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Title: Heliophysics in the SNDD Context

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Heliophysics in the SNDD Context

Space Environment Sun-to-Earth

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Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Goals

After this talk hopefully you will agree that:

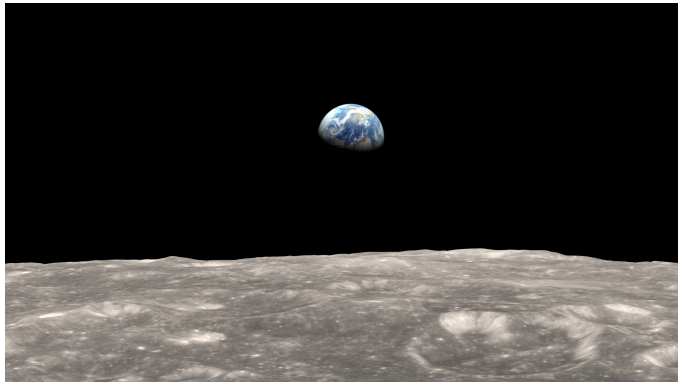
- **Space is big and cannot be treated as one place**
  - Many different regions with different properties/hazards
- **There is a lot of vocabulary and that is hard**
  - This aims to be a non-exhaustive but hopefully helpful reference
- **Further study is needed so that systems can be engineered properly to survive and accomplish mission at the lowest resources**
  - Heather Quinn will talk about aspects of this next session

- **You will also note that:**
  - I am not an artist and have used other's images as much as possible
    - Tried to get acknowledgements correct
  - I think all this is really exciting and hopefully some will rub off on you

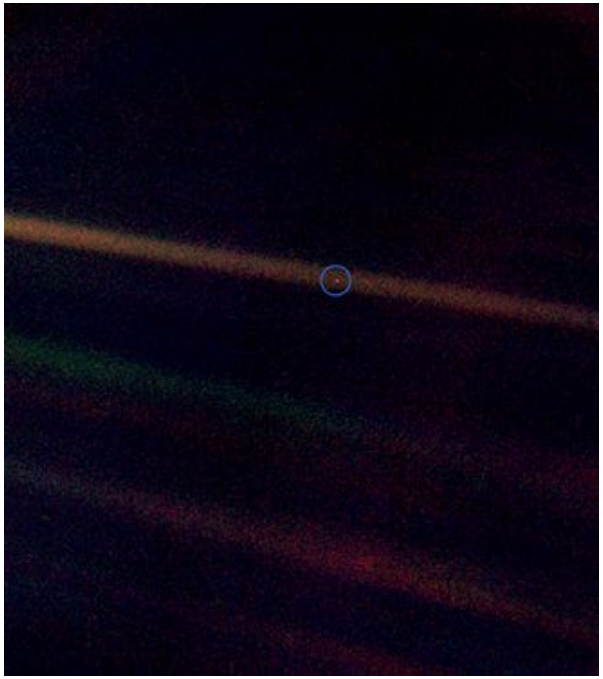
Starting point

- **We live on the 3rd planet from the sun in this system of 8 planets (sorry Pluto) in what is referred to as a habitable zone where liquid water can exist**
  - Astronomers have also found 3,610 exoplanets around other stars

NASA



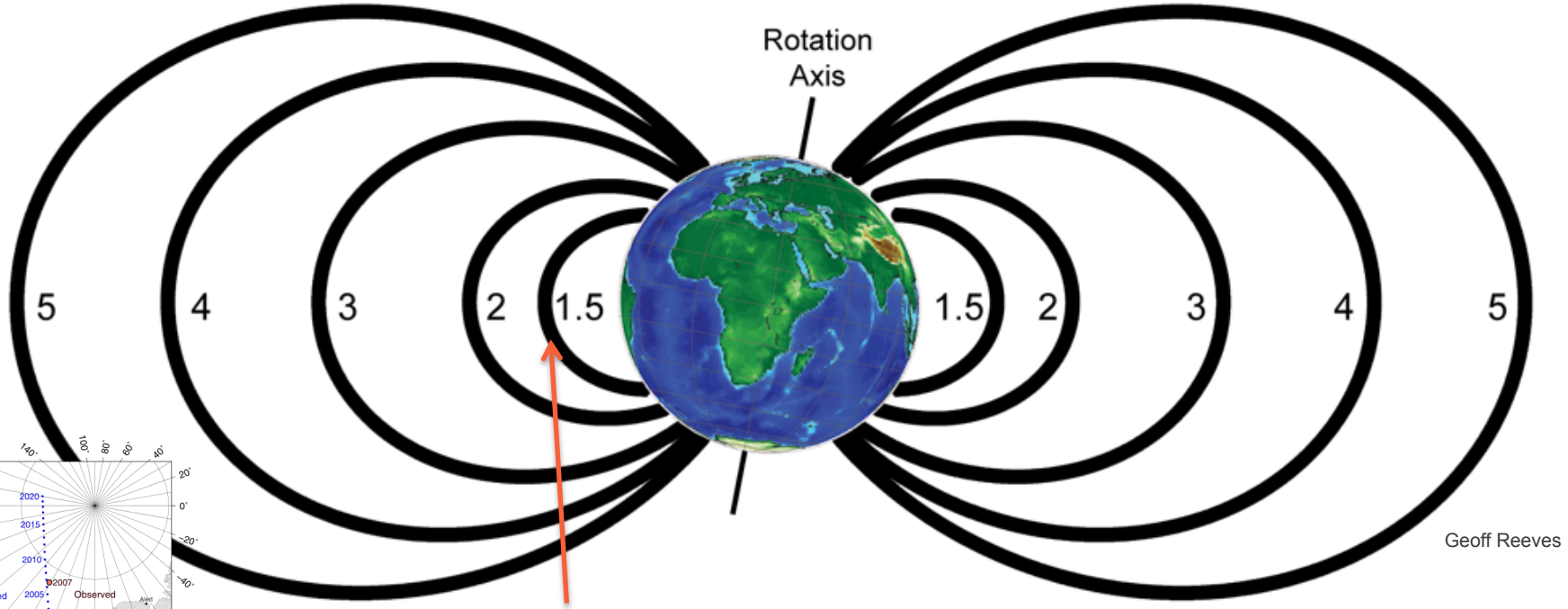
NASA

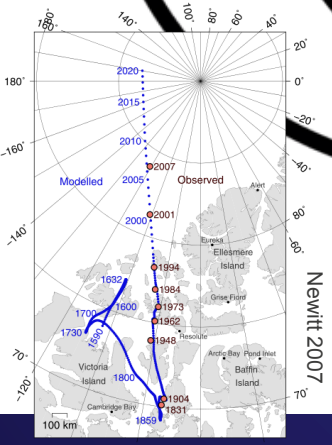


"Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives.".
- Carl Sagan
Voyager 1 image – Pale Blue Dot

Earth's dipole magnetic field

On short (decades-centuries) timescales Earth's magnetic field is stable and if the story ended here all of our space endeavors would be a lot simpler, but a lot less interesting.





L – distance to field line at geomagnetic equator
L-shell – entire torus of that distance

We are a system in a system in a system


NASA

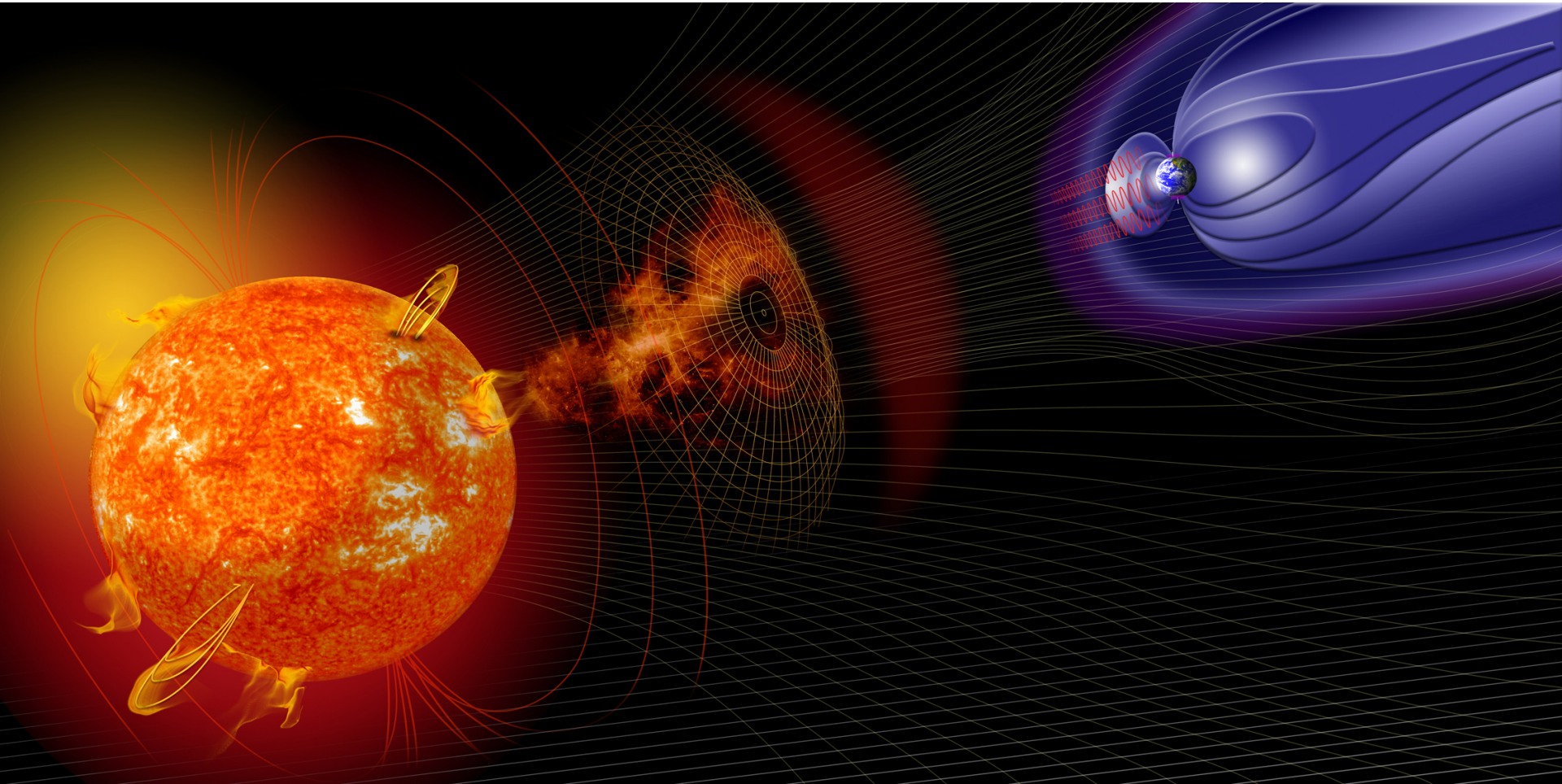
- **Instead of Earth having a stable dipole field in vacuum we are embedded in flowing plasma carrying magnetic fields from the Sun and all the other regions**
  - Heliosphere, region dominated by the sun
    122 au, 1.83×10^{10} km, 16.91 light hours (au – Astronomical Unit – Earth-Sun distance)
  - Local Bubble, cavity in the interstellar medium
    1.897×10^{7} au, 2.838x1012 km, 300 light years
  - Milky Way Galaxy, galaxy in which we live (we are really far form the center)
    9.486×10^{9} au, 1.419×10^{18} km, 150×10^{3} light years

