ECEN 615, Fall 2023
Methods of Electric Power System Analysis

Class 22: Geomagnetically Induced Current (GIC)

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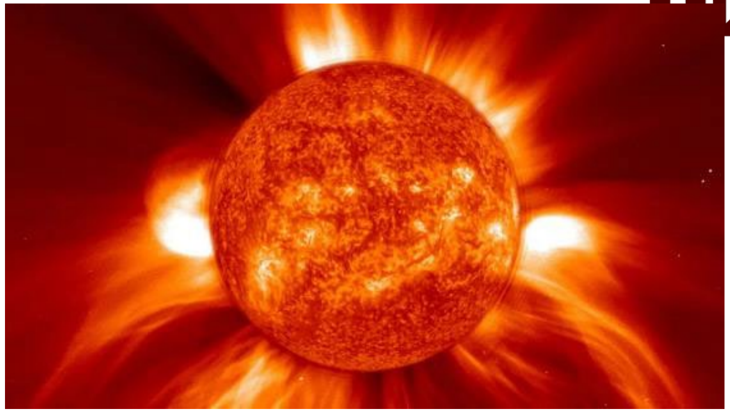
Geomagnetic Disturbances (GMDs)



- GMDs are caused by solar corona mass ejections (CMEs) impacting the earth's magnetic field
  - CMEs come in different sizes, and they may not be directed towards the earth
  - Largest GMD in the last 200 years was in 1859; it is known at the Carrington Event and caused Northern Lights as far south as Mexico
  - A GMD caused a blackout in 1989 of Quebec
  - They have the potential to severely disrupt the electric grid by causing quasi-dc geomagnetically induced currents (GICs) in the high voltage grid
- Until just a few years ago power engineers had few tools to help them assess the impact of GMDs; this has now changed

Image source: www.space.com/coronal-mass-ejections-cme

GMDs and Planning

- GMD assessment tools have moved into the realm of planning and operations
- NERC now has planning standards in the area, with TPL-007-4 (Transmission Planned Performance for Geomagnetic Disturbance Events) establishing requirements for the planned performance of the bulk electric system during GMDs
- Planning challenge is what to do, if anything, beyond the standards. That is, what would you do if a GMD of magnitude xx occurred?

Source: www.nerc.com/pa/Stand/Reliability%20Standards/tpl-007-4.PDF

Earth’s Magnetic Field

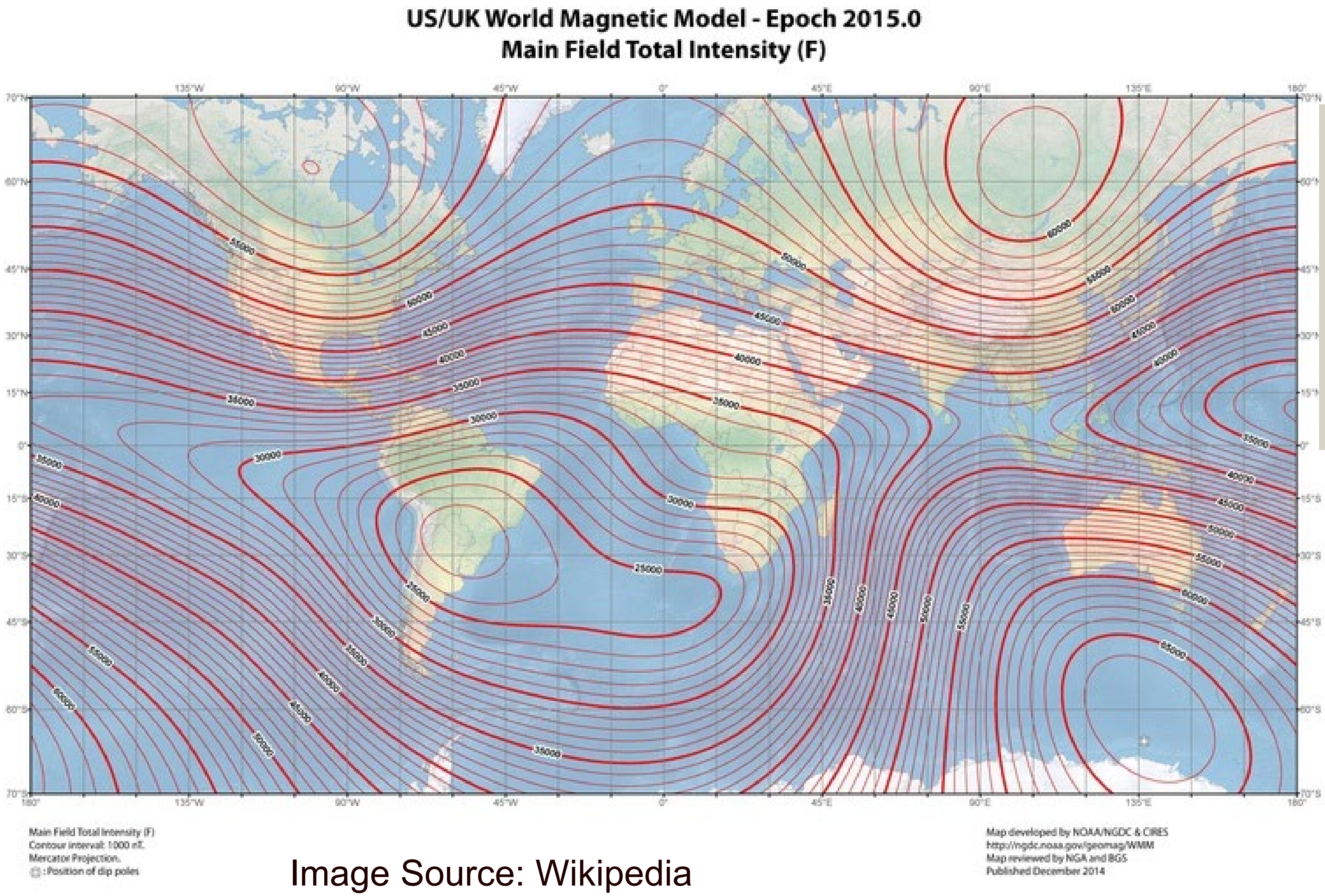


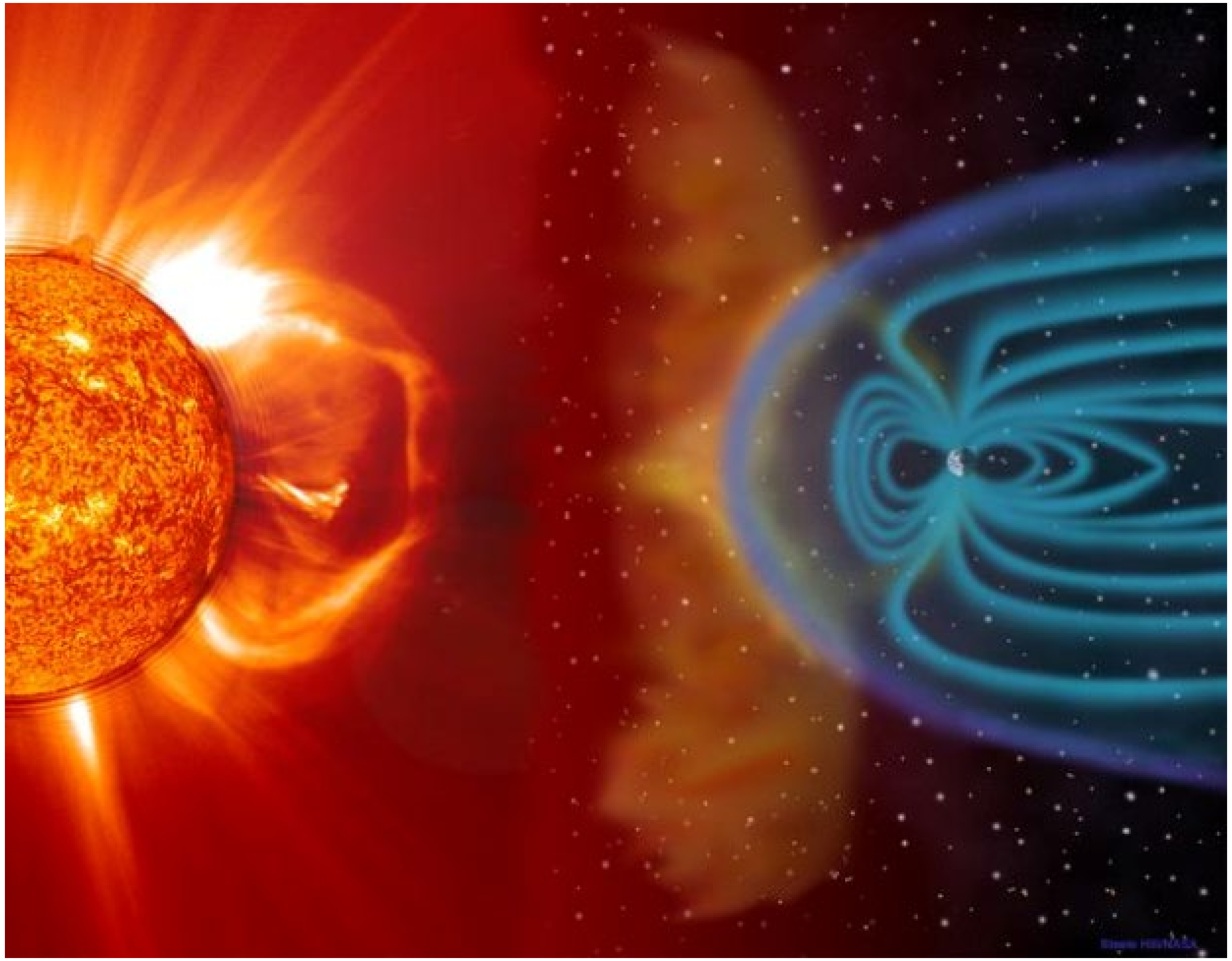
Image Source: Wikipedia

The earth’s magnetic field is usually between 25,000 and 65,000 nT; or equivalently, since one gauss (G) is 100,000 nT, it is between 0.25 and 0.6 G

Space Weather

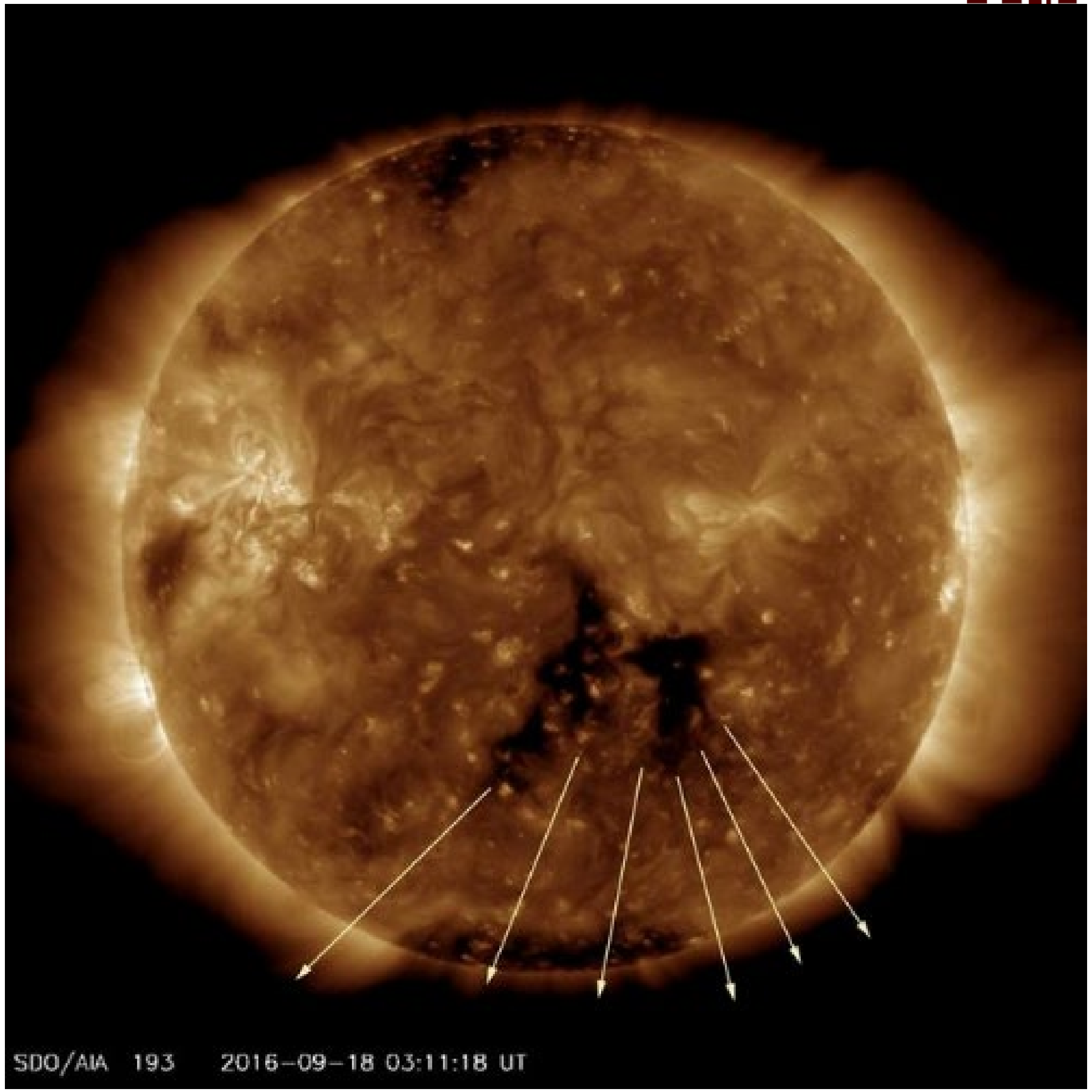
- Space weather is the interaction between the Sun and the Earth. (It's all about the magnetic field)

- Aurora
- Van Allen radiation belts
- Magnetosphere, ionosphere
- Solar wind
- Solar activity (flares, sunspots, etc)



