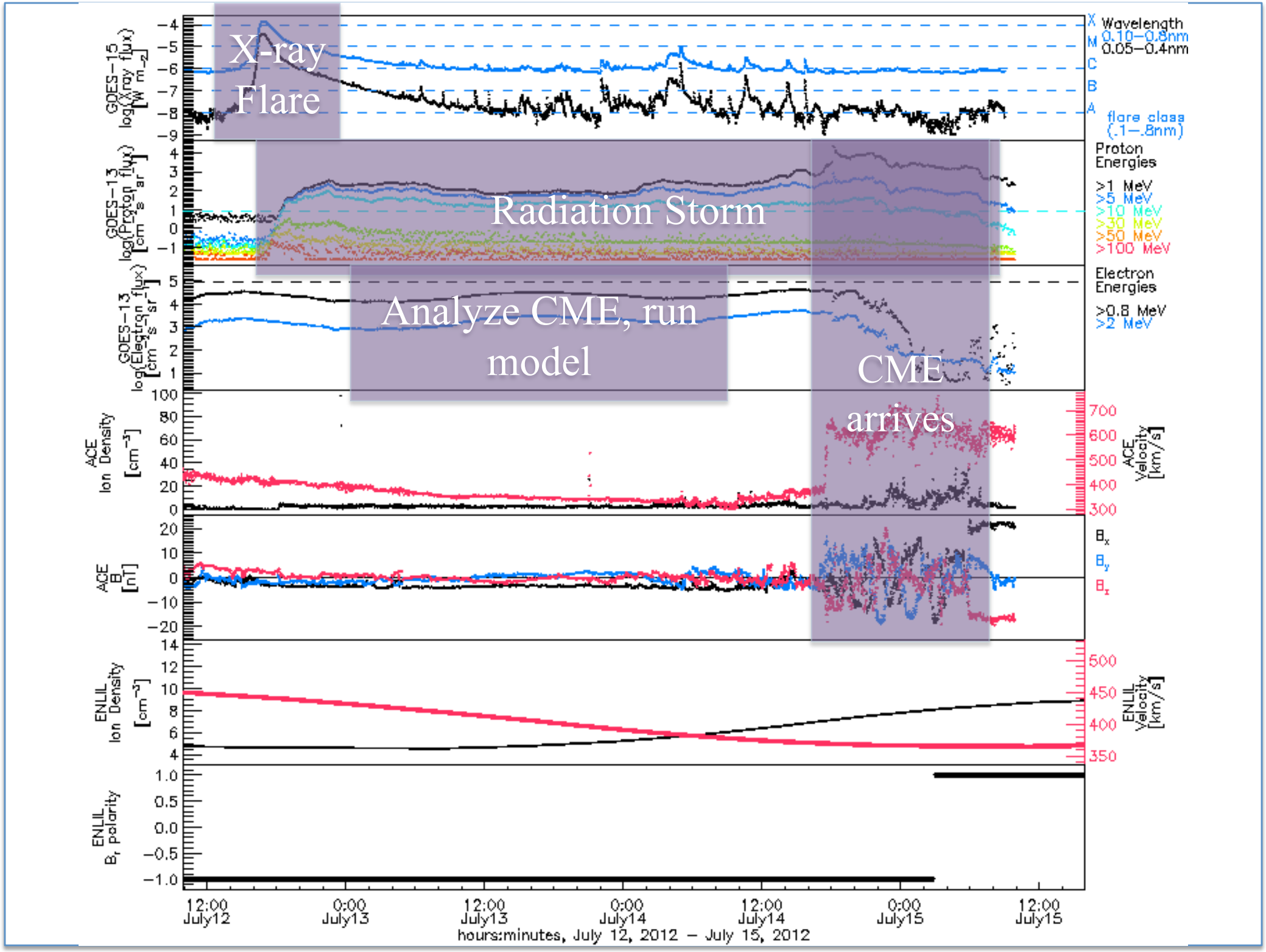
Geomagnetic Storm

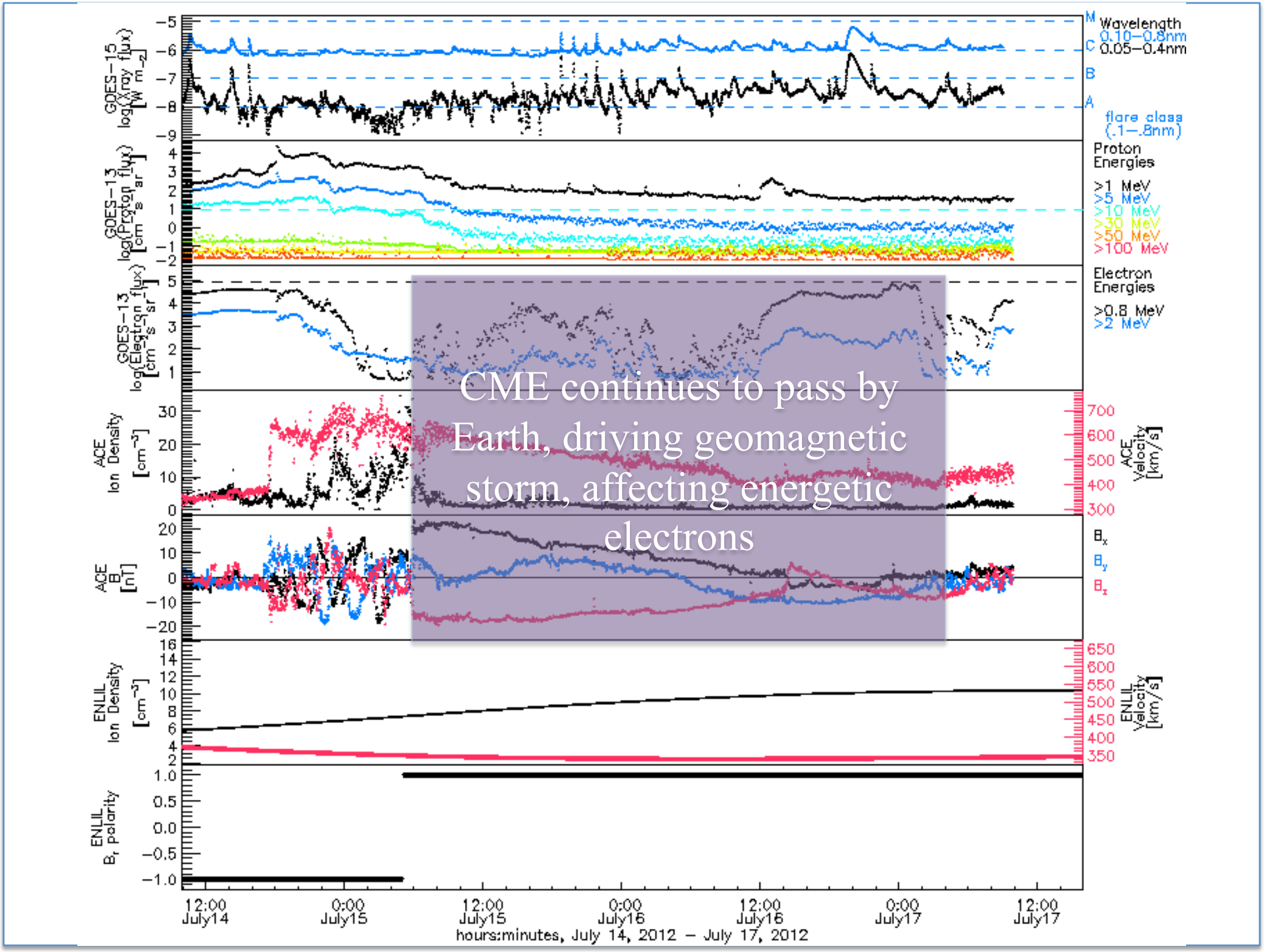


July 15, 2012 17:00 UT
+ 3 days

How to monitor:

- ***Measurements of ground magnetic field perturbations***
- ***ACE drives physics-based model to track location of magnetopause in relation to Geosynchronous Orbit***