- **The closer the driver the more it matters but impacts are seen from all these regions**
  - We will focus on the heliosphere except for galactic cosmic rays and gamma ray bursts

Heliophysics

- **Heliophysics [encompasses] environmental science, a unique hybrid between meteorology and astrophysics, comprising a body of data and a set of paradigms (general laws—perhaps mostly still undiscovered) specific to magnetized plasmas and neutrals in the heliosphere interacting with themselves and with gravitating bodies and their atmospheres.**
  Dr. George Siscoe – Boston University

NASA

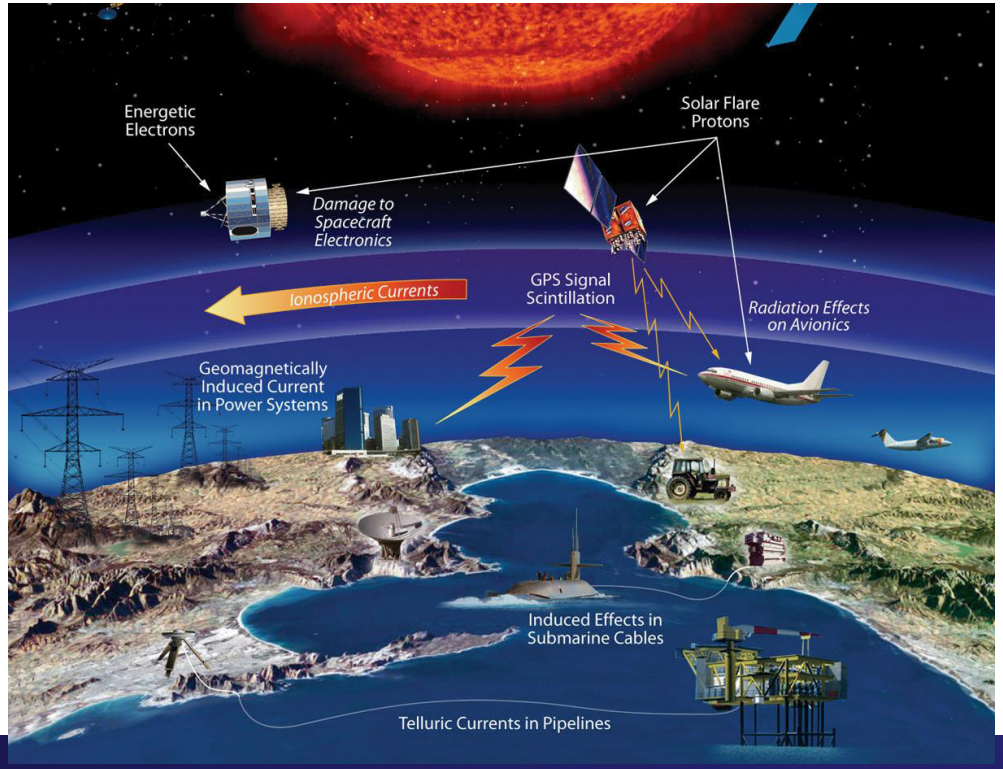


Space Weather

- **Term coined in the 1950s**
  - Popular in the1990's to 2000's
- **Distinct form space physics as encompassing the day-to-day and larger variations that impact technological systems**
  - Analogy to terrestrial weather

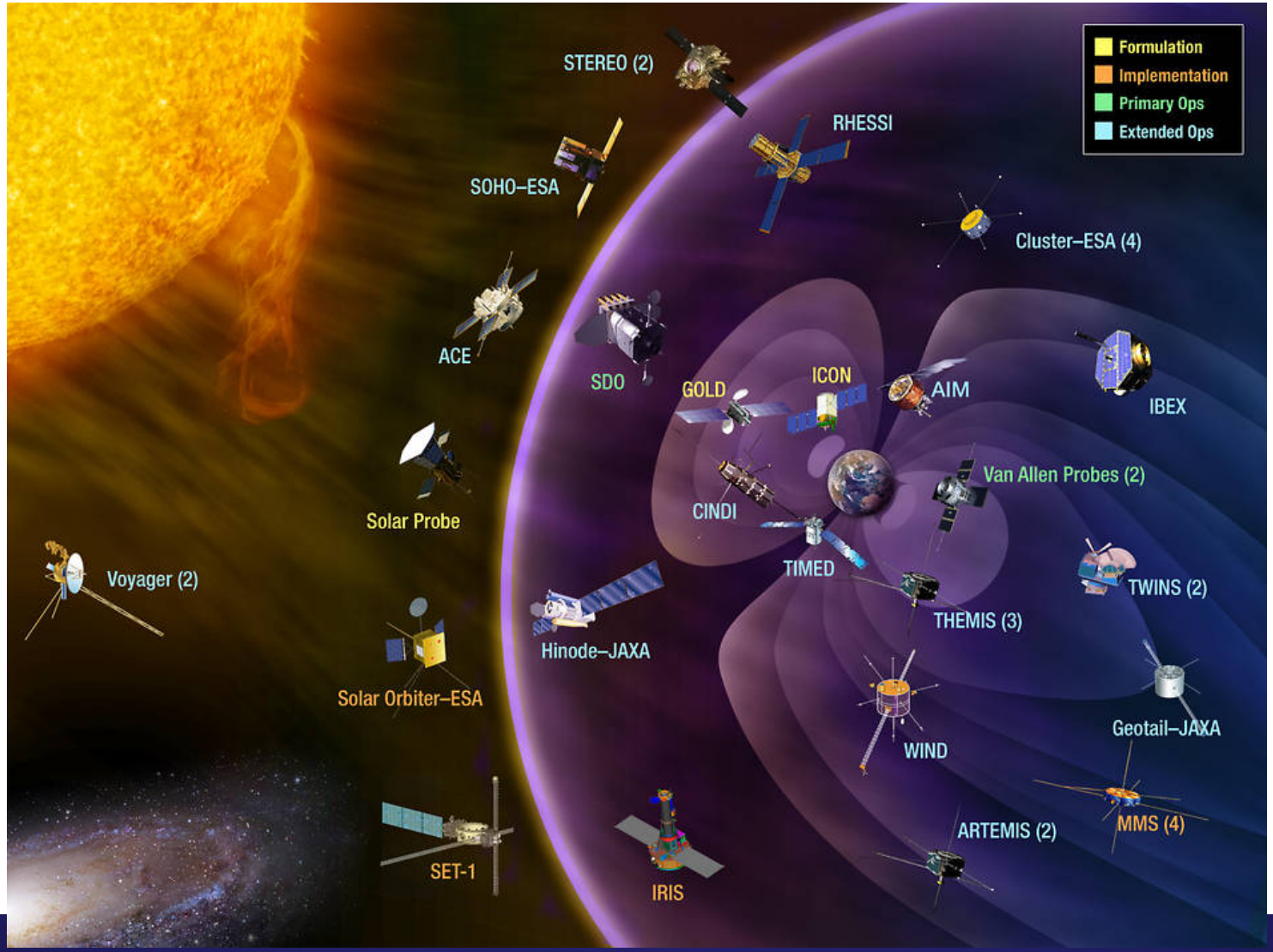
NASA

NASA



There are a lot of current science missions enabling studies
(National security missions too but at lower public profile)