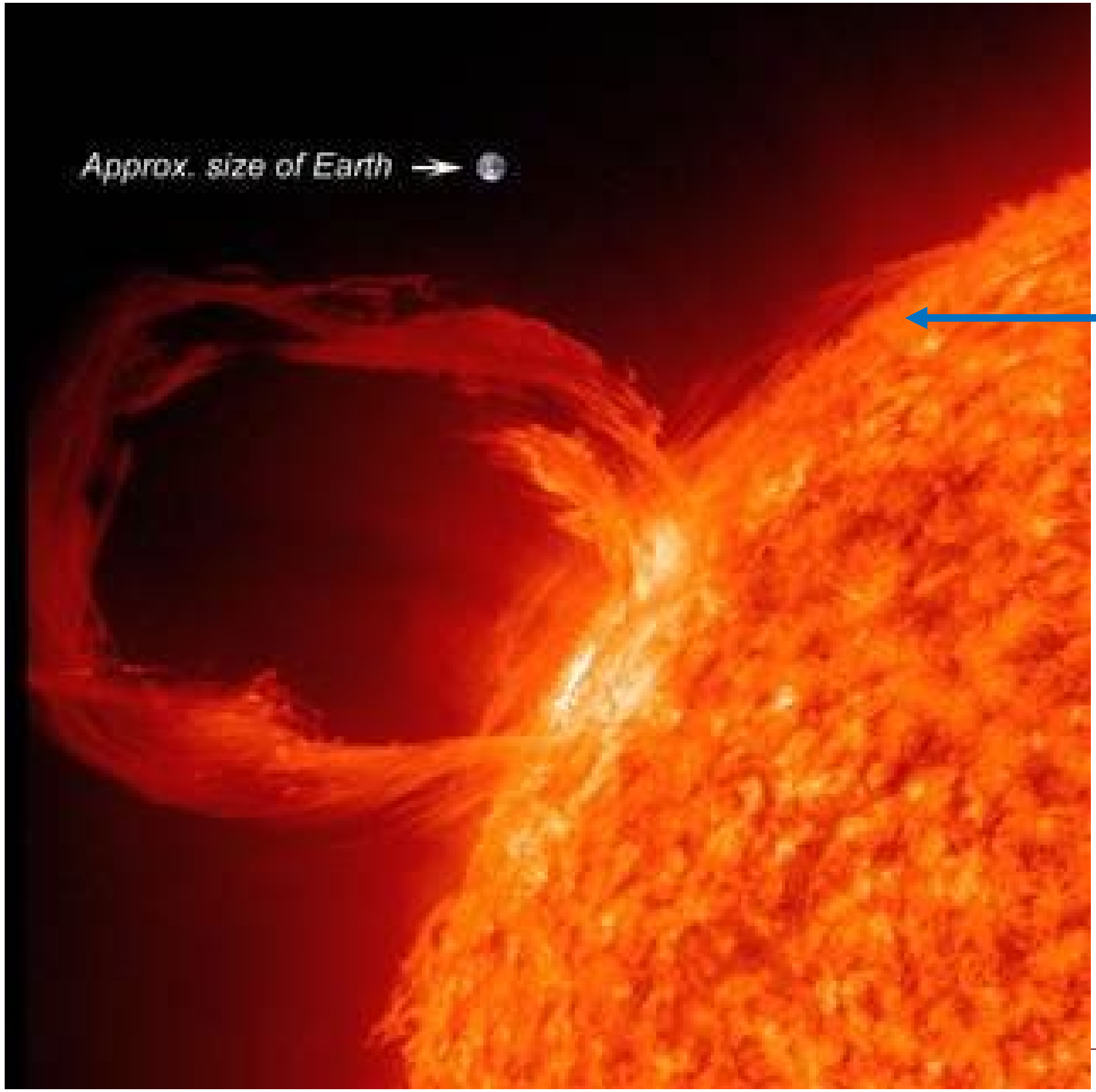
The Sun

- On the sun, lots of activity is happening:
  - Flares, CMEs, sunspots, high speed streams, CIRS
  - For GIC analysis, what's important is what might hit the earth



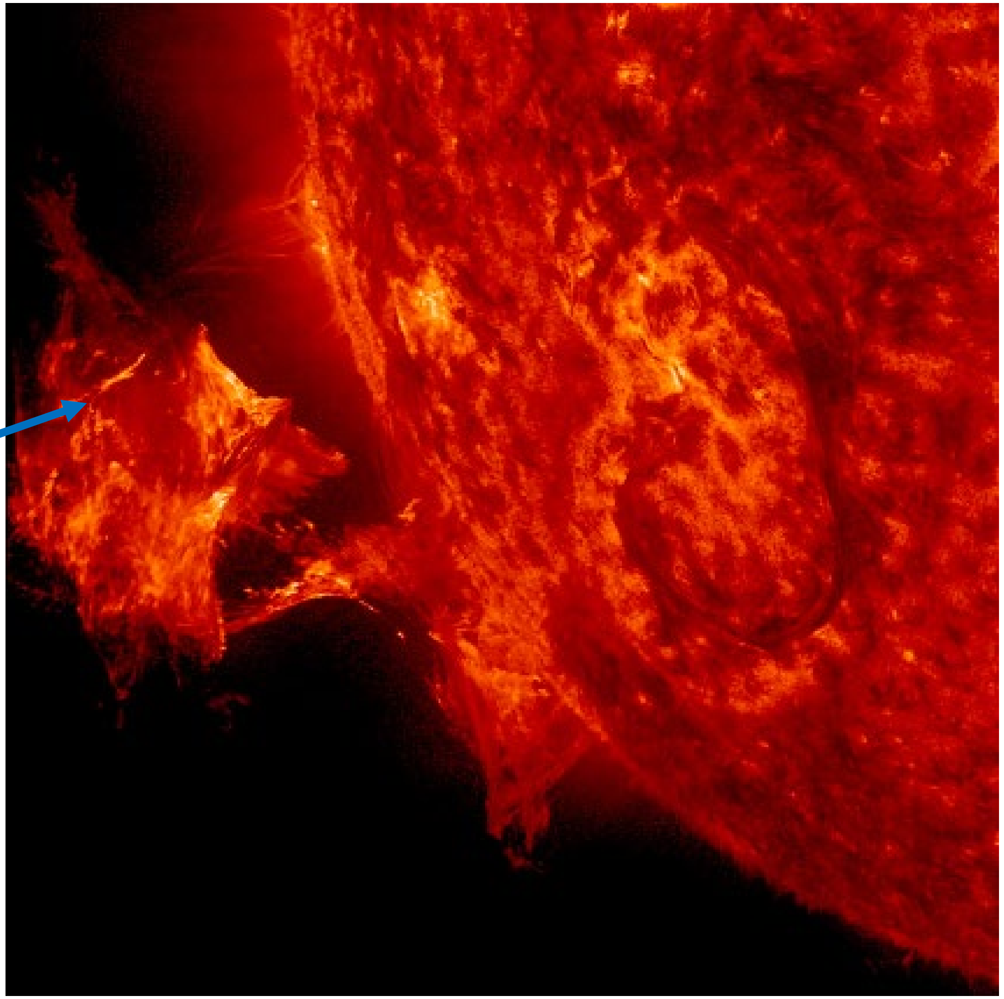
A look at electromagnetic activity of the sun