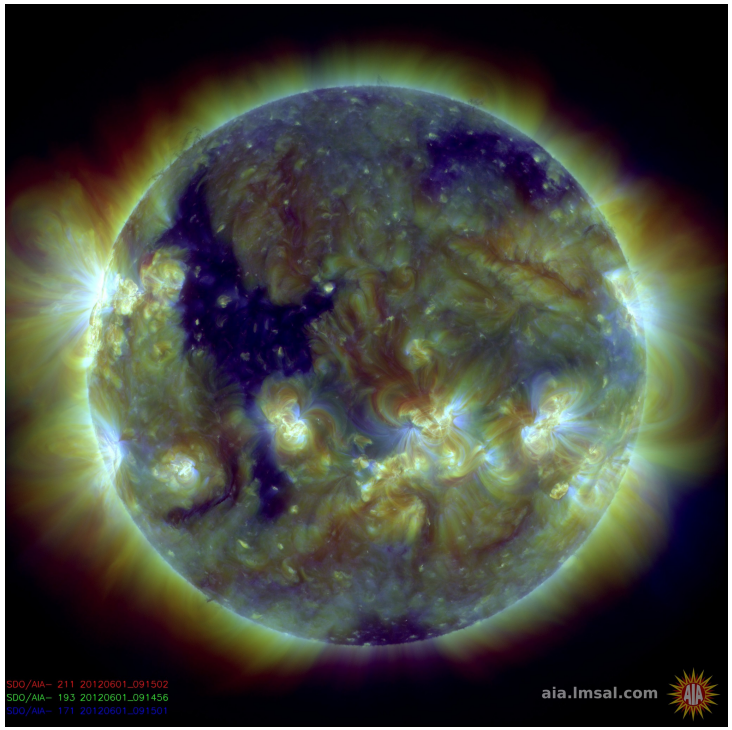

X-ray Flare
Radiation Storm
Analyze CME, run model
CME arrives
GOES-15 log(X-ray flux) [W m^-2]
X
M
C
B
A
Wavelength
0.10–0.8nm
0.05–0.4nm
flare class (.1–.8nm)
GOES-13 log(Proton flux) [cm^-2 s^-1 sr^-1]
Proton Energies
>1 MeV
>5 MeV
>10 MeV
>30 MeV
>50 MeV
>100 MeV
GOES-13 log(Electron flux) [cm^-2 s^-1 sr^-1]
Electron Energies
>0.8 MeV
>2 MeV
ACE Ion Density [cm^-3]
ACE Velocity [km/s]
ACE B [nT]
B_x
B_y
B_z
ENLIL Ion Density [cm^-3]
ENLIL Velocity [km/s]
ENLIL B_r polarity
12:00 July12
0:00 July13
12:00 July13
0:00 July14
12:00 July14
0:00 July15
12:00 July15
hours:minutes, July 12, 2012 – July 15, 2012


CME continues to pass by Earth, driving geomagnetic storm, affecting energetic electrons
GOES-15 log(X-ray flux) [W m-2]
Wavelength
0.10–0.8nm
0.05–0.4nm
flare class (.1–.8nm)
GOES-13 log(Proton flux) [cm-2 s-1 sr-1]
Proton Energies
>1 MeV
>5 MeV
>10 MeV
>30 MeV
>50 MeV
>100 MeV
GOES-13 log(Electron flux) [cm-2 s-1 sr-1]
Electron Energies
>0.8 MeV
>2 MeV
ACE Ion Density [cm-3]
ACE Velocity [km/s]
ACE B [nT]
ENLIL Ion Density [cm-3]
ENLIL Velocity [km/s]
ENLIL Br polarity
12:00 July14
0:00 July15
12:00 July15
0:00 July16
12:00 July16
0:00 July17
12:00 July17
hours:minutes, July 14, 2012 – July 17, 2012

Finally, aurora…

Summary of Intro to Space Weather

- **Technology-dependent society demands that we understand space weather**
- **Main drivers are Flares, CMEs and HSS**
- **There are many research topics to be explored**



Other lectures will go into more details on all of these topics!

Summary: HSS SWx Impacts

HSS: usually long-duration (3-4 days)

Radiation belt electron flux enhancement - takes 2-3 days from the CIR interface

Spacecraft Surface charging

Satellite drag due to neutrals

Equatorial bubbles/irregularities – communication problems

Geomagnetic disturbances (moderate at most)

Magnetopause compression

Summary: 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 on dayside
- Heating of upper atmosphere: satellite drag
- Contribute to SEP – proton radiation, lasting a couple of days
- Affect radio comm., GPS, directly by its radio noises at different wavelengths
  - *This noise is generally short-lived but can cause interference for sensitive receivers including radar, GPS, and satellite communications.*

Summary: CME SWx Impacts

- Contribute to SEP (particle radiation): 20-30 minutes from the occurrence of the CME
- Result in a geomagnetic storm: takes 1-2 days arriving at Earth
- Magnetopause compression
- Result in electron radiation enhancement in the near-Earth space (multiple CMEs): takes 1-3 day
- Affect spacecraft electronics – surfacing charging/internal charging, single event upsets
- Radio communication, navigation
- Power grid, pipelines

More impacts on robotic missions

1. **Spacecraft surface charging caused by low-energy (< 100 keV)** electrons, which are abundant, for example, in the inner magnetosphere during magnetospheric substorms.
2. **Spacecraft internal electrostatic discharge caused by high-energy** electrons (> 100 keV) that exist, for example, in the dynamic outer radiation belt of the Earth.
3. **Single event effects due to high-energy (> 10 MeV) protons and heavier** ions generated, for example, in solar flares and in coronal mass ejection (CME) shock fronts.
4. **Total dosage effects caused by cumulative charged particle radiation** received by spacecraft.
5. **Increased spacecraft drag caused by the thermal expansion of the** Earth's upper atmosphere during space weather storms.
6. **Communication disruptions between ground stations and spacecraft due** to ionospheric irregularities
7. **Attitude control disruptions caused, for example, by large storm-time** magnetic field fluctuations in the geostationary orbit.