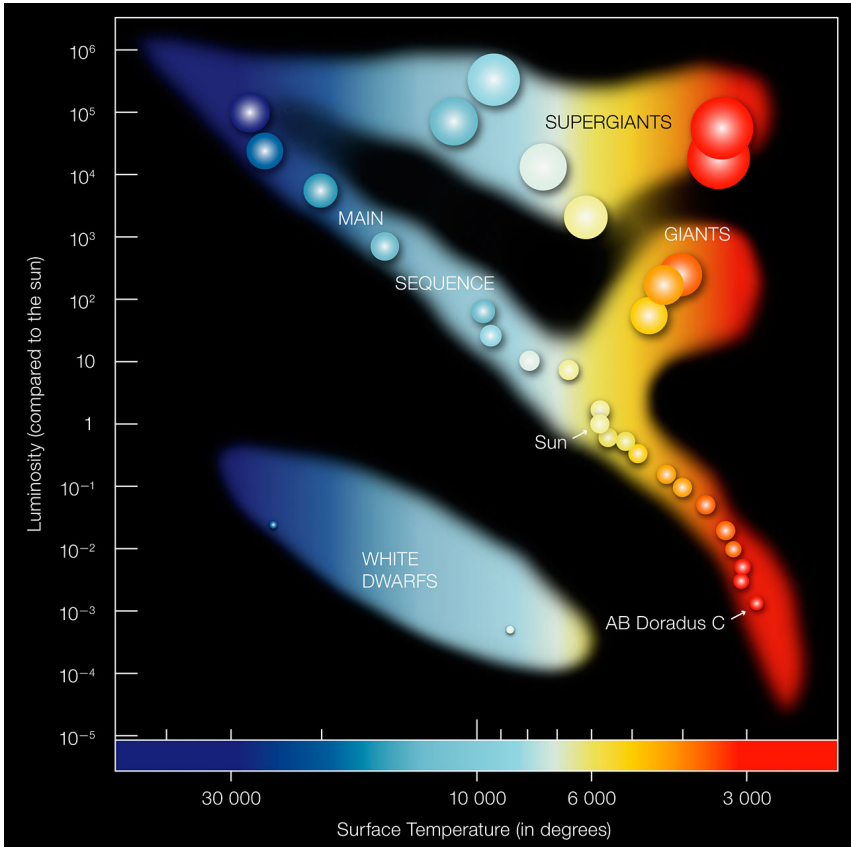
NASA



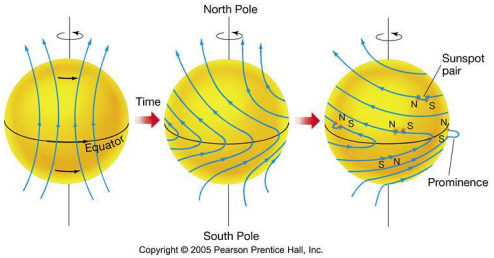
The Sun

- **The sun is a middle aged G-type main-sequence star**
  - Formed about 4.6 billion years ago
  - 1 astronomical unit (au) away, 1.496×10^8 km, 8 min 19sec at light speed
  - 695,700 km across ball of plasma
    - 1.57×10^7 K core
    - 5,772 K Photosphere
    - 5×10^6 K Corona
    - 73% Hydrogen, 25% Helium, trace O, C, Fe, Ne, N, Si, Mg, S
  - Emits 3.828×10^{26} W, 1,368 W/m^2 at Earth

European Southern Observatory

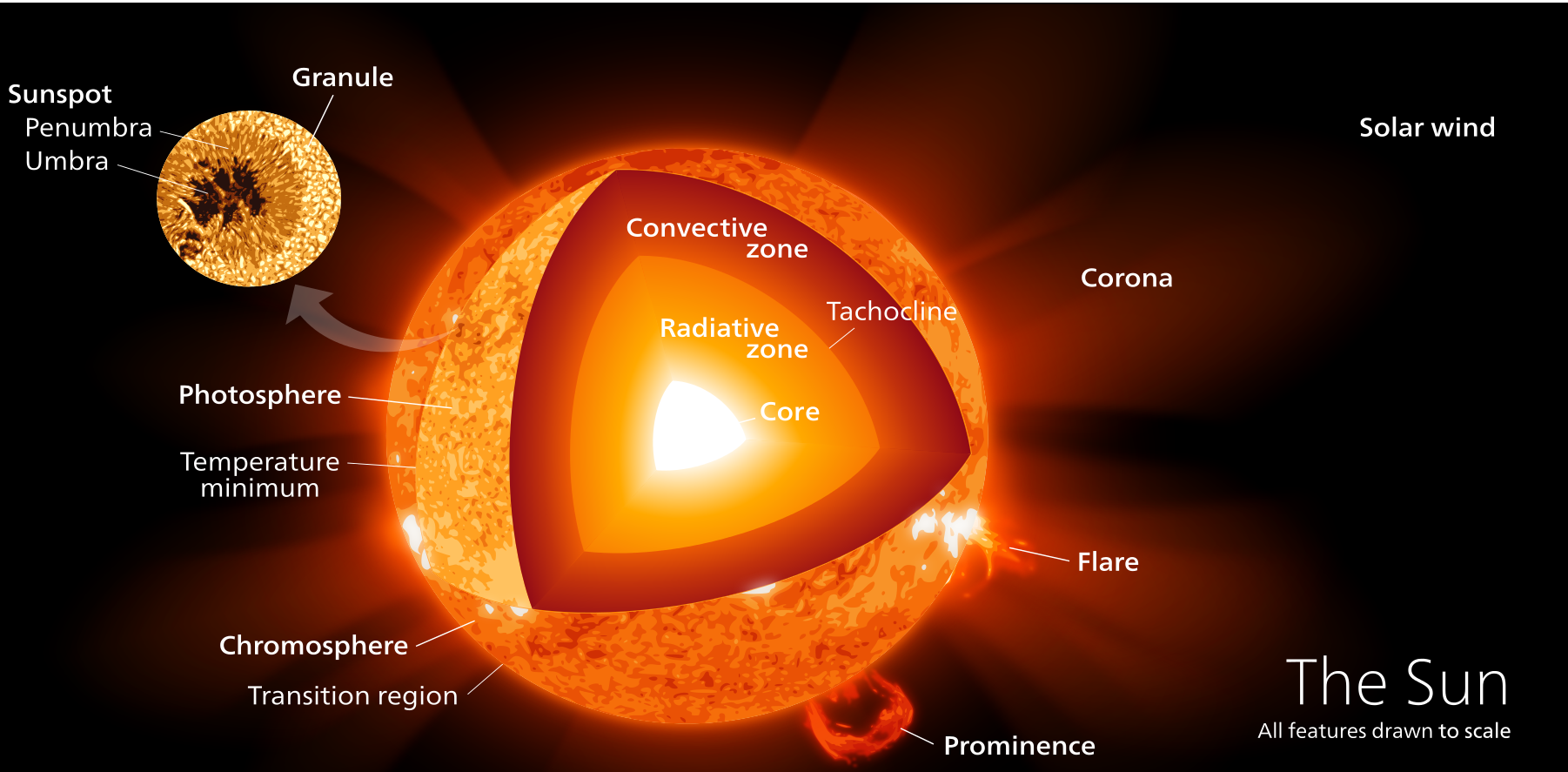


Parts of the sun



- Regions change radially from the center
- Pressure balance between nuclear fusion in the core and gravity

Kelvinsong, wikipedia

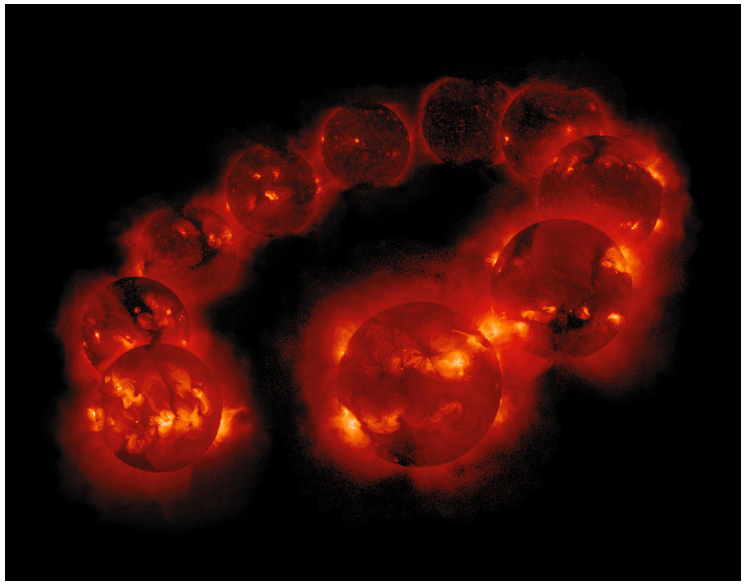


Solar cycle (AKA sunspot cycle)

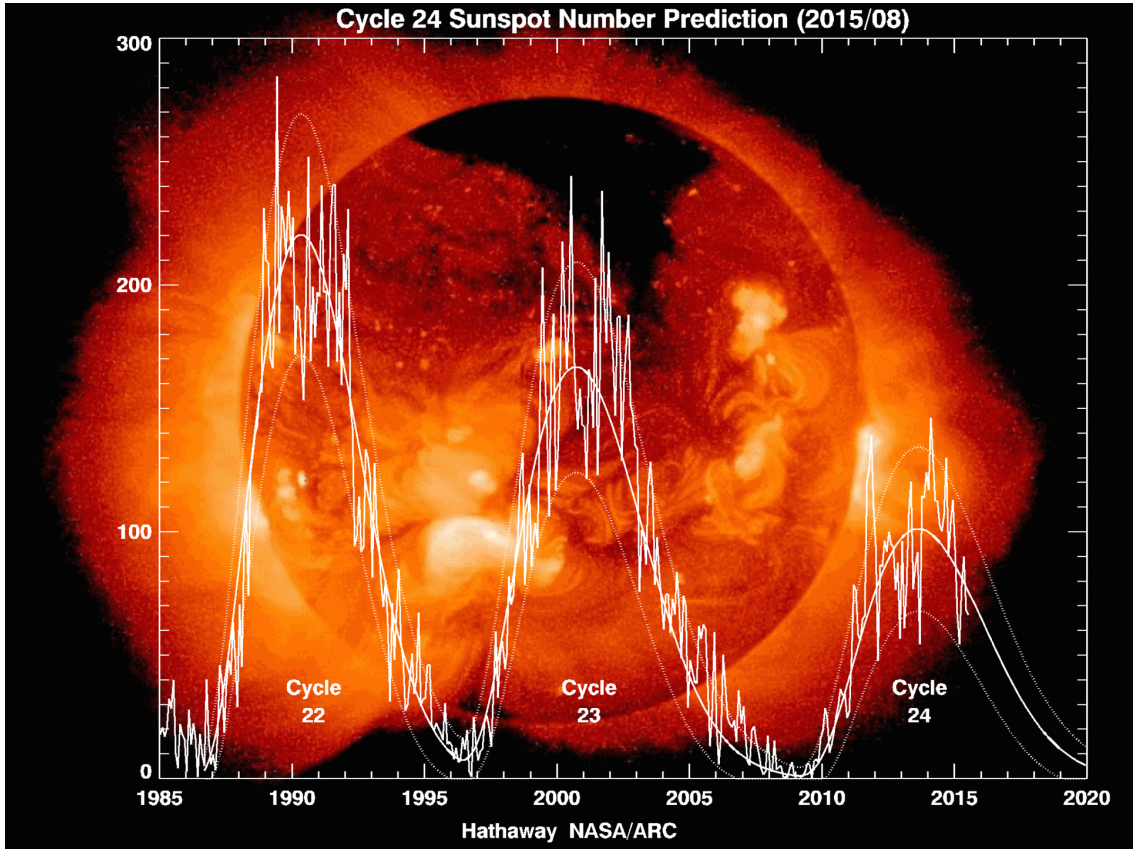
- Sun has an 11 year activity cycle (ok actually 22 year)
- During this cycle there are more sunspots and the sun becomes more active
- Starspot cycles are also observed on other stars