There are Different Kinds of Solare Effects that Can Produce GMDs

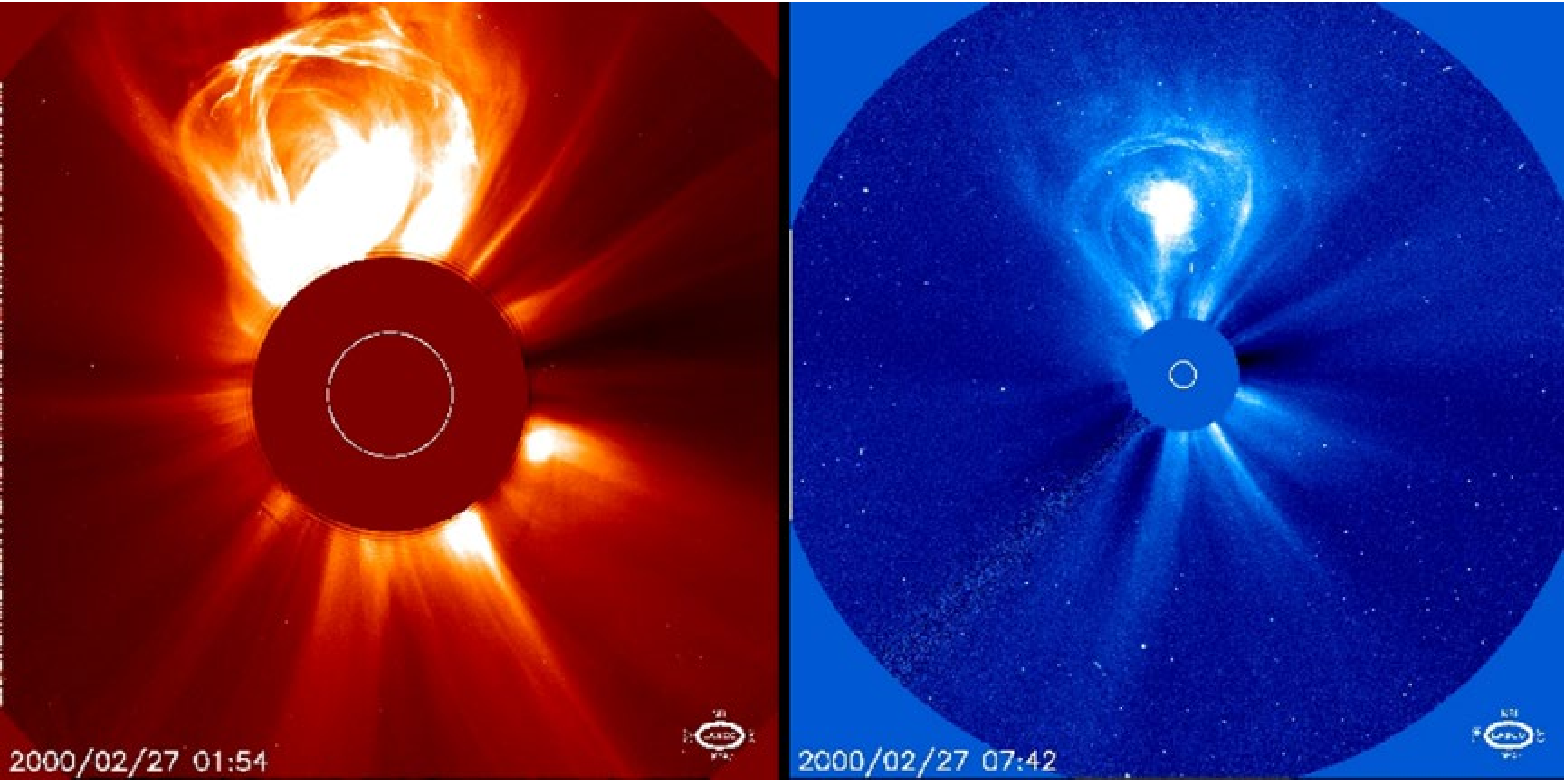


Prominence

CME

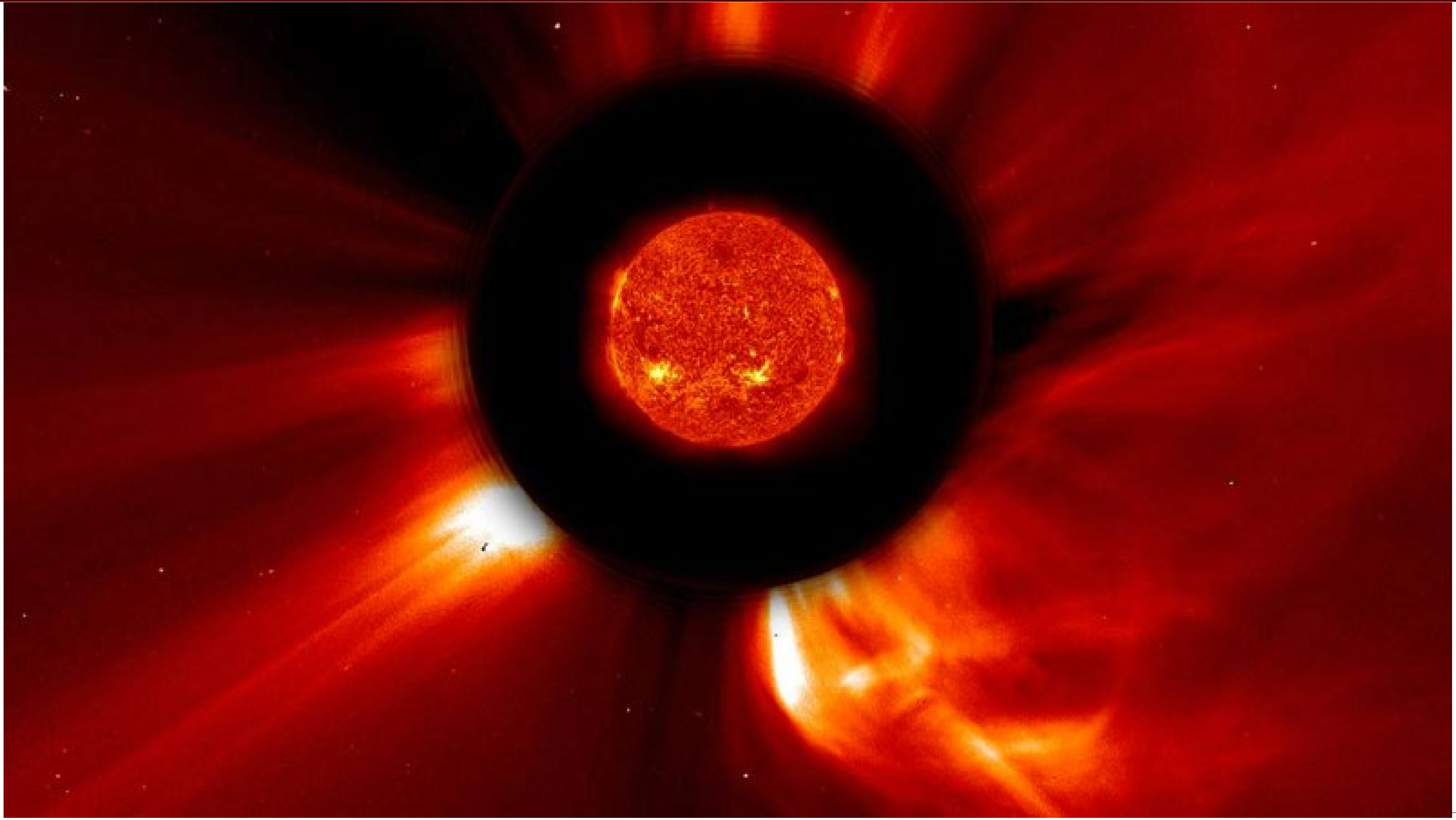


CMEs Cause the Largest GMDs



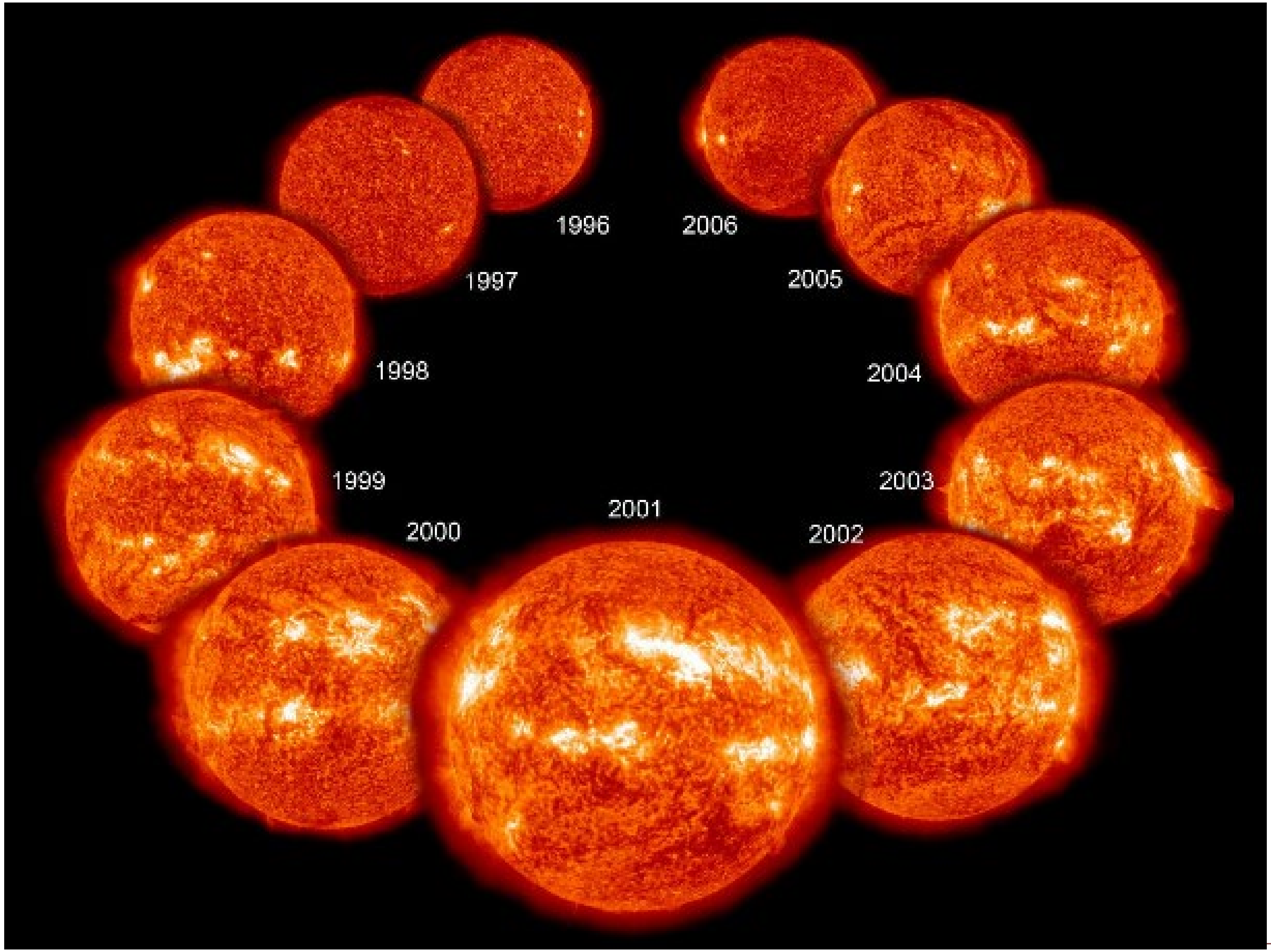
- Fast speed in the solar wind
- High density plasma
- Very large relative to the Earth
- Uncertainty in direction (towards/away from Earth)

There Was a "Near Miss" in 2012



- Large events have been observed every 20 or years or so
- Observations from 2012

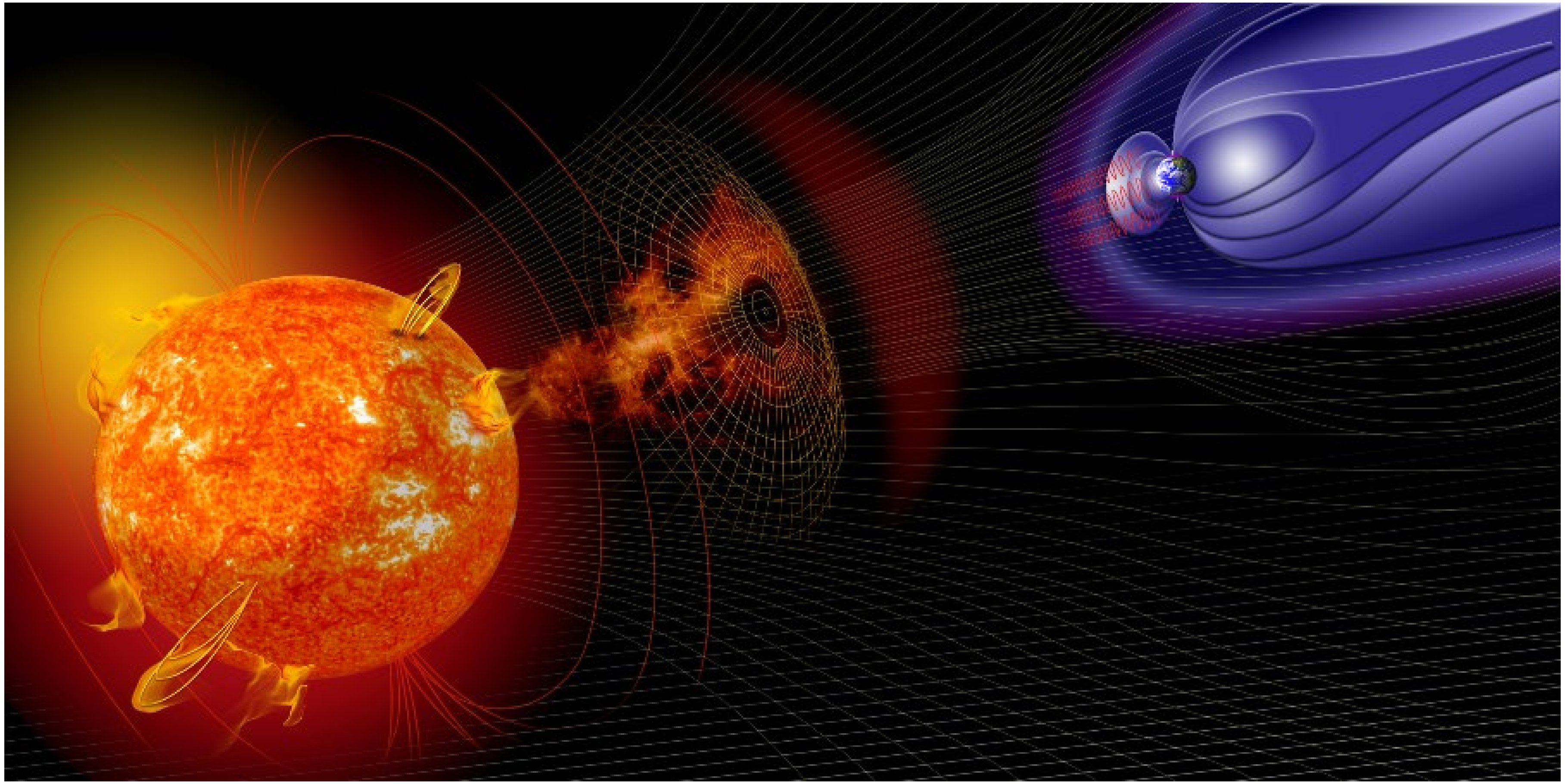
Sunspot Maximum and Minimum



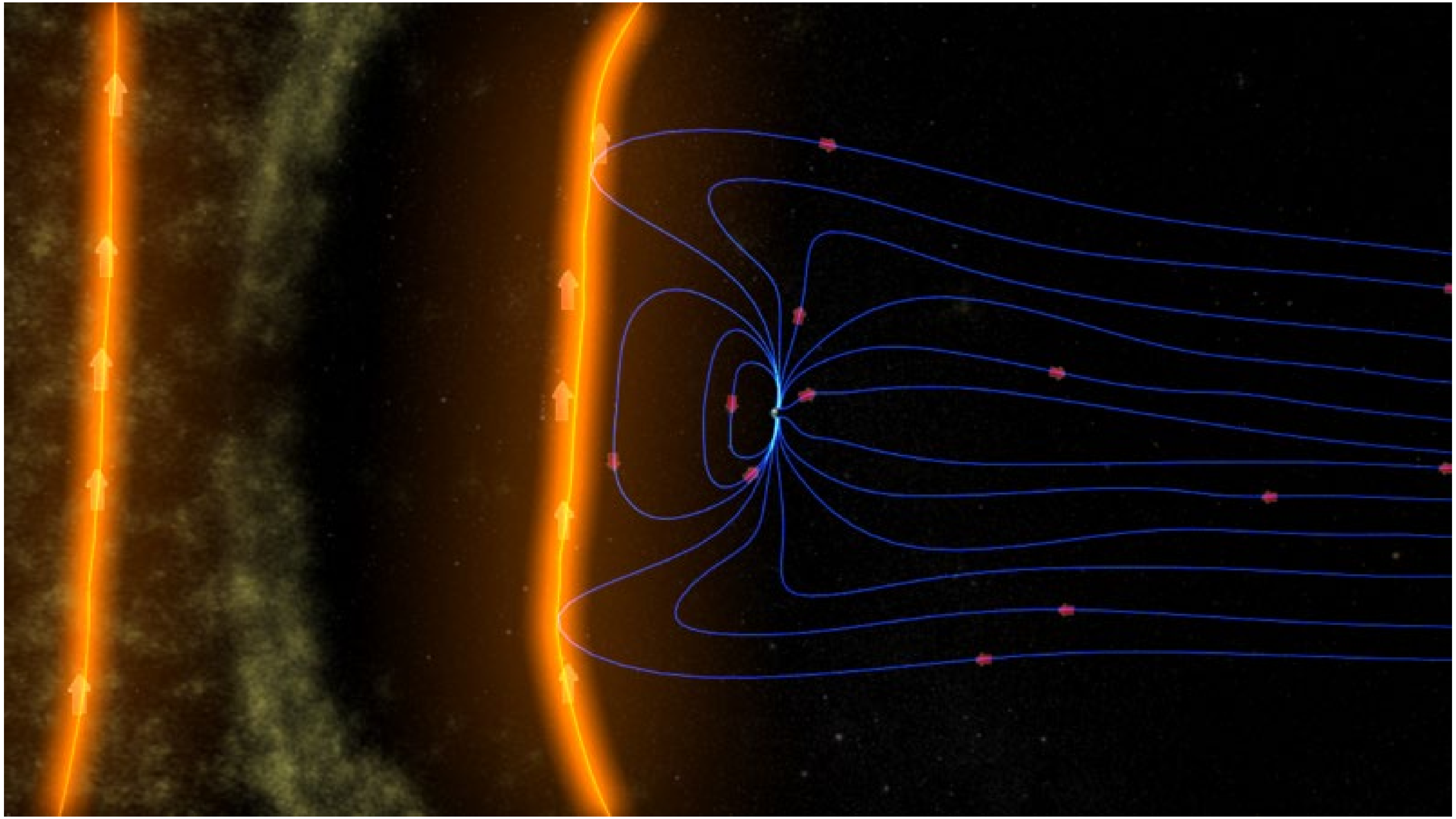
- One cycle is 10 or 11 years long, typically
- Based on sunspot count and solar activity
- The largest CMEs can happen any time during the solar cycle

The Solar Wind is the Connection Between the Sun and the Earth

- Fields and particles
- Typical speeds ~400 km/s, much higher during solar events
- Measured by ACE and DSCOVR
- Deflected by the Earth's magnetic field



Orientation of the Solar Wind Magnetic Field

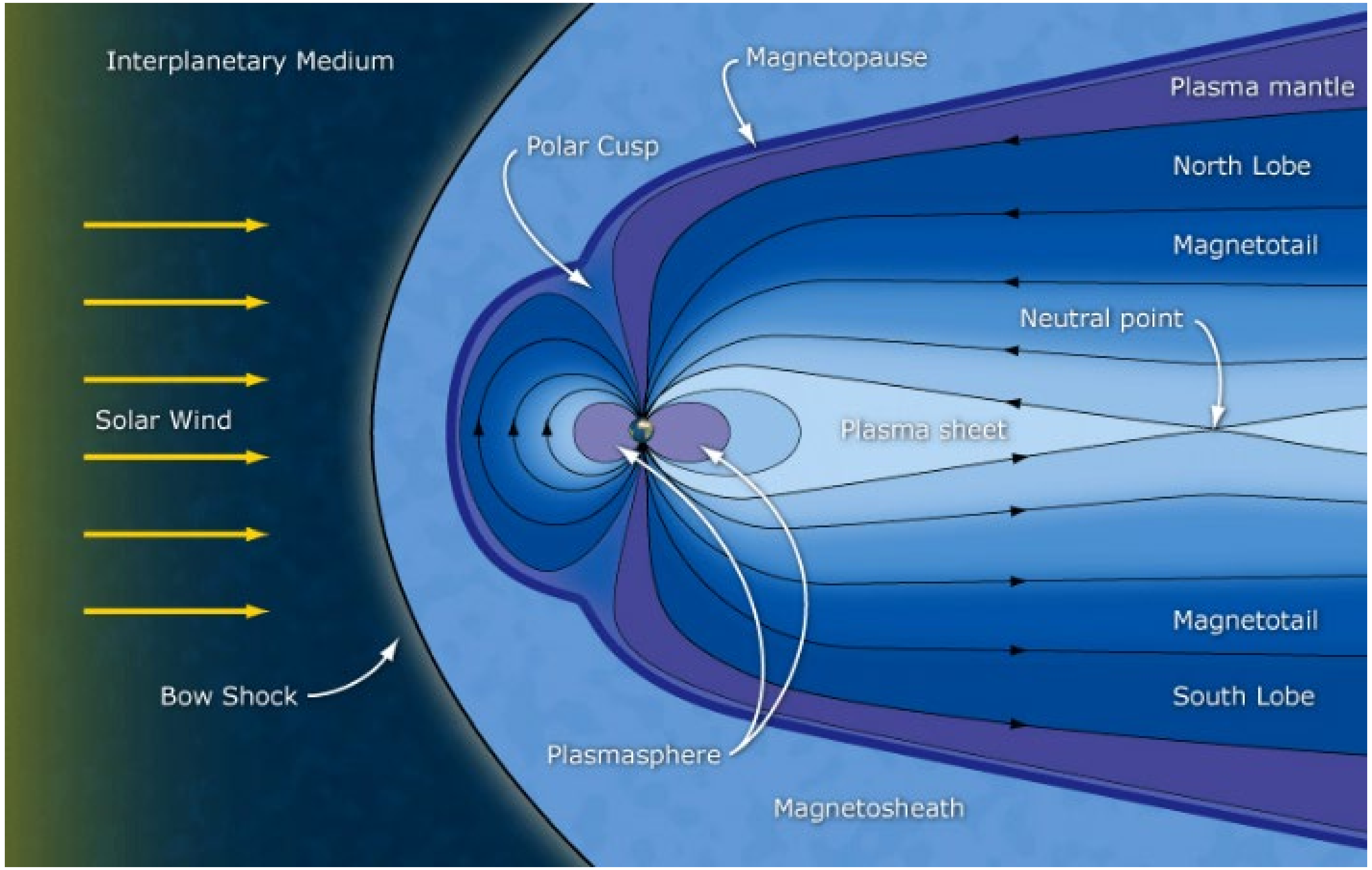


- The orientation of the solar wind magnetic field determines how the storm evolves.
- Observations in 1972 were "Carrington" event sized, but the solar wind was oriented Northward.

Compression and Reconnection

- The Earth's magnetic field is our shield against plasma from the Sun.
- Earth and solar wind magnetic fields in the same direction (both North) -> compression.
- Earth and solar windmagnetic fields in the opposite directions -> reconnection.

Magnetosphere, Ionosphere and Atmosphere



During a geomagnetic storm the magnetosphere, ionosphere, and atmosphere are affected:

- Solar wind impacts the Earth's magnetic field
- Magnetophere is compressed
- Current systems are reconfigured
- New radiation belts are formed
- Satellites and astronauts can be in danger
- Long range communications affected

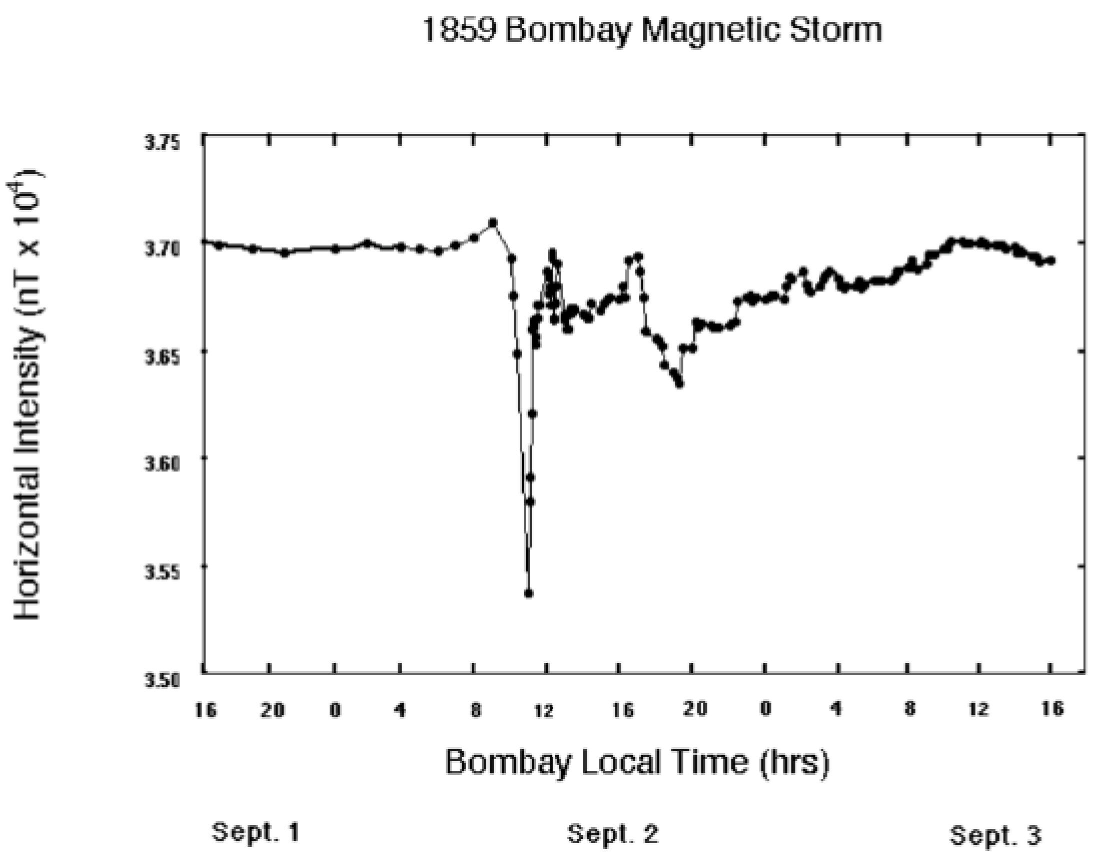
A Geomagnetic Storm is a Reconfiguration of Fields

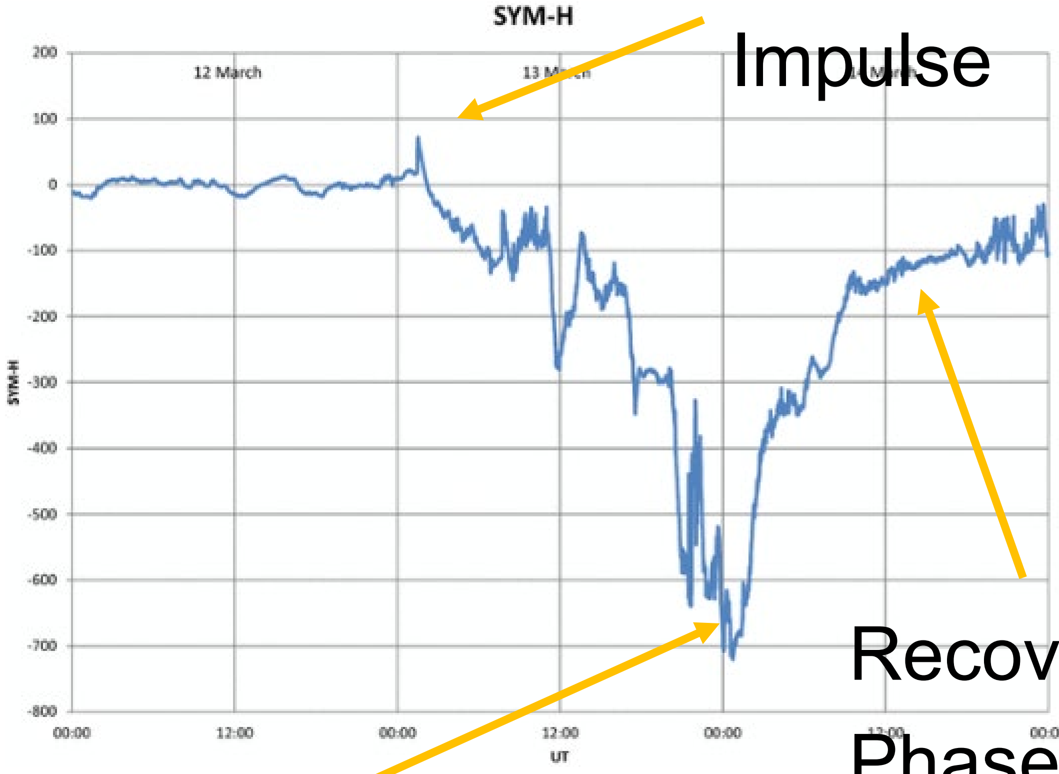
- “Active” geomagnetic field – specific definition
- Small storms happen regularly.
- The effect is a rapidly changing magnetic field on the ground.

Ionospheric Currents Drive the Large GMDs.

- Ionospheric currents (auroral electrojet) drive GMDs.
- For GICs, the location of the auroral boundary is key.

Geomagnetic Field During a GMD Event





Sudden Impulse

Recovery Phase

Main Phase

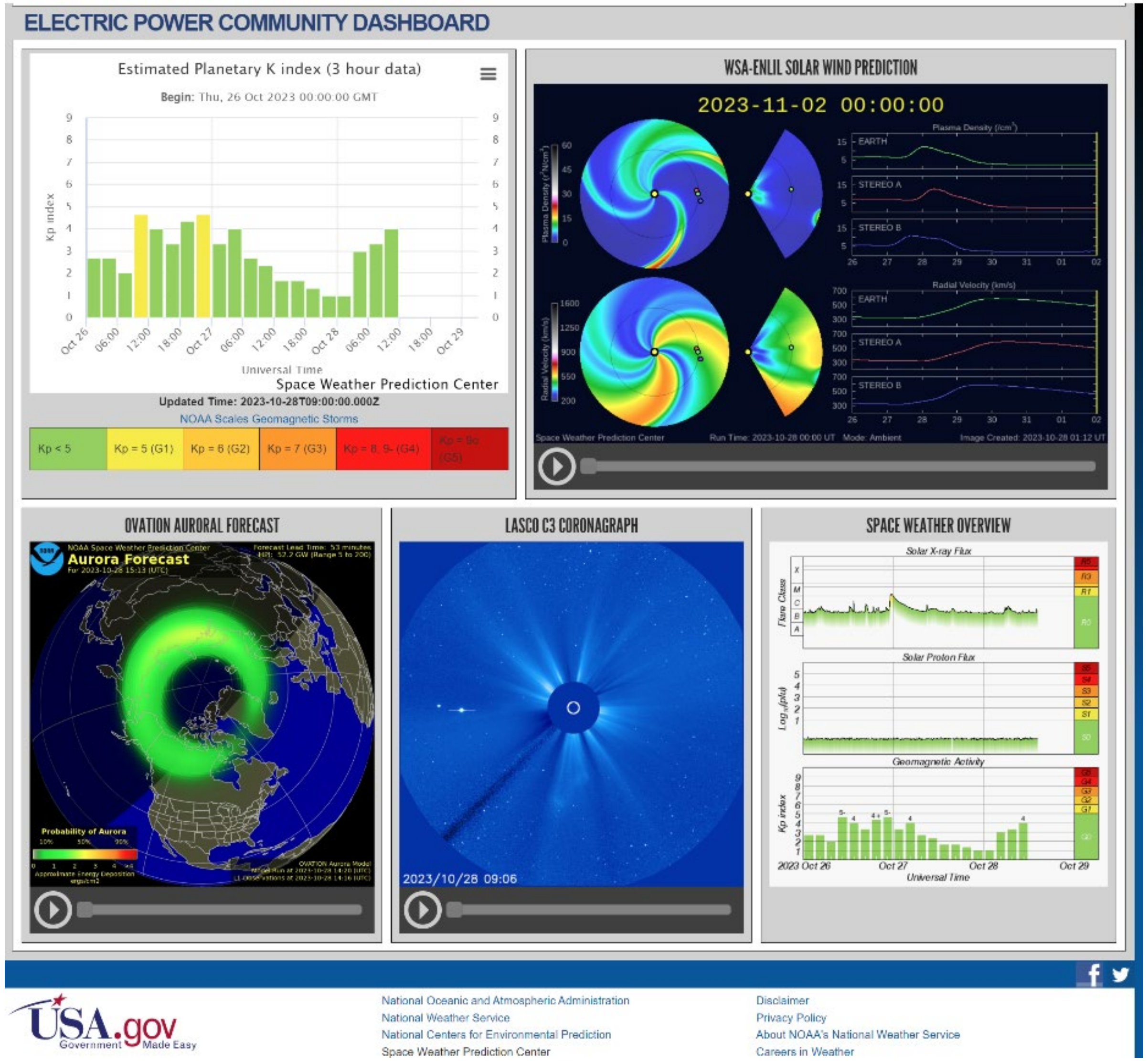
(image: Lakhina and Tsurutani, 2016)

Space Weather Prediction Center (NOAA)

http://swpc.noaa.gov

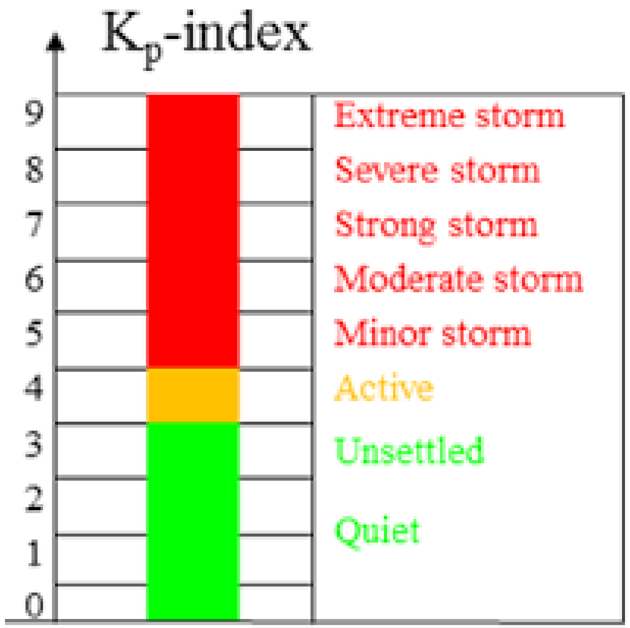
- Federal agency tasked with space weather
- 24-7 operations center
- Sends out space weather alerts: G, Kp, Dst

Space Weather Prediction Center has an Electric Power Dashboard

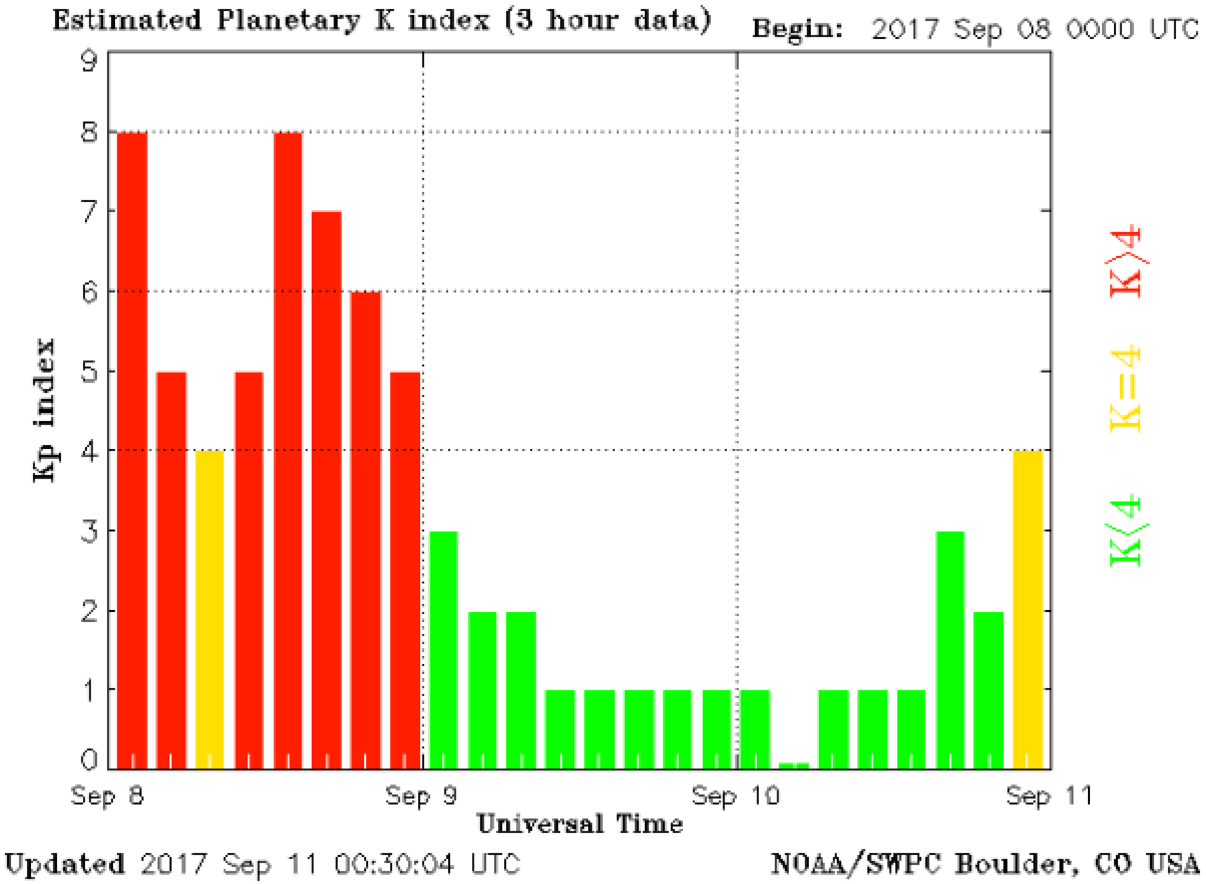


www.swpc.noaa.gov/communities/electric-power-community-dashboard

Space Weather Indices (Kp)



This is a GLOBAL index (p is for "planetary")!