- Solar cycle in soft x-rays

Yohkoh mission of ISAS (Japan) and NASA (US)

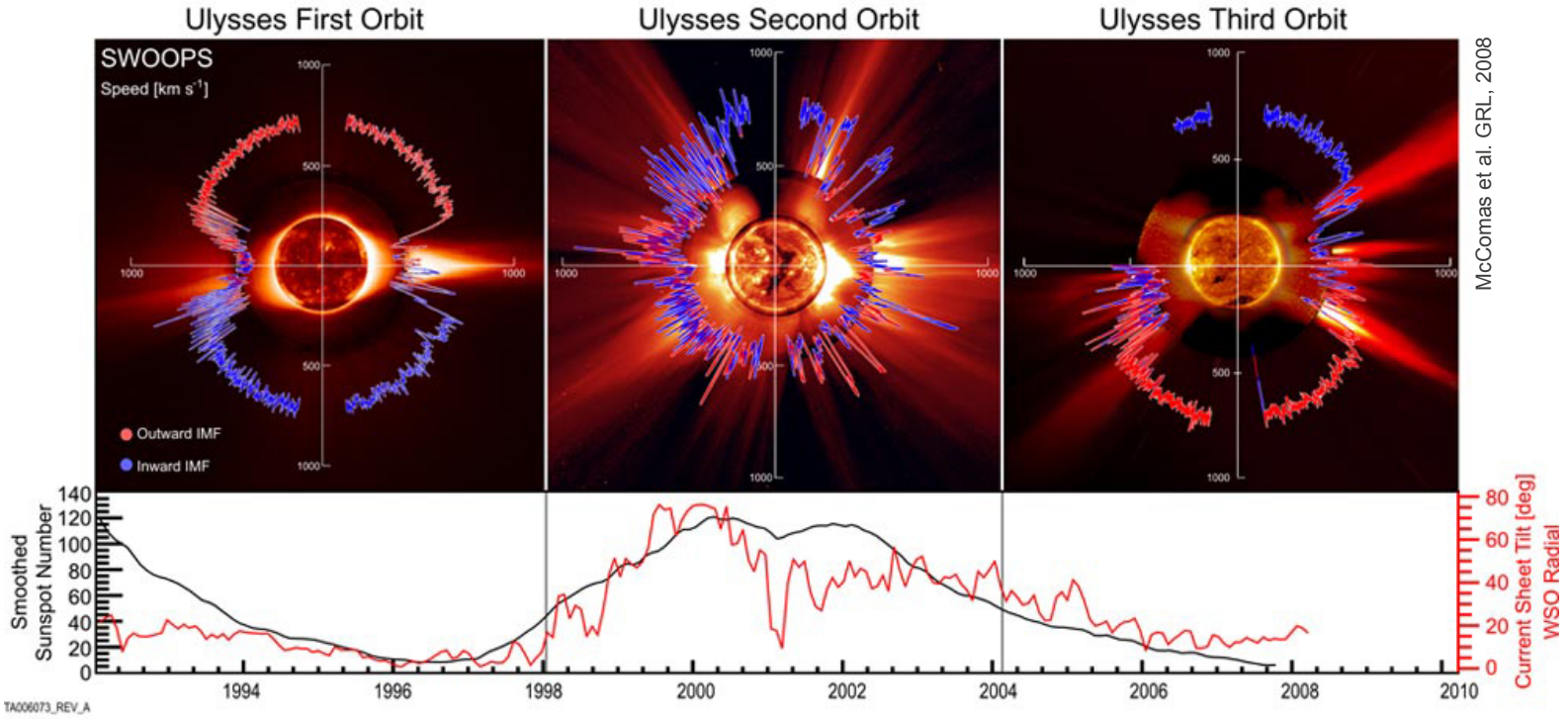


ISAS/NASA



Solar wind

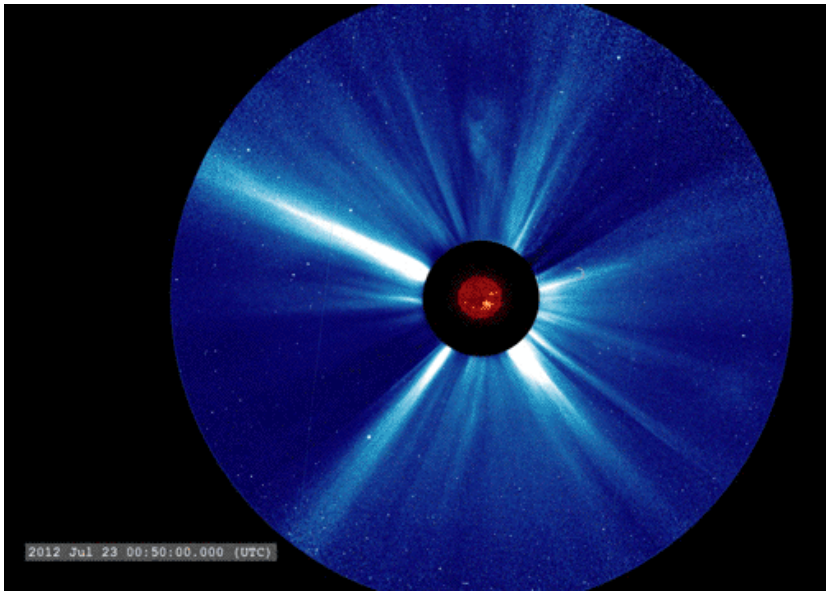
- Hot plasma streaming radially outward from the sun
- 1.5 to 10 keV, ~1.5x10^6 K
- 300 to 800 km/s (supersonic)
- 1 to 50 particles/cm^3
- 50 to 50 nT magnetic field
- Stable at solar min, variable during solar max



Solar impulsive events

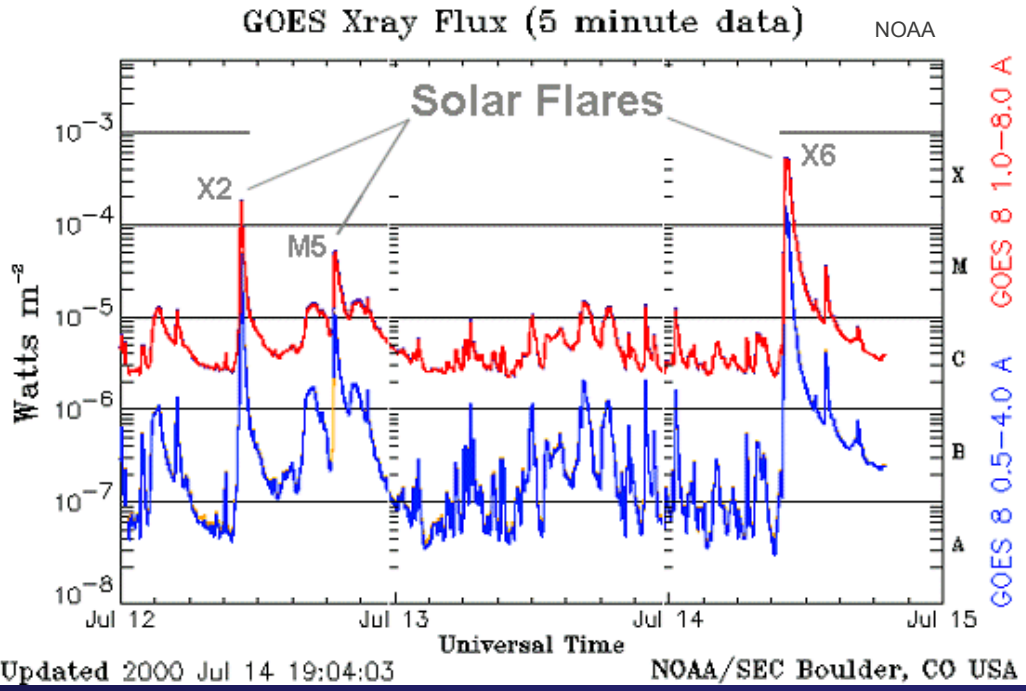
- **Three main types:**
  - Solar flare: electromagnetic sudden, rapid, and intense variation in brightness
  - Coronal Mass Ejection (CME): large release of plasma and magnetic field from the solar corona
  - Solar Energetic Particles (SEP): high energy electrons and protons (and neutrons)
    - Solar Proton Event (SPE)

NASA

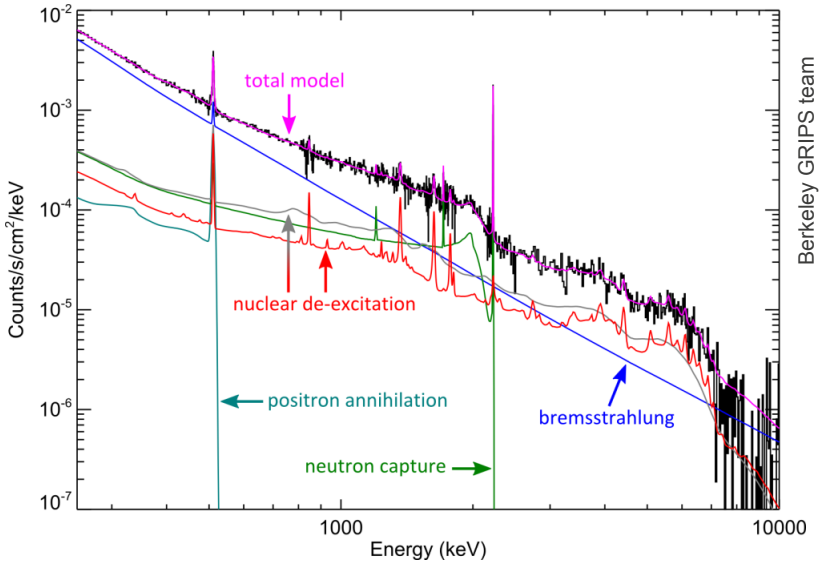


Solar flares

Classification	Peak Flux Range 100-800 pm (1.5-12keV) (watts/m**2)
A	$<10^{-7}$
B	$10^{-7} – 10^{-6}$
C	$10^{-6} – 10^{-5}$
M	$10^{-5} – 10^{-4}$
X	$> 10^{-4}$