(image: NOAA SWPC)

Space Weather Indices (Dst, AE, G)

Dst:

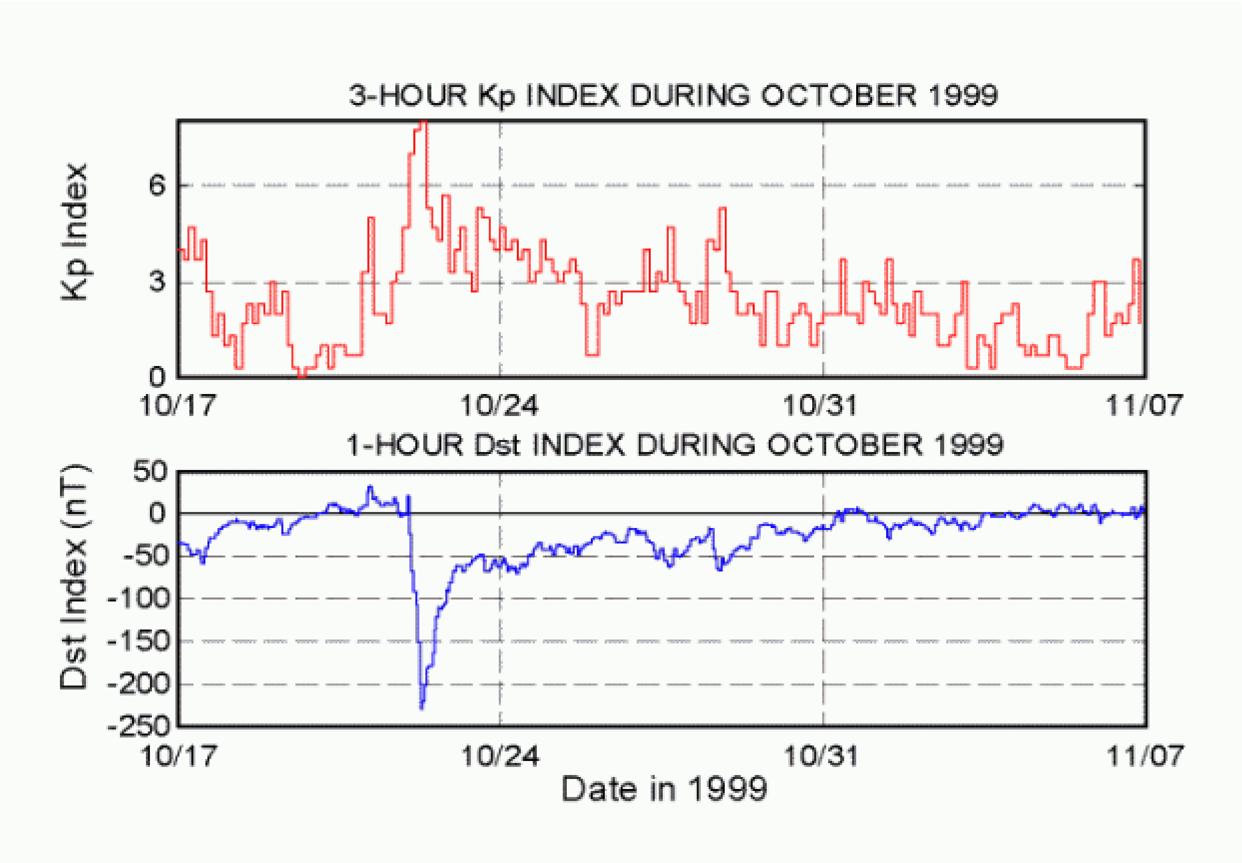
- indicator of geomagnetic storm strength
- lower latitudes

AE:

- indicator of geomagnetic sub-storm strength
- higher latitudes

G-index:

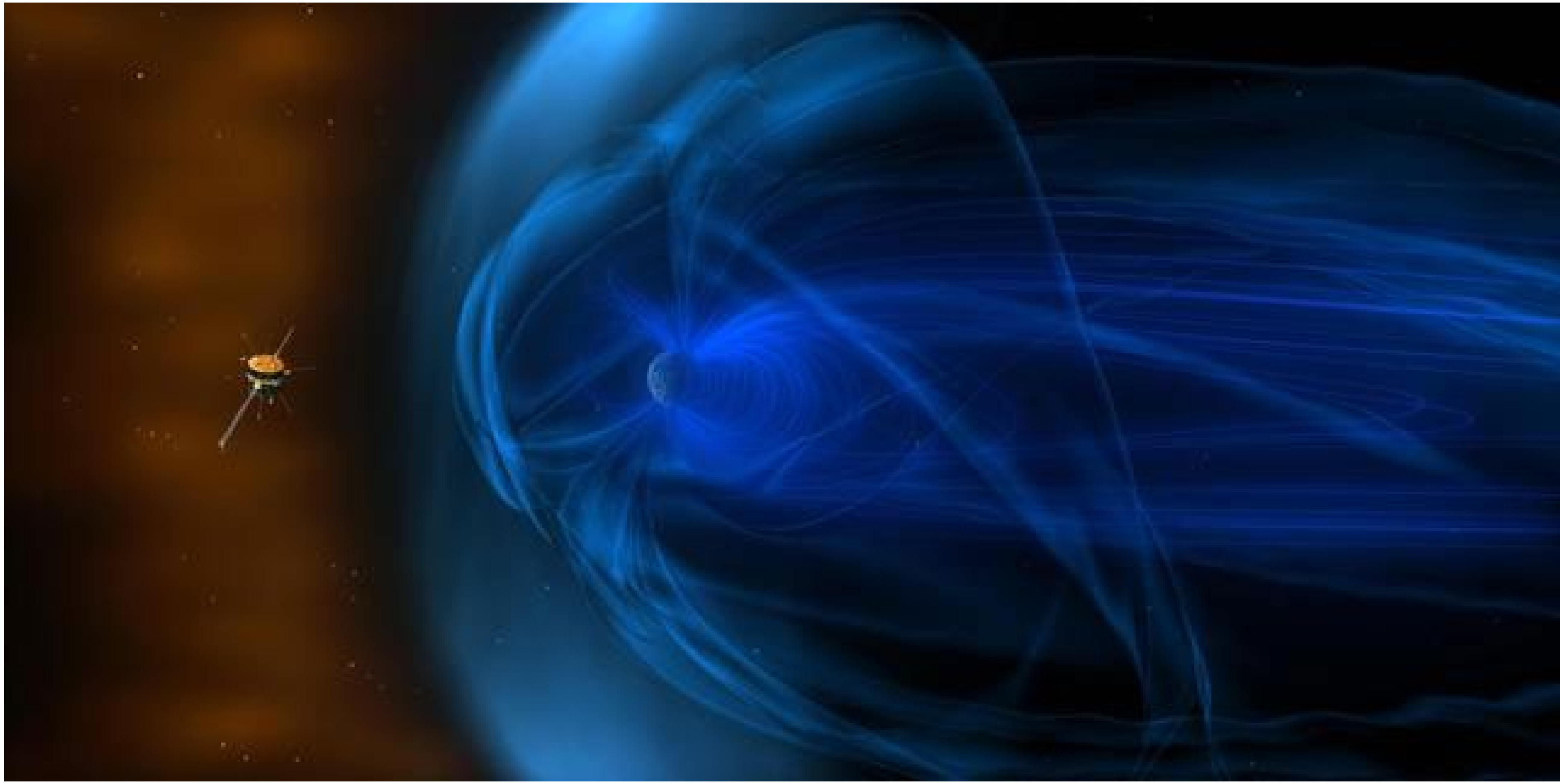
- SWPC define storm strength



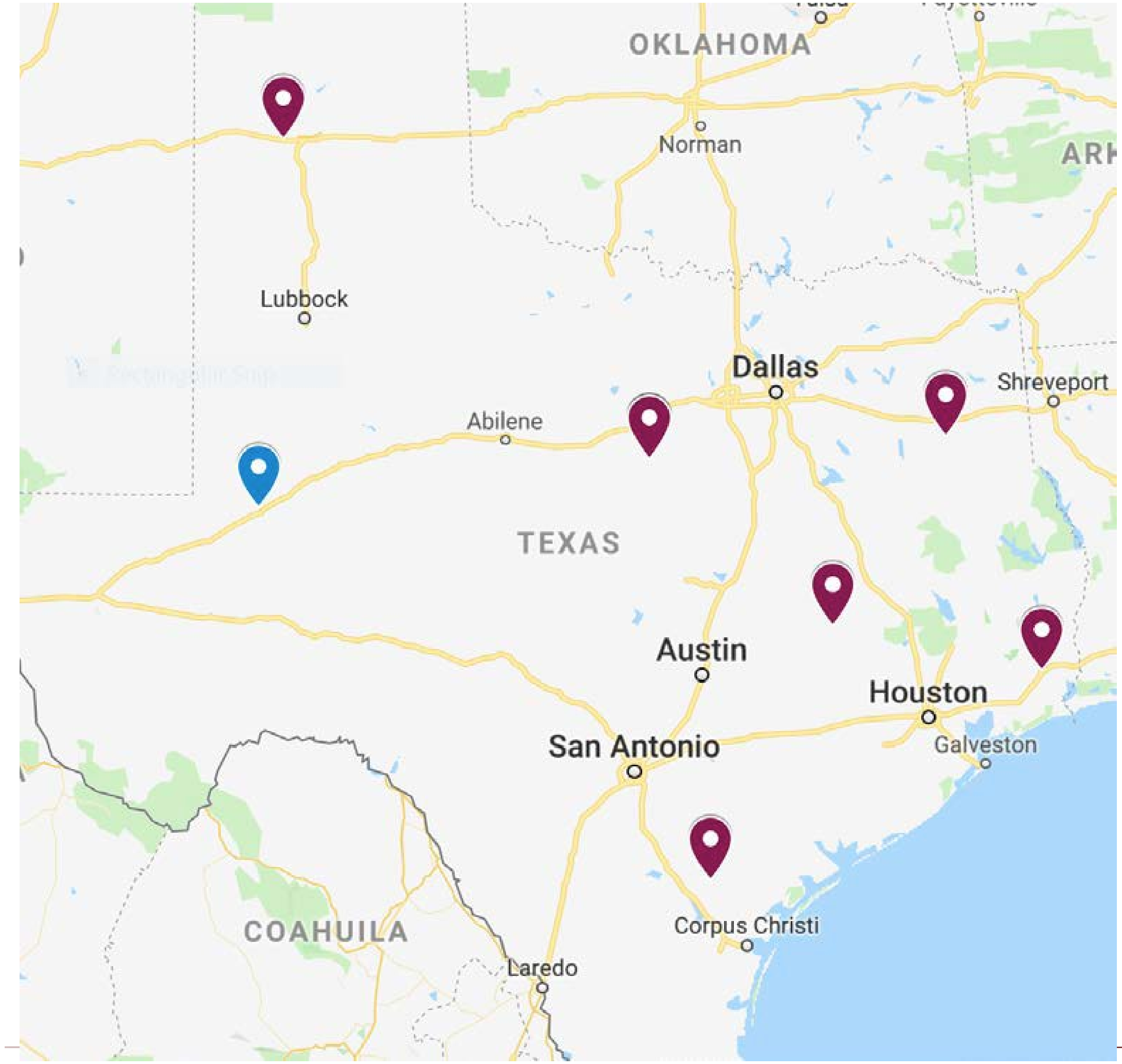
(image: UCLA IGPP)

Measurements of Space Weather are Sparse.

- Ace
- DSCOVR
- Stereo
- RBSP
- Ground based magnetometers



Texas A&M Magnetometer Network



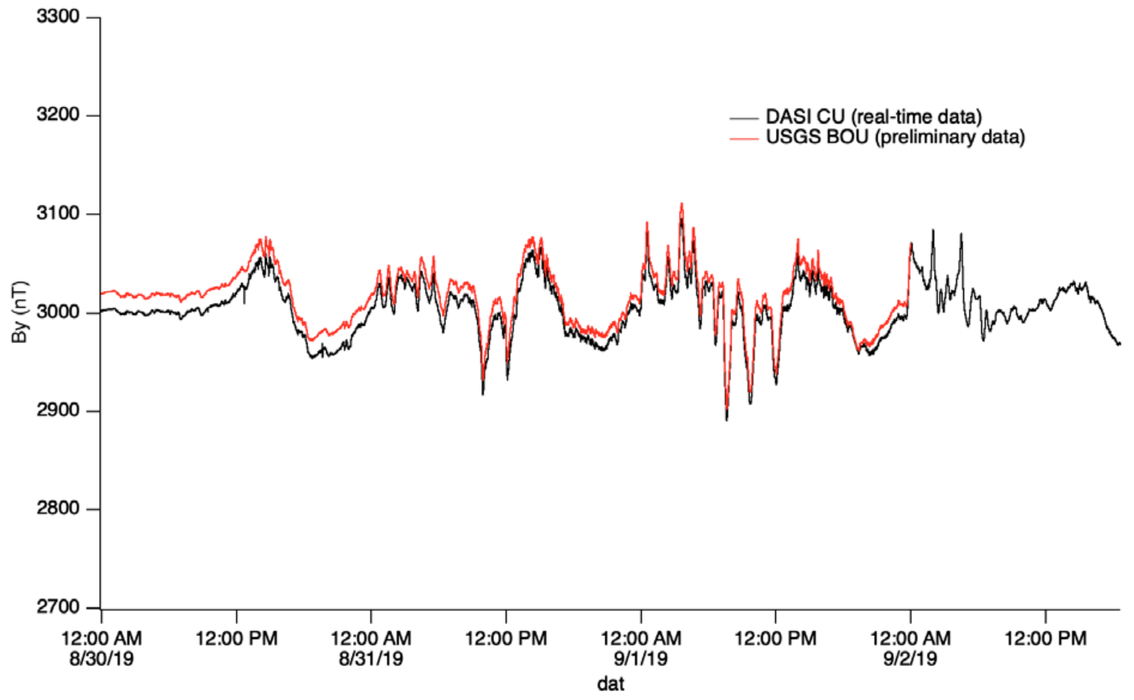
- 6 magnetometers installed by Texas A&M and Computational Physics Inc. (CPI)
  - Completed Dec 2019
  - Building on the results of our NSF project design
- Locations
  - 5 Texas A&M AgriLife Research sites (Amarillo, Beaumont, Beeville, Overton, Stephenville)
  - 1 local on RELLIS Campus (Bryan, TX)
- 1 mag installed under prior NSF project at Odessa

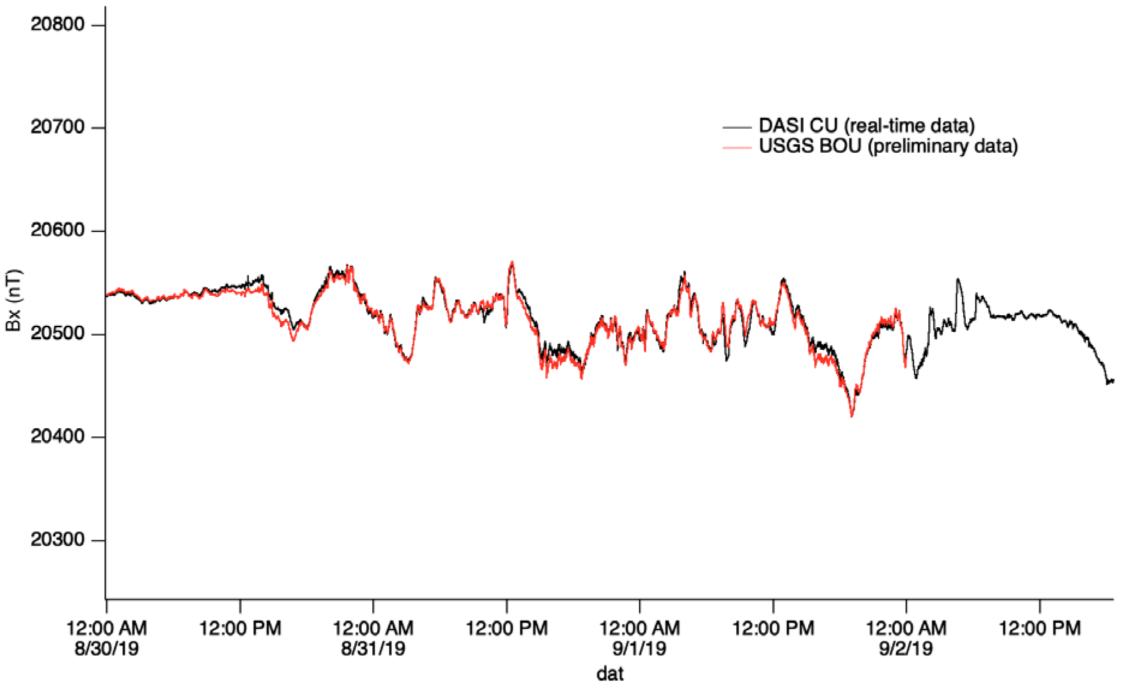
Magnetometer Setup

Connect through wireless access point for secure communication

Autonomous operation (low power, solar panels)

Magnetometer Data Validation





Real-time data delivery (fraction of a second latency) 1-second resolution

Web-based data download in CSV format

Real-time temperature correction

Low-noise magnetic field measurements

What is the Maximum Possible GMD

- Could millions die as some have speculated?
- Previously many thought the 1859 Carrington Event was the largest possible
- However, a March 2019 article in the Proceedings of the U.S. National Academy of Sciences indicates that larger GMDs could occur, with ice core evidence indicating potentially much larger events occurring in 775 , 994, and now 2610 BC
- We're still not exactly sure on the largest potential GMD!

Multiradionuclide evidence for an extreme solar proton event around 2,610 B.P. (~660 BC)

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Edited by Lennard A. Fisk, University of Michigan, Ann Arbor, MI, and approved February 4, 2019 (received for review September 13, 2018)

Recently, it has been confirmed that extreme solar proton events can lead to significantly increased atmospheric production rates of cosmogenic radionuclides. Evidence of such events is recorded in annually resolved natural archives, such as tree rings [carbon-14 (^{14}C)] and ice cores [beryllium-10 (^{10}Be), chlorine-36 (^{36}Cl)]. Here, we show evidence for an extreme solar event around 2,610 years B.P. (~660 BC) based on high-resolution ^{10}Be data from two Greenland ice cores. Our conclusions are supported by modeled ^{14}C production rates for the same period. Using existing ^{36}Cl ice core data in conjunction with ^{10}Be, we further show that this solar event was characterized by a very hard energy spectrum. These results indicate that the 2,610-years B.P. event was an order of magnitude stronger than any solar event recorded during the instrumental period and comparable with the solar proton event of AD 774/775, the largest solar event known to date. The results illustrate the importance of multiple ice core radionuclide measurements for the reliable identification of short-term production rate increases and the assessment of their origins.

solar storms | radionuclides | ice cores | solar proton events

Our Sun sometimes produces highly energetic particles, which are accelerated either by magnetic reconnection in solar flares or by shock waves associated with coronal mass ejections. Such energetic particles then follow trajectories along the interplanetary magnetic field lines, which together with the location of the event on the Sun, determine whether these particles hit the Earth's atmosphere. These phenomena are referred to as solar proton events (SPEs). Such events represent a threat to modern society in terms of communication and navigation systems, space technologies, and commercial aircraft operations (1, 2). Therefore, better understanding the possible magnitudes and occurrence frequency of such events is of great importance for safeguarding space technologies and modern technological infrastructure. During the past ~60 y, these events have been

While the use of ice core nitrate to document these events has been rejected (5–7), an extended record of the fluence, frequency, and energy distribution of SPEs can be obtained through the analysis of cosmogenic radionuclides, such as beryllium-10 (^{10}Be), carbon-14 (^{14}C), and chlorine-36 (^{36}Cl) (8–10). These radionuclides are mainly produced via a nuclear cascade triggered by galactic cosmic rays reaching the Earth's atmosphere on average with much higher kinetic energy than the solar protons. Incoming galactic cosmic rays are modulated by the heliomagnetic and geomagnetic fields, with the strength of this modulation changing from decadal to millennial timescales (11–13). However, strong SPEs can lead to large fluxes of solar protons, causing a short-term rapid increase in the atmospheric production of radionuclides, which are subsequently stored in environmental archives, such as tree rings (^{14}C) and ice cores (^{10}Be and ^{36}Cl). A recent study by Mekhaldi et al. (9) used a series of ice core records (14) to confirm a solar origin for two rapid increases in $\Delta^{14}C$ ($^{14}C/^{12}C$ corrected for fractionation and decay relative to a standard) in AD 774/775 and AD 993/994 first identified in tree rings (15–18). Mekhaldi et al. (9) have proposed that the stronger

EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

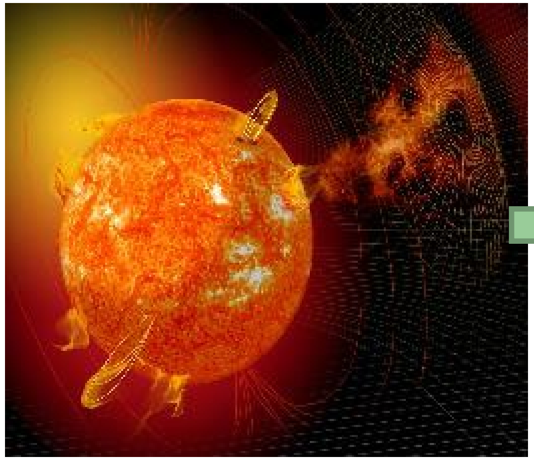
Significance

This study provides evidence of an enormous solar storm around 2,610 B.P. It is only the third such event reliably documented and is comparable with the strongest event detected at AD 774/775. The event of 2,610 years B.P. stands out because of its particular signature in the radionuclide data [i.e., carbon-14 (^{14}C) data alone does not allow for an unequivocal detection of the event]. It illustrates that present efforts to find such events based solely on ^{14}C data likely lead to an underestimated number of such potentially devastating events for our society. In addition to ^{14}C data, high-resolution records of beryllium-10 and chlorine-36 are crucial for reliable estimates of the occurrence

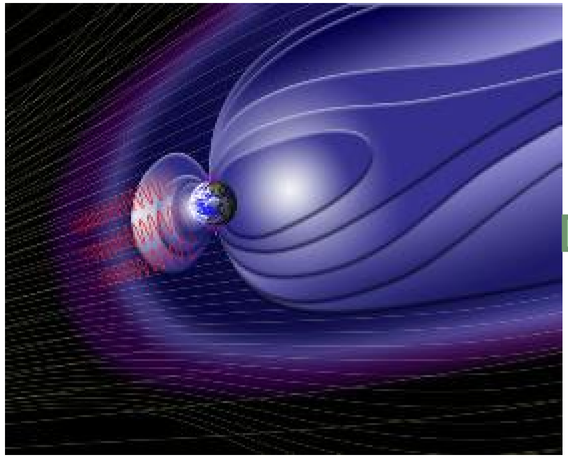
Source: www.pnas.org/content/early/2019/03/05/1815725116

What Does the Earth's Conductivity Have To Do with Space Weather?

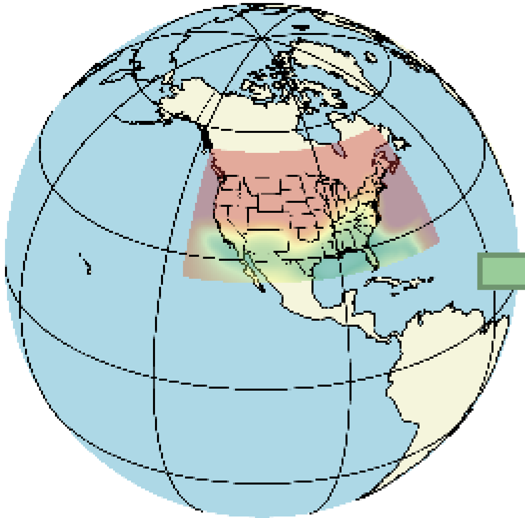
Solar Wind Drivers



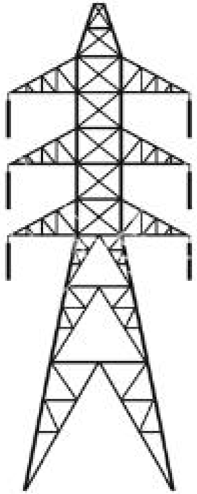
Currents in the Magnetosphere-Ionosphere System



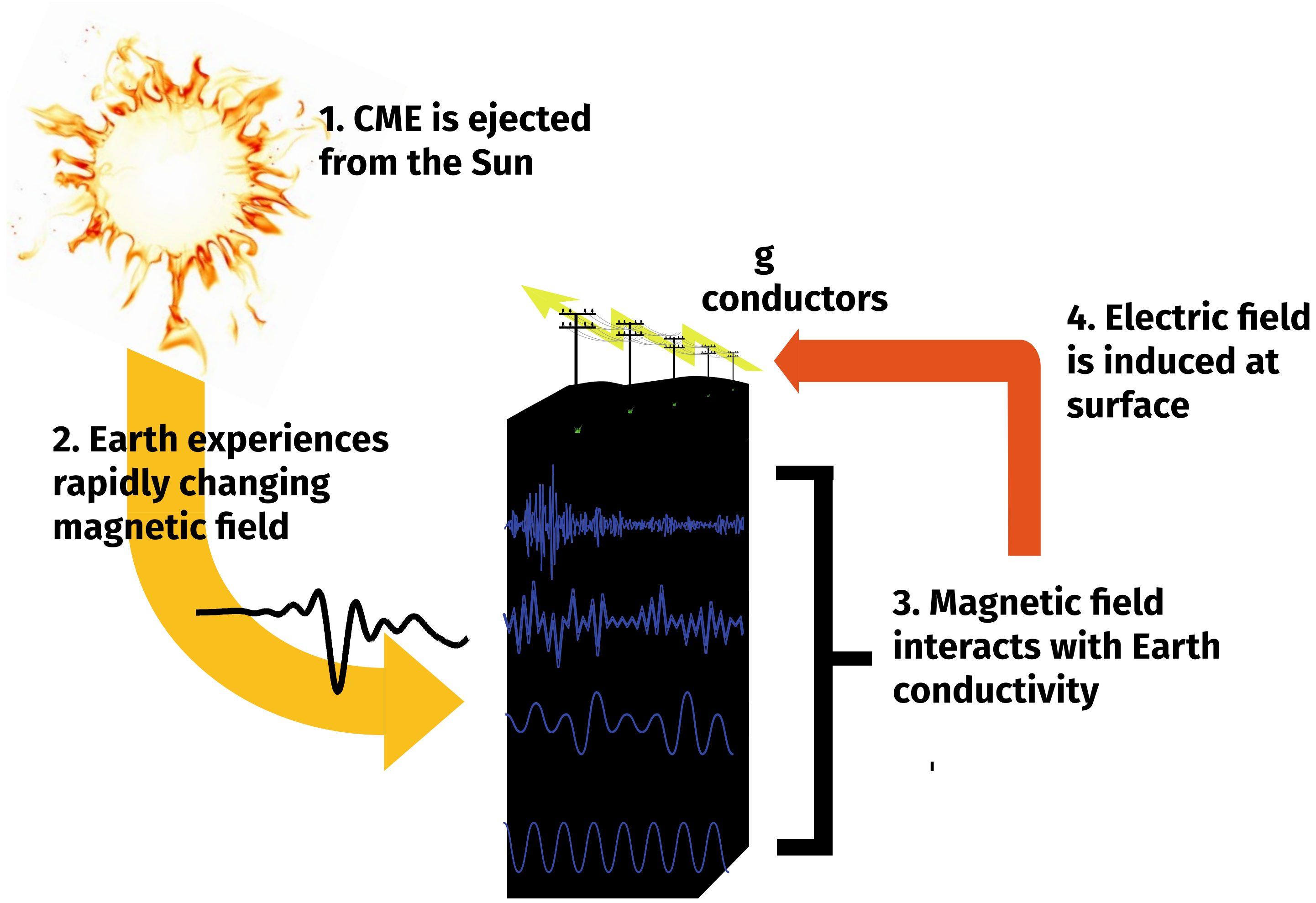
Geomagnetic Fields and Induced Electric Fields at Ground-Level