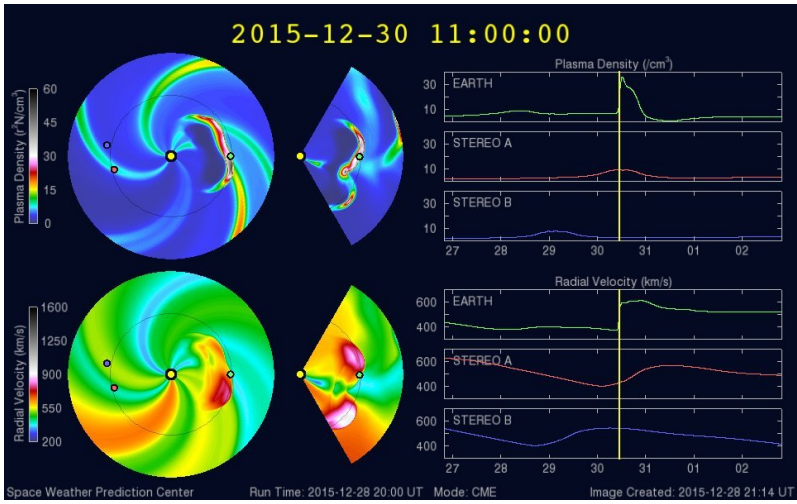


Spectra is complex and carries significant information

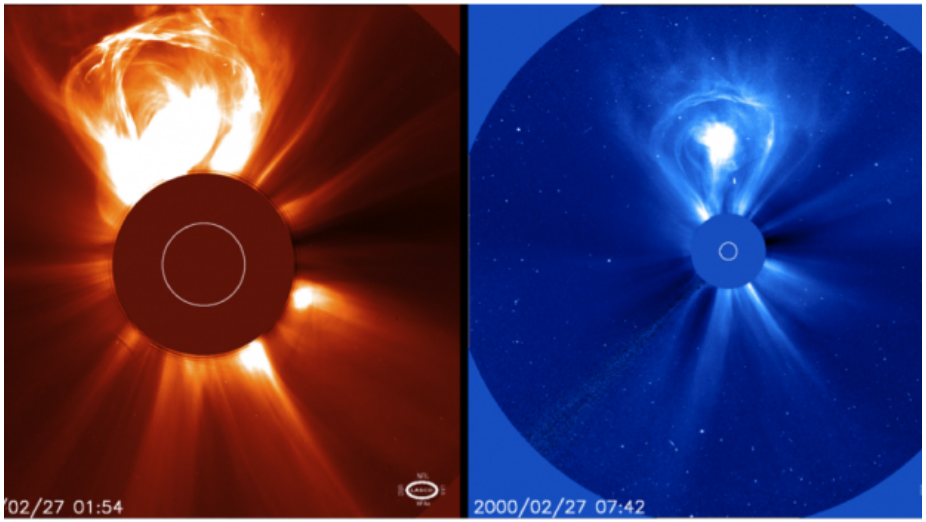


Coronal Mass Ejection

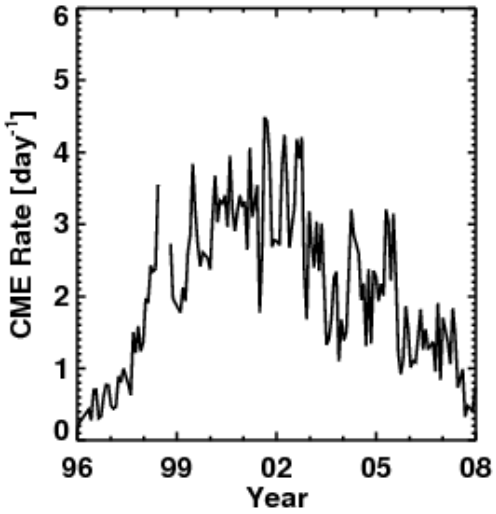
- **Most important driver of large Space Weather events when geoeffective**
  - Geoeffective – “Made up” word for when an event impacts Earth, no rigid definition
- **Drives large geomagnetic storms**



NASA



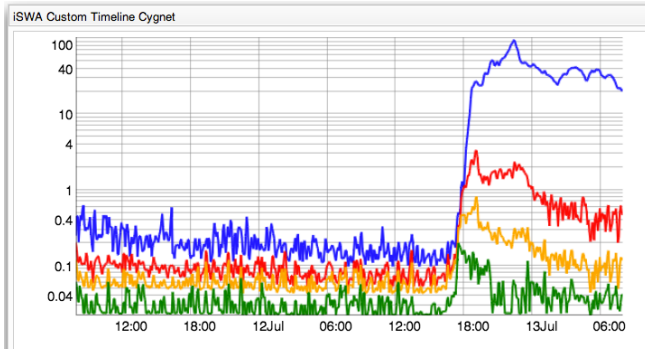
Gopalswamy 2010

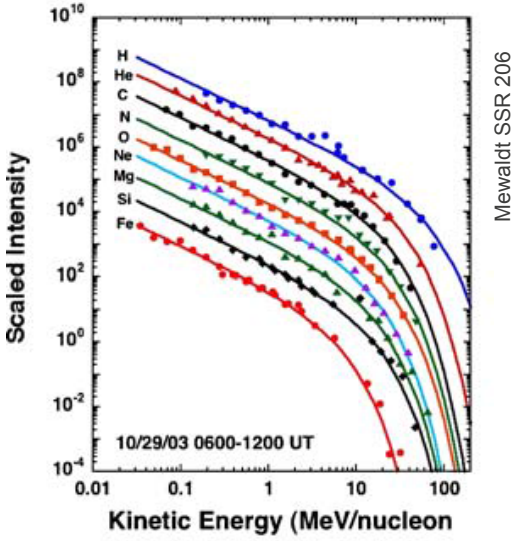


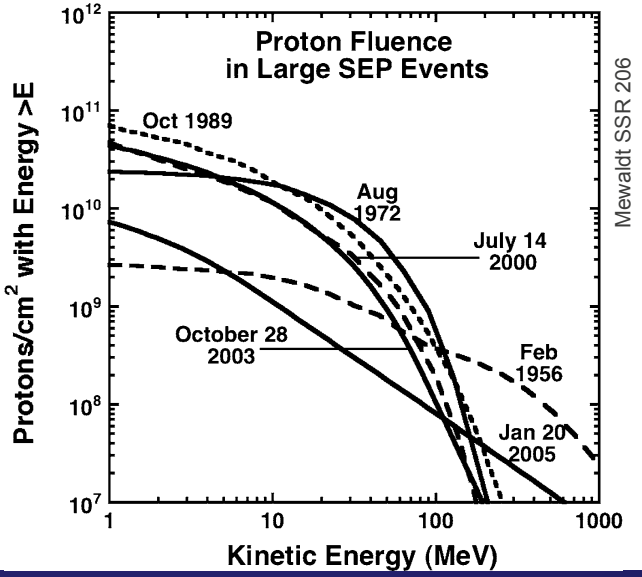
Solar energetic particles

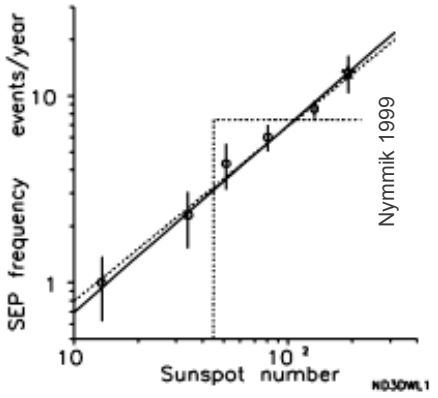
- High energy particles accelerated near the sun keV to GeV energies
- GOES Proton 10MeV channel > 10 pfu
  100 MeV channel > 1 pfu
- Mostly protons but all solar species
- Spectra is variable
- Occurrence correlated with solar cycle

NOAA



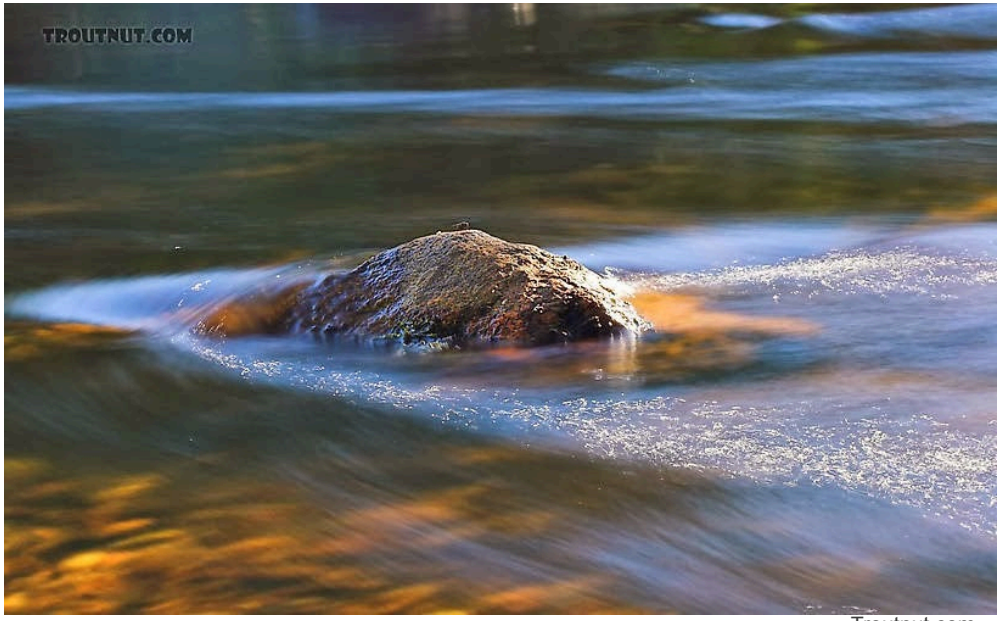




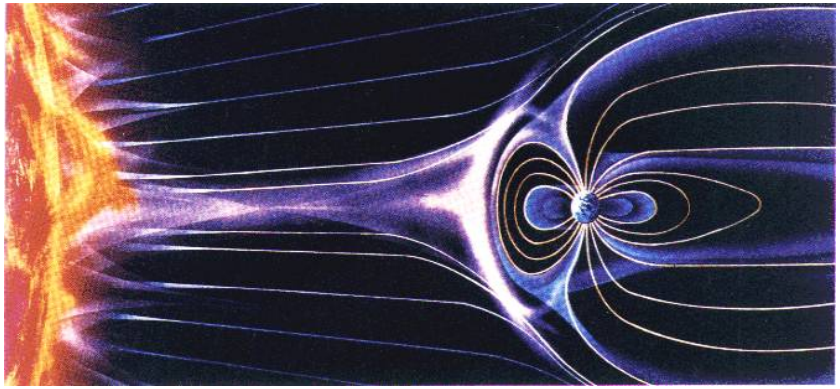


Earth's dipole is not sitting alone

- **Just like water piles up on the front of this rock and forms a long tail of impacted flow behind the plasma in the solar wind does the same to the magnetosphere**



Troutnut.com



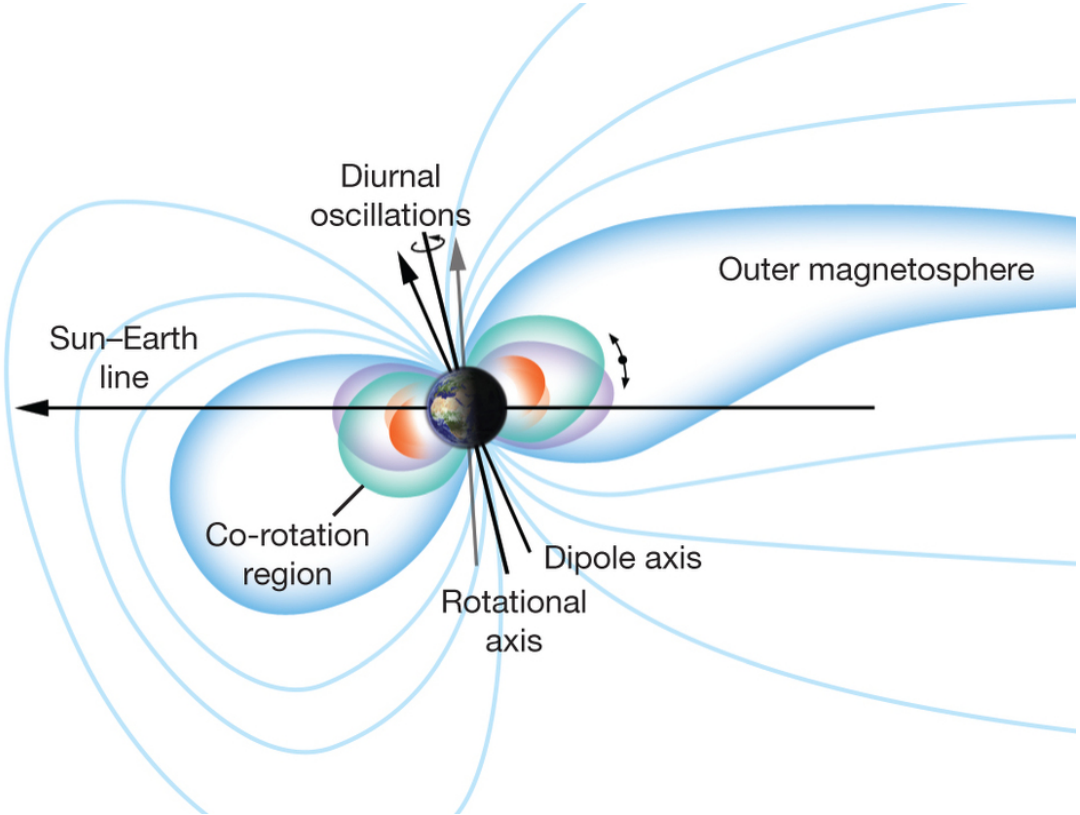
NASA

Hydrodynamics

Magnetohydrodynamics

Earth's dipole magnetic field

Dipole is offset from rotation axis but about 11 degrees
Also not centered

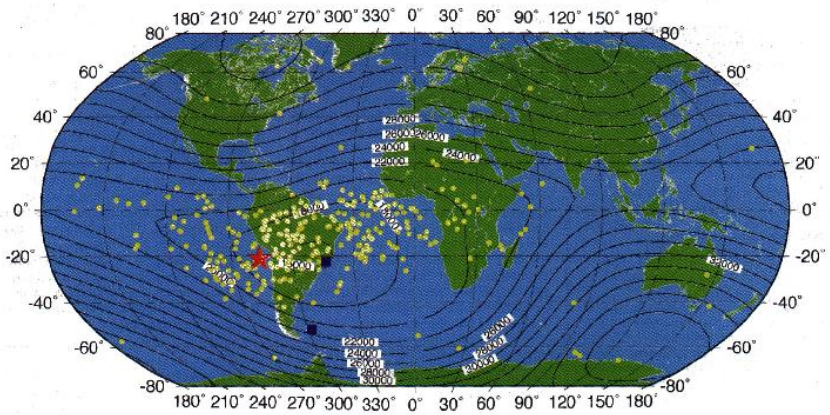


Ukhorskiy 2014

South Atlantic (Geomagnetic) Anomaly

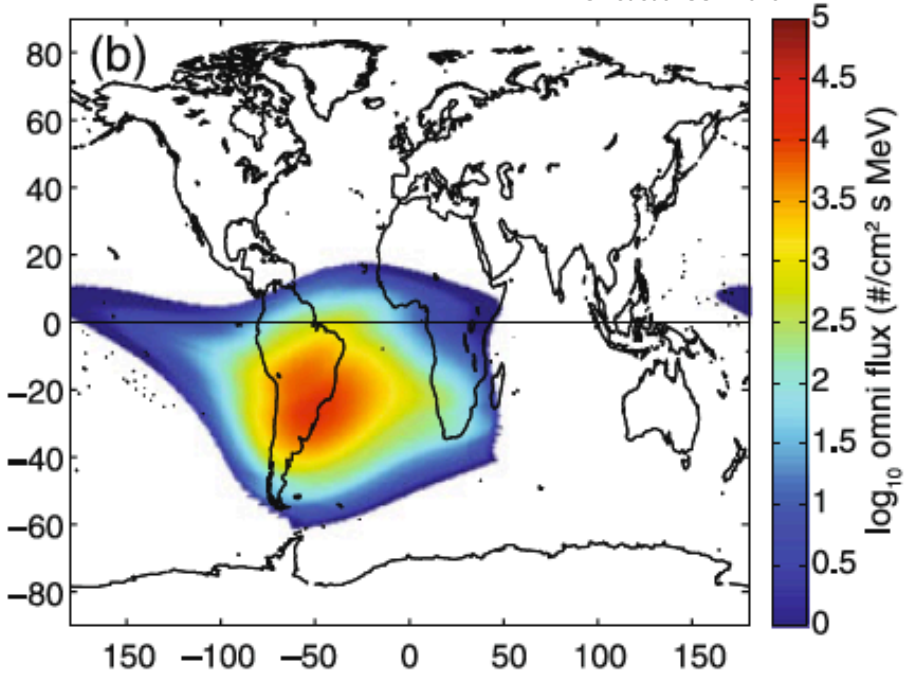
- **Earth's dipole field is offset and in this region radiation belt particles are closer to Earth**
- **Increased number of satellite anomalies**

TOPEX anomaly locations



Jim Heirtzler

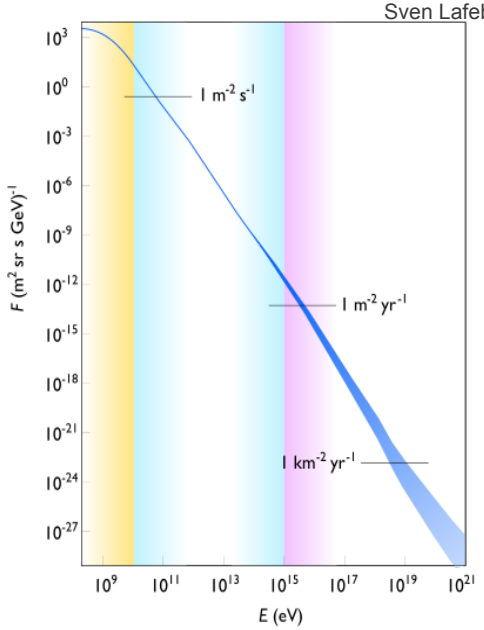
Ginet et al SSR 2013



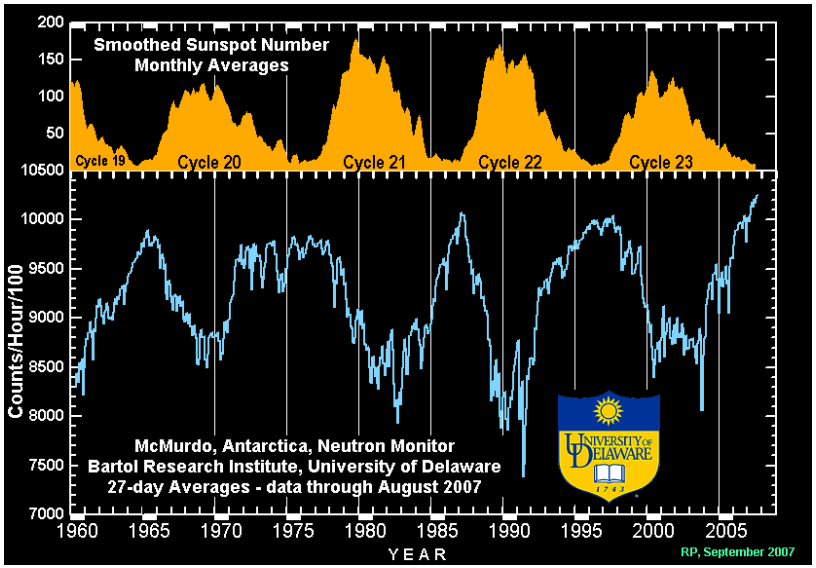
Cosmic Rays

- **High energy radiation originating outside the solar system, found 1909**
  - Vastly improved by Hess, 1912 balloon measurements
- **Steep spectra to incredibly high energies**
- **Inversely modulated by solar cycle**
  - Scattered by magnetic field
- **Modulated by CMEs**
  - Scattered by magnetic field
    - "Forbush decrease"