GICs induced in long conductors



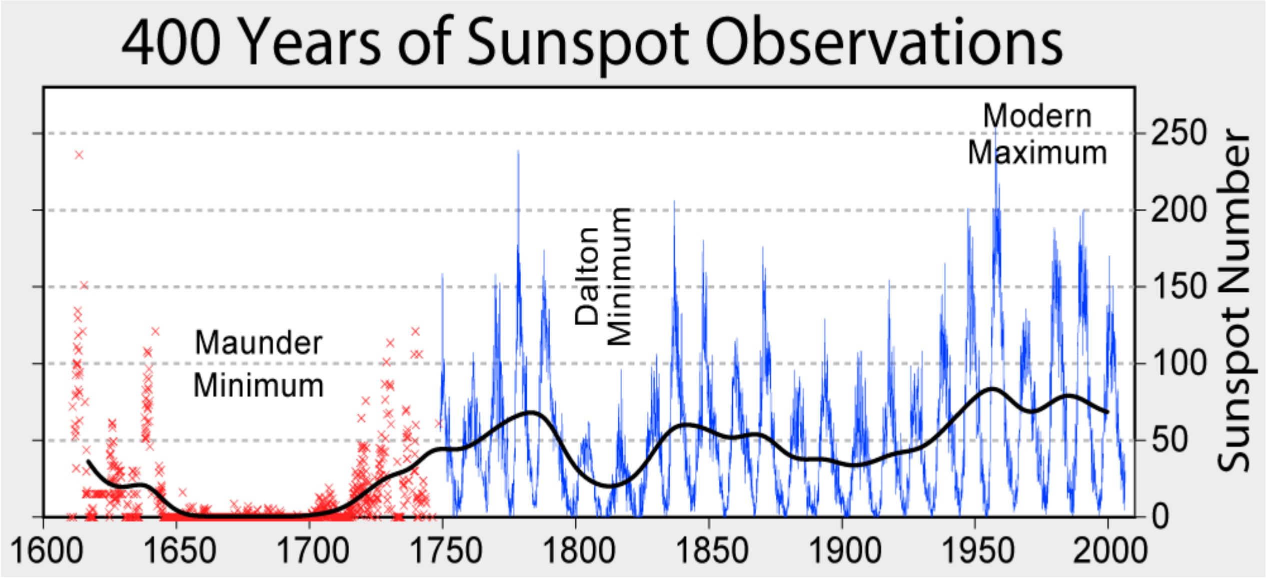
The Earth is a Non-Uniform Conductor

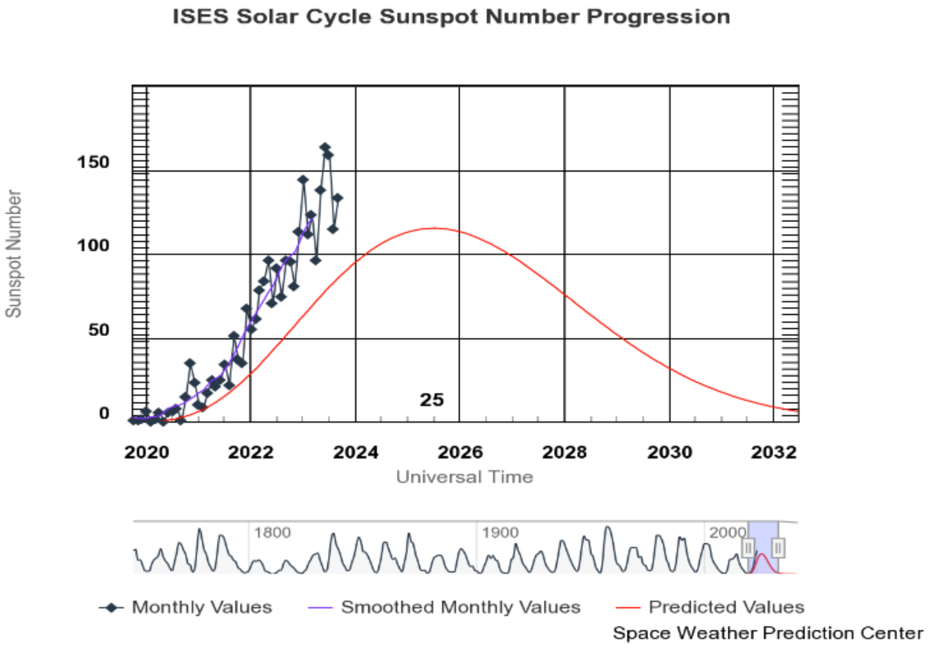


- Changing magnetic field produces an electric field.
- Conductivity varies with depth (and also laterally)
- Skin depth is frequency dependent

Solar Cycles

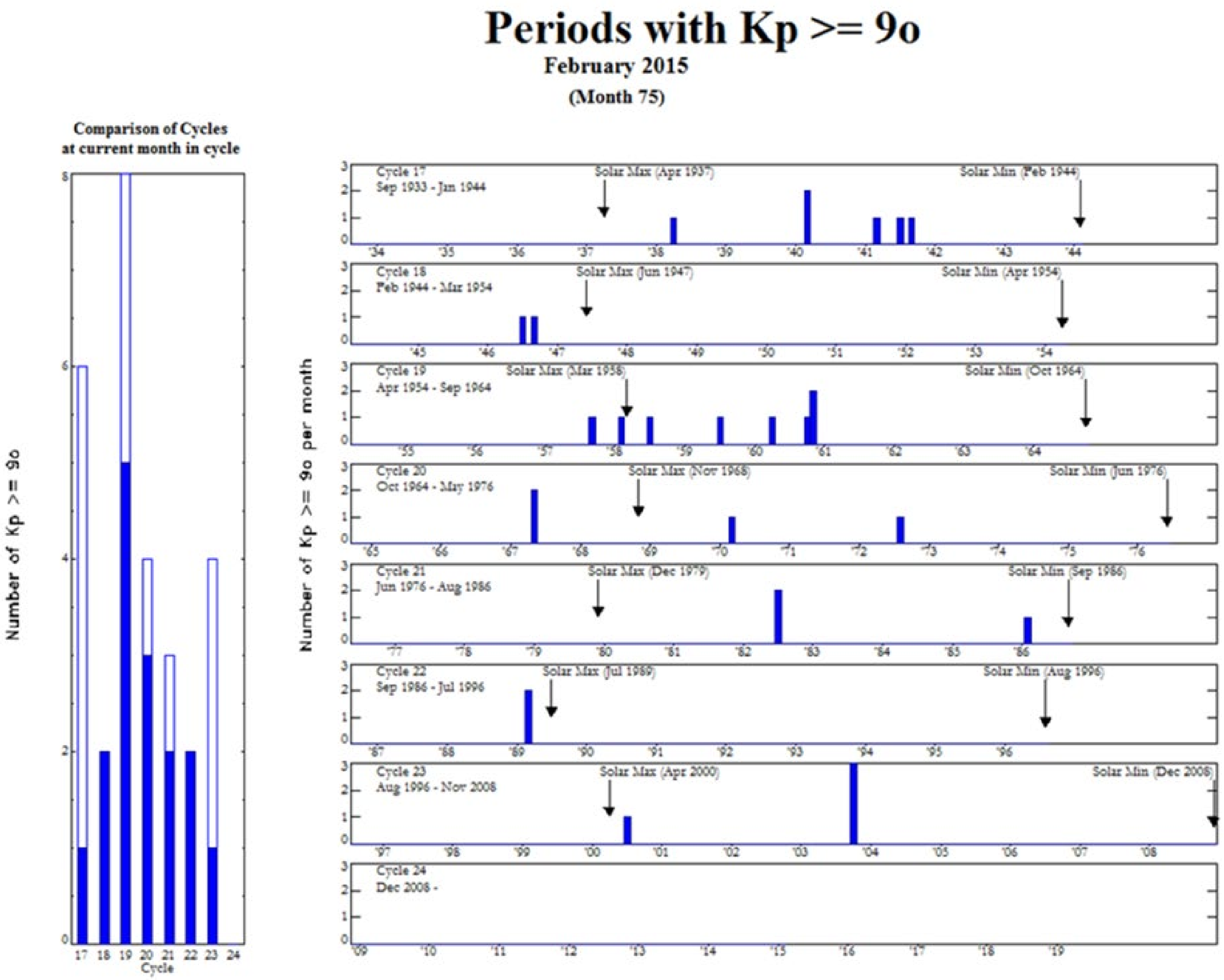
- Sunspots follow an 11 year cycle, and have been observed for hundreds of years
- We're in solar cycle 25 (first numbered cycle was in 1755); minimum was in 2020, maximum in 2025/2026 (cycle 24 had less sunspots than normal)





Images from NASA, NOAA

But Large CMEs Are Not Well Correlated with Sunspot Maximums



The large 1921 storm occurred four years after the 1917 maximum

Image: en.wikipedia.org/wiki/File:Polarlicht_2.jpg

July 2012 GMD Near Miss

- In July 2014 NASA said in July of 2012 there was a solar CME that barely missed the earth
  - It would likely have caused the largest GMD that we have seen in the last 150 years
- There is still lots of uncertainly about how large a storm is reasonable to consider in e

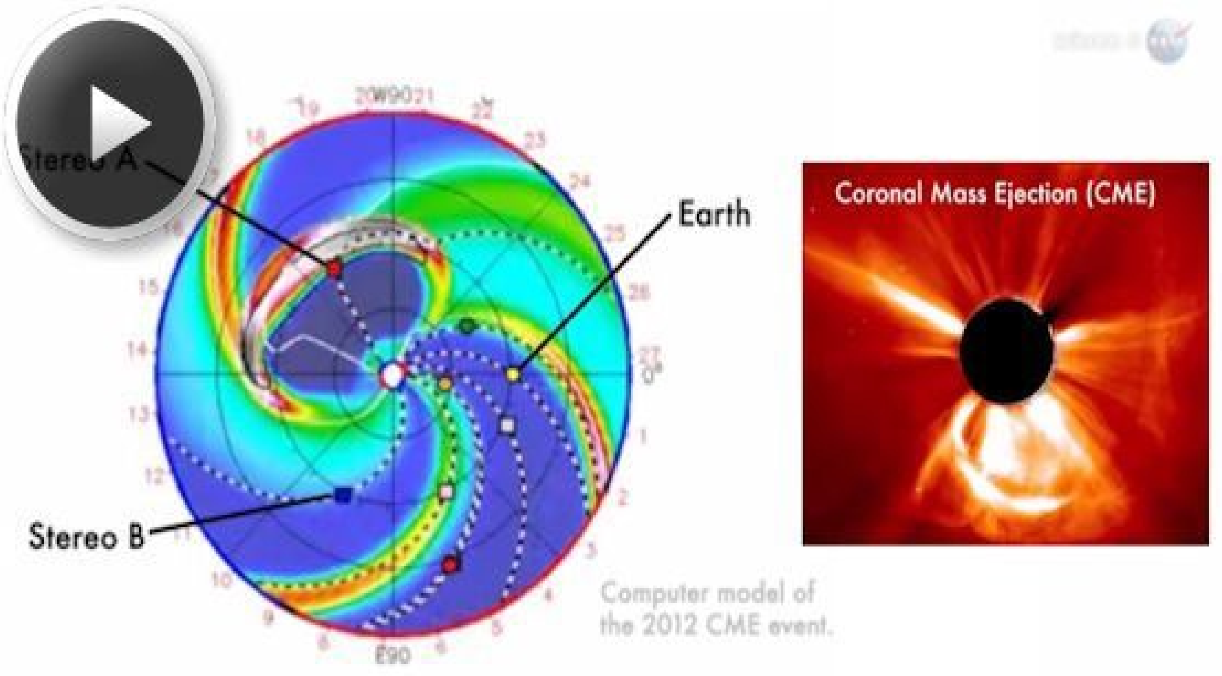
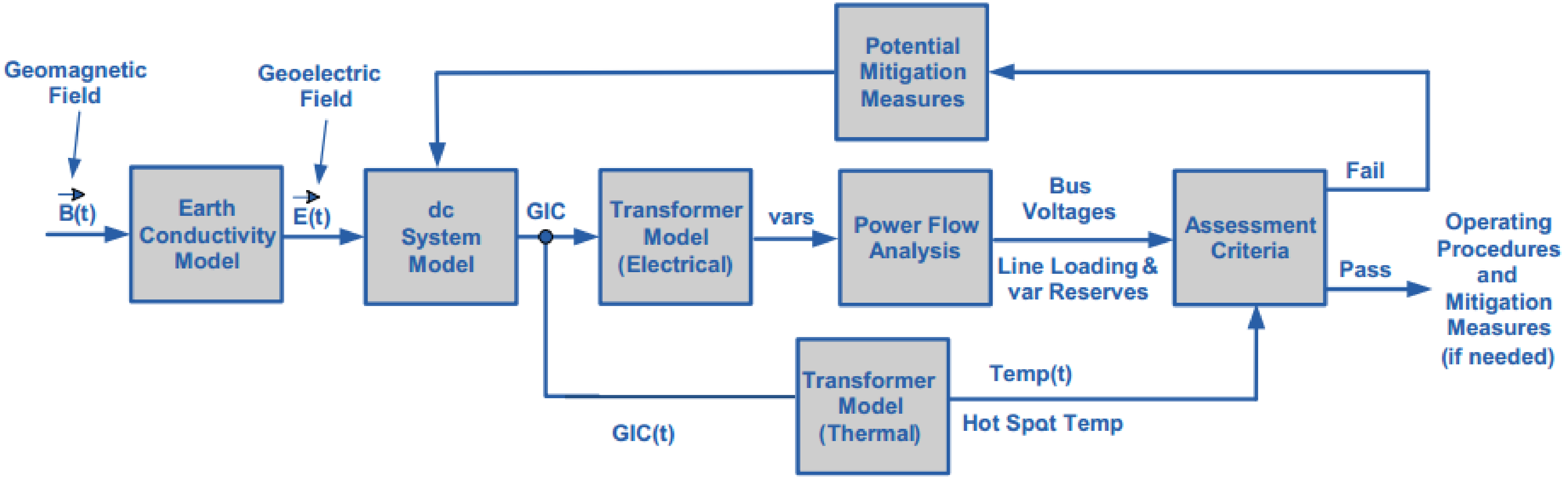


Image Source: science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

Overview of GMD Assessments

It is a quite interdisciplinary problem

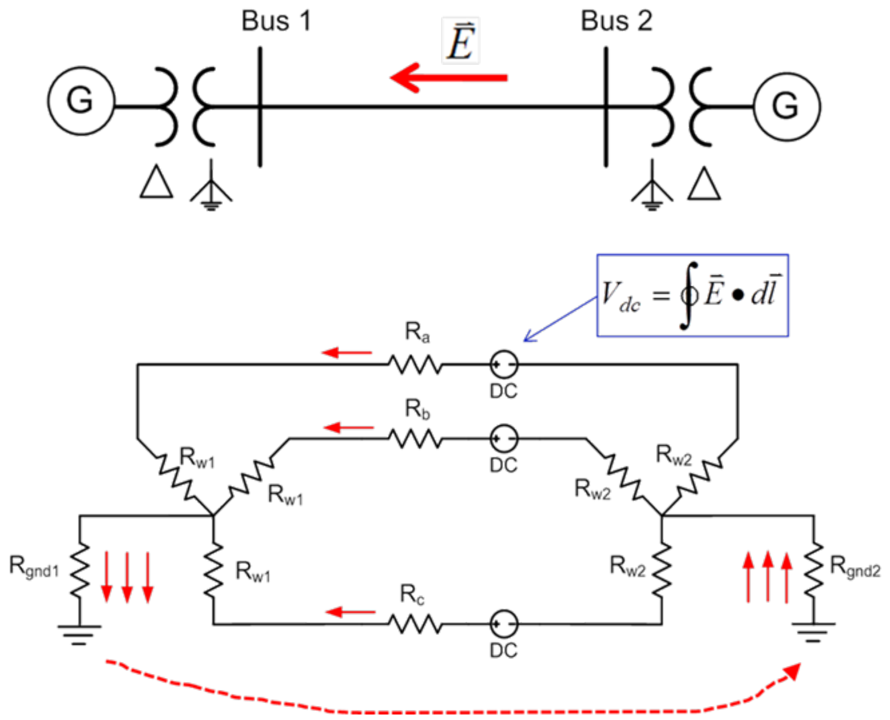


The two key concerns from a big storm are 1) large-scale blackout due to voltage collapse, 2) permanent transformer damage due to overheating

Image Source: http://www.nerc.com/pa/Stand/WebinarLibrary/GMD_standards_update_june26_ec.pdf

Geomagnetically Induced Currents (GICs)

- GMDs cause slowly varying electric fields
- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- These voltage sources produce quasi-dc geomagnetically induced currents (GICs) that are superimposed on the ac (60 Hz) flows