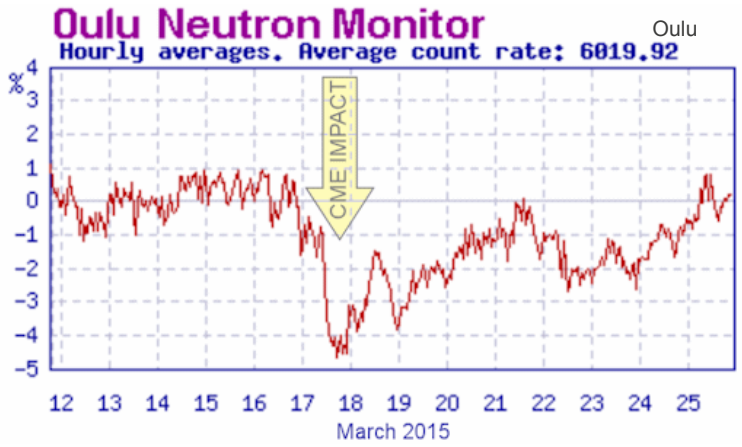
Sven Lafebre



Univ of Delaware



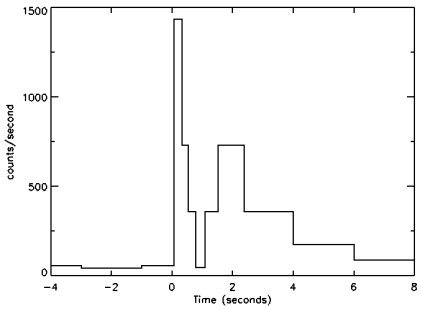
Oulu



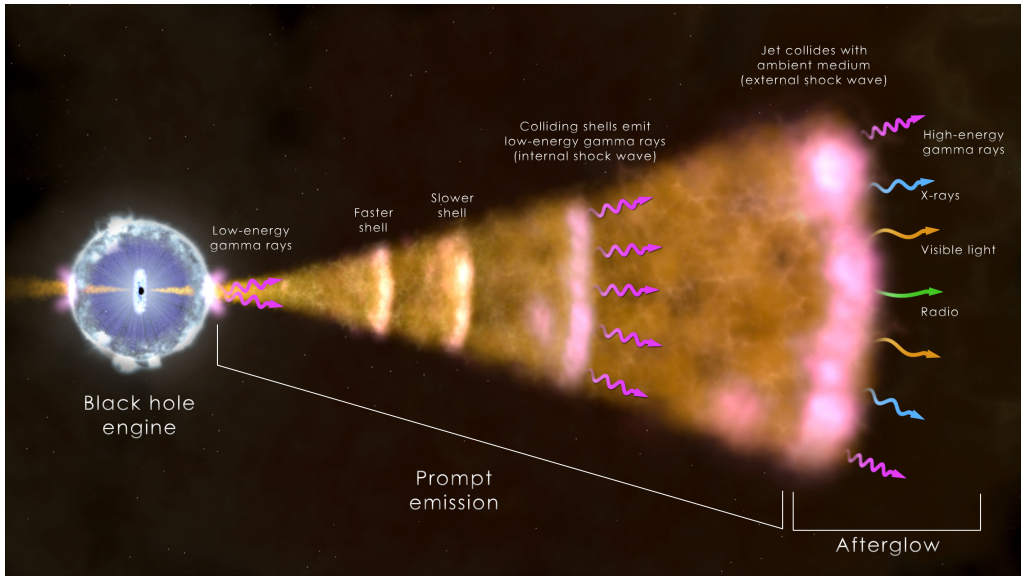
Gamma Ray Bursts

- **Vela 4a,b on July 2, 1967**
  - "Observations of Gamma-Ray Bursts of Cosmic Origin" Klebesadel R.W., Strong I.B., and Olson R.A. 1973, Ap.J. 182, L85. **Los Alamos**