GIC Calculations for Large Systems

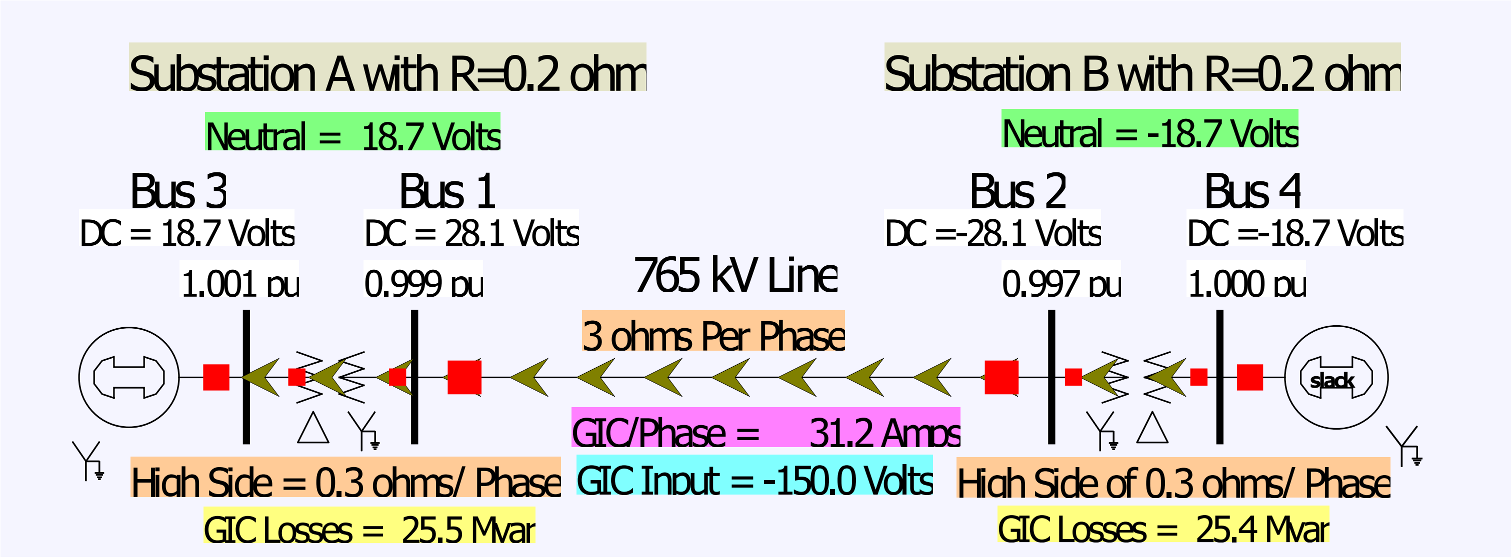
- With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and flows are found by solving linear equations
  - The approach is actually similar to what is done in the power flow with the bus admittance matrix, except 1) the matrix is augmented to include substation neutrals, and 2) is just resistive values (conductances)
    - Only depends on resistance, which varies with temperature
  - Being a linear equation, superposition holds
  - The current vector contains the Norton injections associated with the GMD-induced line voltages

GIC Calculations for Large Systems

- Factoring the sparse conductance matrix and doing the forward/backward substitution takes about 1 second for the 60,000 bus Eastern Interconnect Model
- The current vector (I) depends upon the assumed electric field along each transmission line
  - Requires that substations have correct geo-coordinates
- With nonuniform fields an exact calculation would be path dependent, but just a assuming a straight line path is probably sufficient (given all the other uncertainties!)

Four Bus Example (East-West Field)

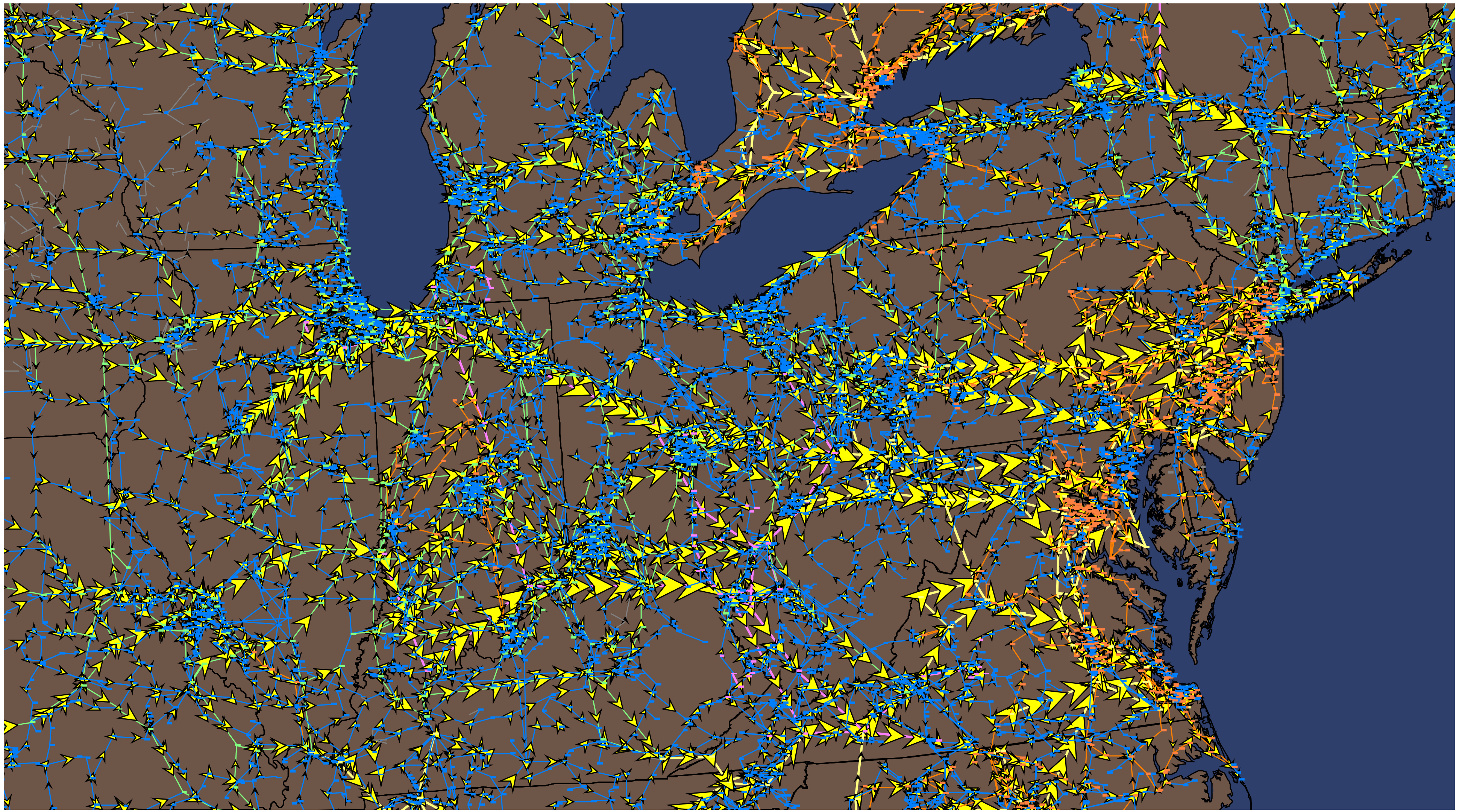
$$I_{GIC,3Phase} = \frac{150 \text{ volts}}{(1+0.1+0.1+0.2+0.2)\Omega} = 93.75 \text{ amps or } 31.25 \text{ amps/phase}$$



The line and transformer resistance and current values are per phase so the total current is three times this value. Substation grounding values are total resistance. Brown arrows show GIC flow.

PowerWorld case name is **GIC_FourBus**

GICs, Generic EI, 5 V/km East-West



Determining GMD Storm Scenarios

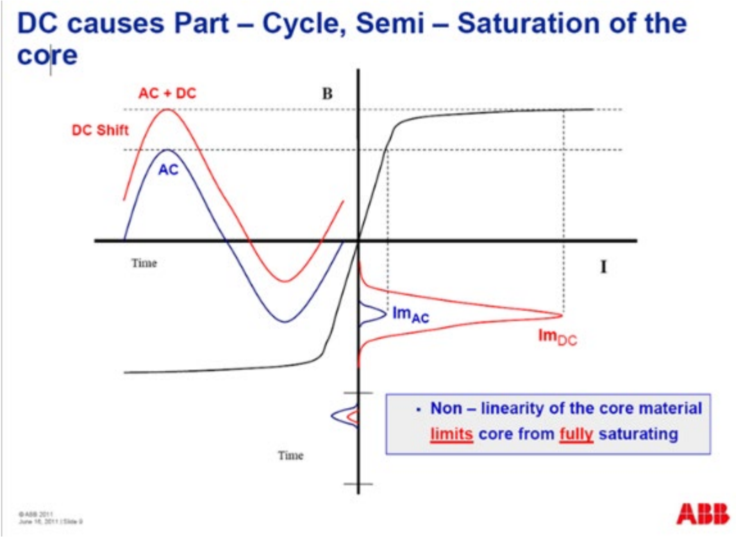
- The starting point for the GIC analysis is an assumed storm scenario; sets the line dc voltages
- Matching an actual storm can be complicated, and requires detailed knowledge of the geology
- GICs vary linearly with the assumed electric field magnitudes and reactive power impacts on the transformers is also mostly linear
- Working with space weather community to determine highest possible storms
- NERC proposed a non-uniform field magnitude model that FERC partially accepted

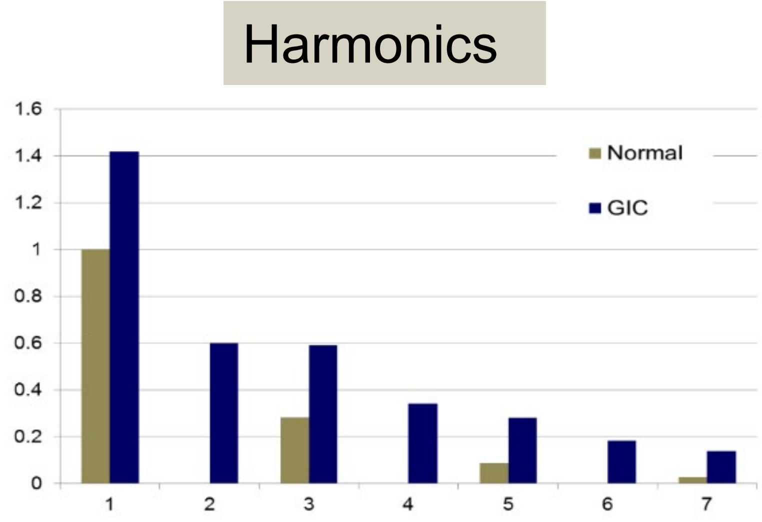
Electric Field Linearity

- If an electric field is assumed to have a uniform direction everywhere (like with the current NERC model), then the calculation of the GICs is linear
  - The magnitude can be spatially varying
- This allows for very fast computation of the impact of time-varying functions (like with the NERC event)
- PowerWorld now provides support for loading a specified time-varying sequence, and quickly calculating all of the GIC values

Transformer Impacts of GICs

- The GICs superimpose on the ac current, causing transformers saturation for part of the ac cycle
- This can cause large harmonics; in the positive sequence these harmonics can be represented by increased reactive power losses in the transformer





Images: Craig Stiegemeier and Ed Schweitzer, JASON Presentations, June 2011

Relating GICs to Transformer Mvar Losses

- Transformer positive sequence reactive power losses vary as a function of both the GICs in the transformer coils and the ac voltage
- A common approach is to use a linear model

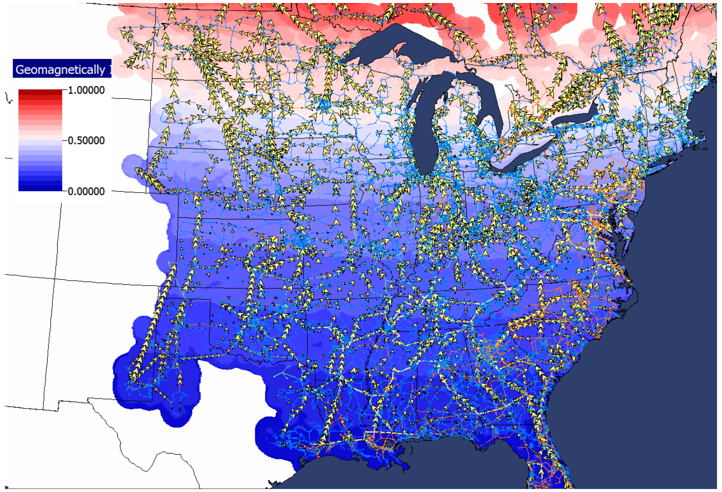
$$Q_{loss} = KV_{pu} I_{GIC,Eff}$$

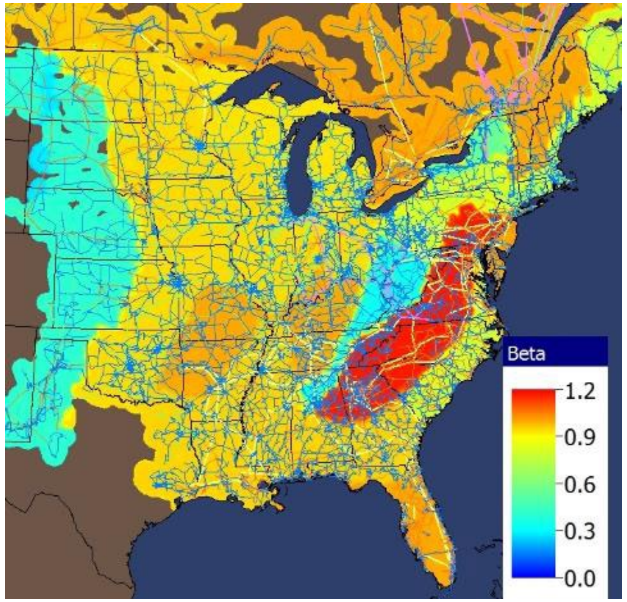
- The IGIC,Eff is an effective current that is a function of the GICs in both coils; whether auto or regular the equation is

$$I_{GIC,Eff} = \left| \frac{a_t I_{GIC,H} + I_{GIC,L}}{a_t} \right| \quad \text{where } a_t \text{ is the turns ratio}$$

NERC GMD Scenario Approach

- Time varying, derived from the March 1989 event
- Peak electric field is 8 V/km for a reference location (60 deg. N, resistive Earth)
- Electric field for other regions scaled by two factors
  - Epeak = 8 * α * β V/km
  - “1 in a 100 year” event





The Impact of a Large GMD From an Operations Perspective

- Maybe a day warning but without specifics
  - Satellite at Lagrange point one million miles from earth would give more details, but with less than 30 minutes lead time
  - Could strike quickly; rise time of minutes, rapidly covering a good chunk of the continent
- Reactive power loadings on hundreds of high voltage transformers could rapidly rise

ISO New England Control Room

- Increased transformer reactive loading causes heating issues and potential large-scale voltage collapses; power system software like state estimation could fail; control room personnel would be overwhelmed
- The storm could last for days with varying intensity

GIC Mitigation

- Tools are needed for mitigation strategies
  - Cost-benefit analysis
- GIC flows can be reduced both through operational strategies such as opening lines, and through longer term approaches (e.g. blocking devices)
- Redispatching the system can change transformer loadings, providing margins for GICs
- Algorithms are needed to provide real-time situational awareness for use during GMDs