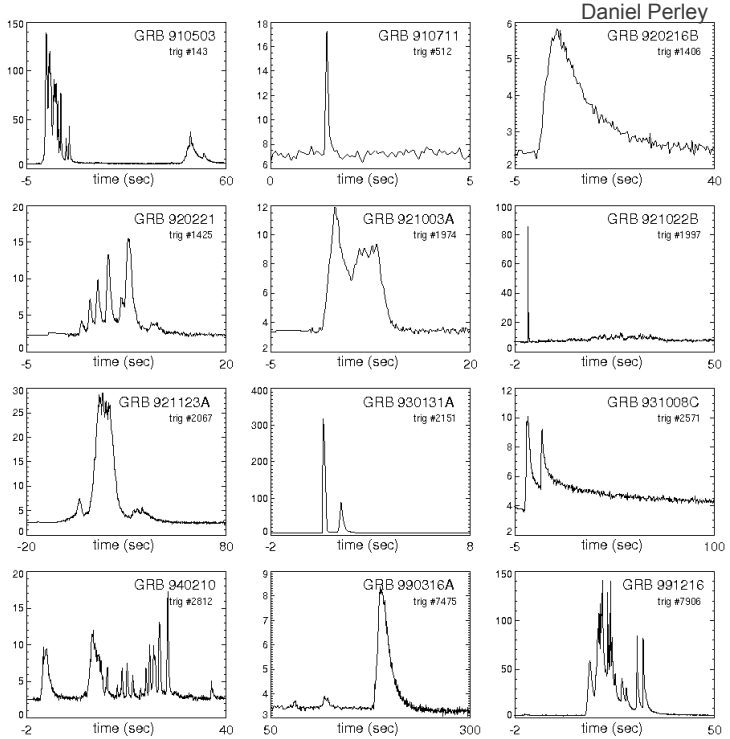
Klebesadel 1973



NASA

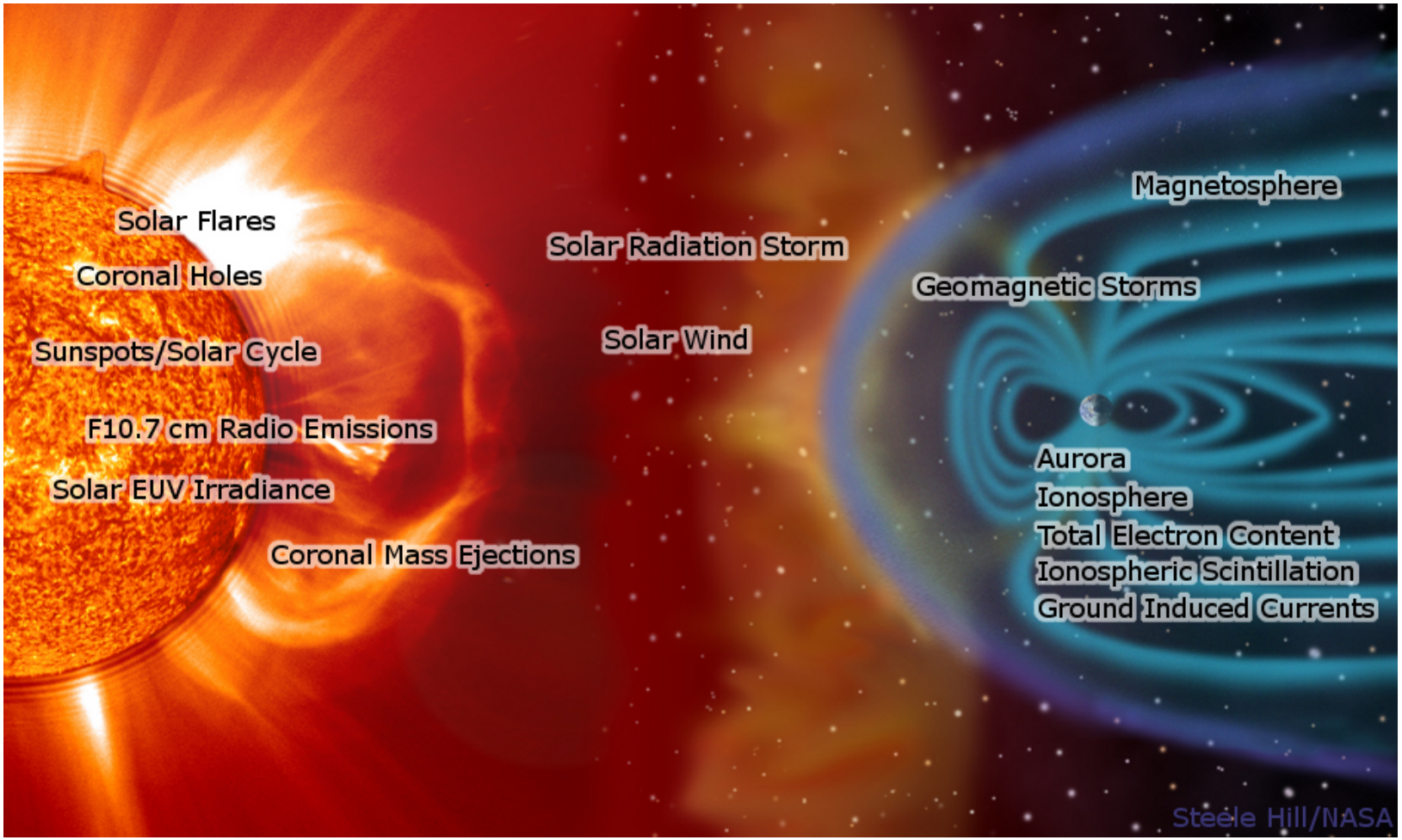


Daniel Perley

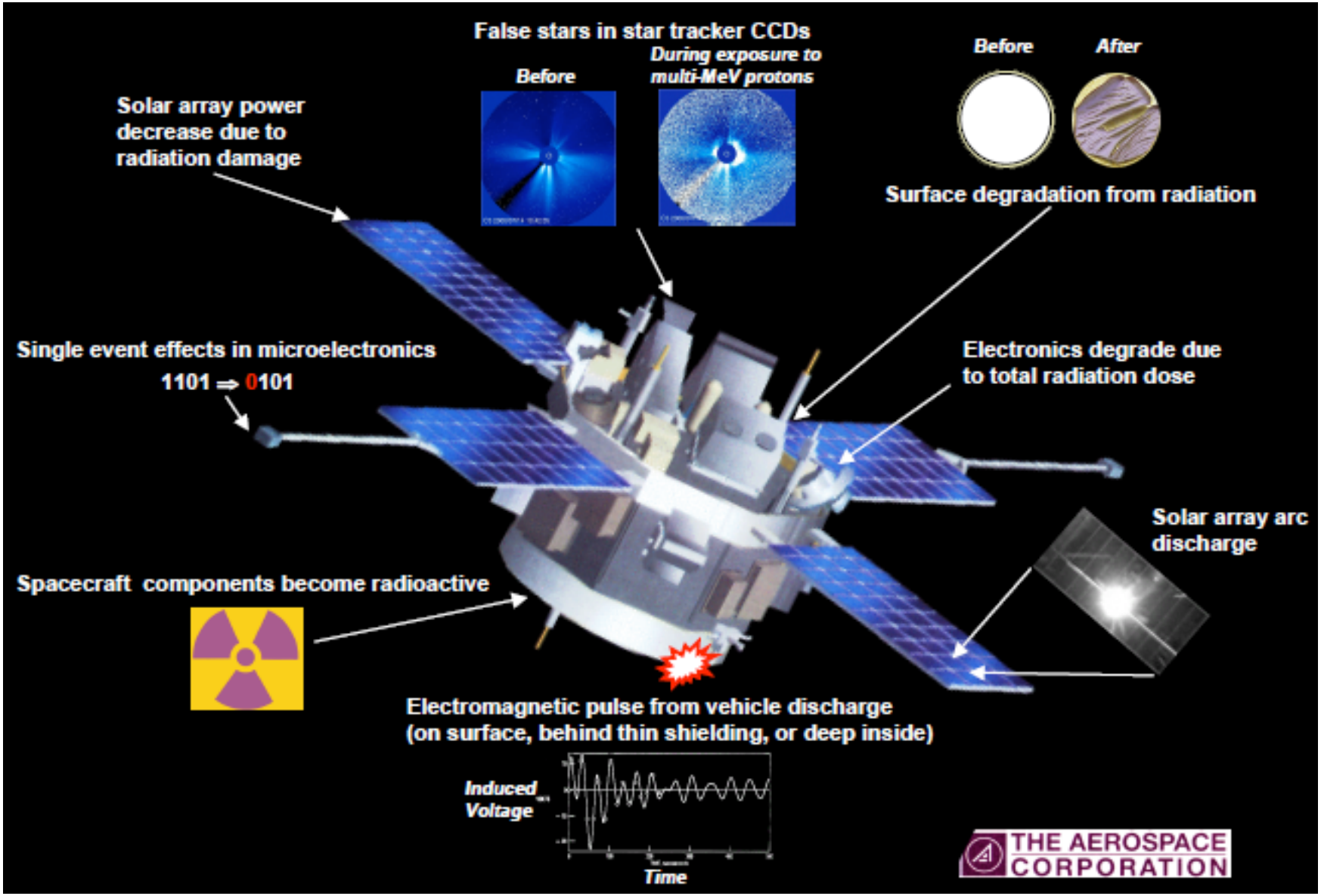


BATSE, Compton Gamma-Ray Observatory.

Space Weather Phenomena

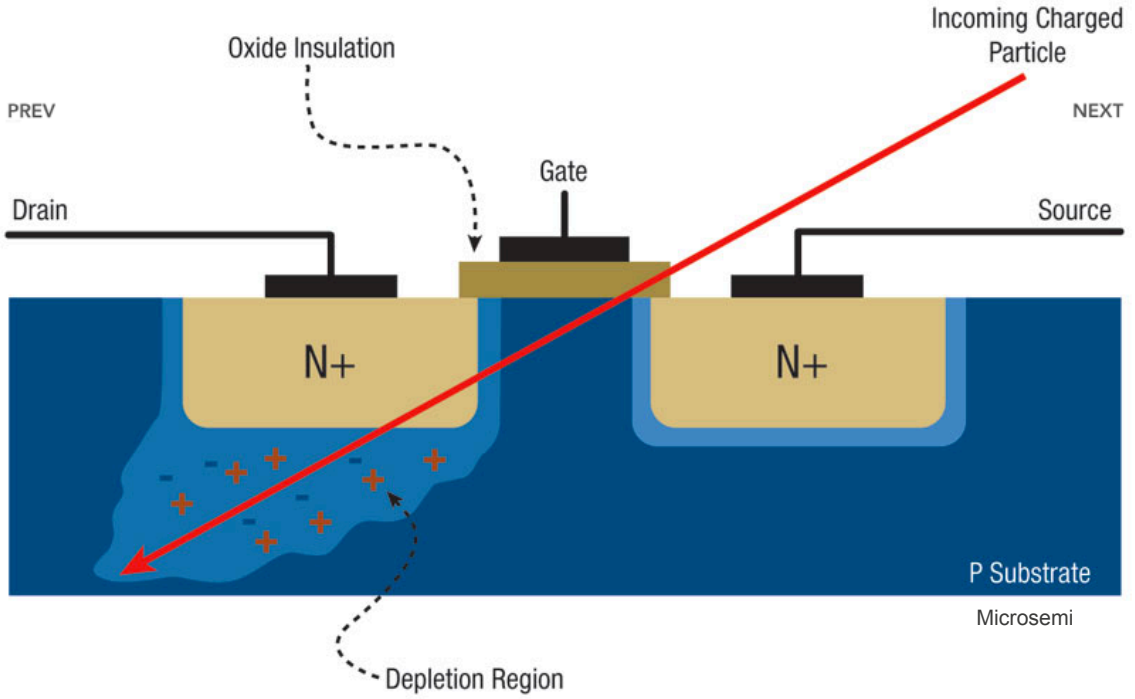


Space Environment Hazards



Space Weather Hazards

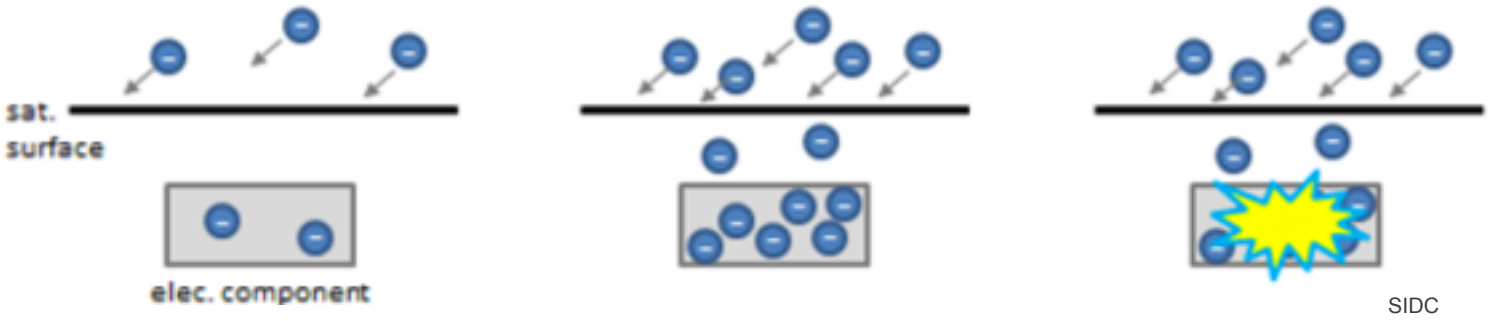
- **Single event upset**
  - Change of state in a electronic device causes by a single charged particle
  - Discovered during early nuclear testing
- **MeV electrons, 10's MeV protons**
- **Space systems have to design around this vulnerability**



Microsemi

Space Weather Hazards

- **Deep dielectric charging**
  - 100's keV electrons embed themselves into insulators until a breakdown occurs
- **Space systems have to design around this vulnerability**

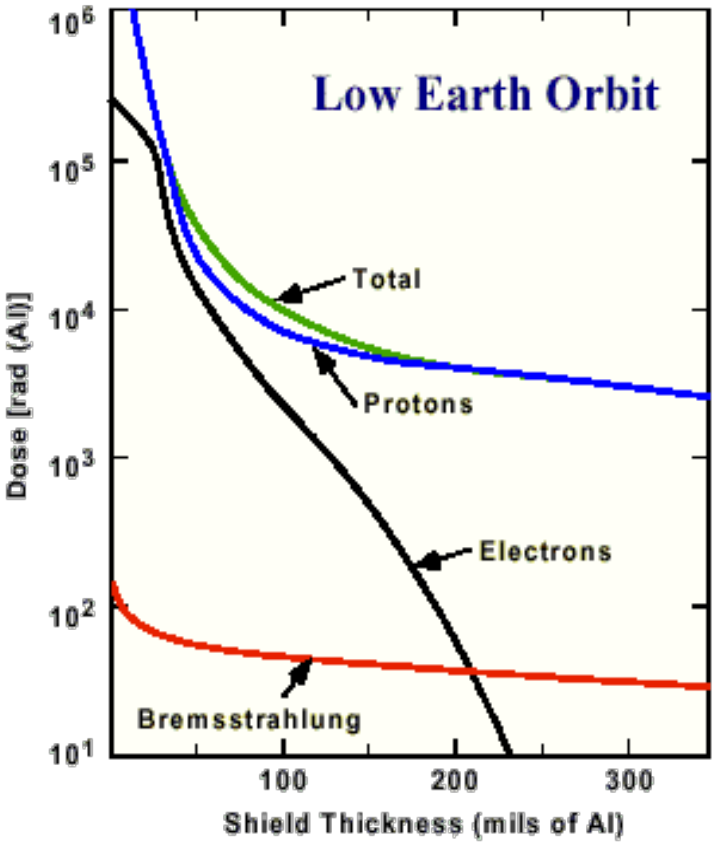


SIDC

Space Weather Hazards

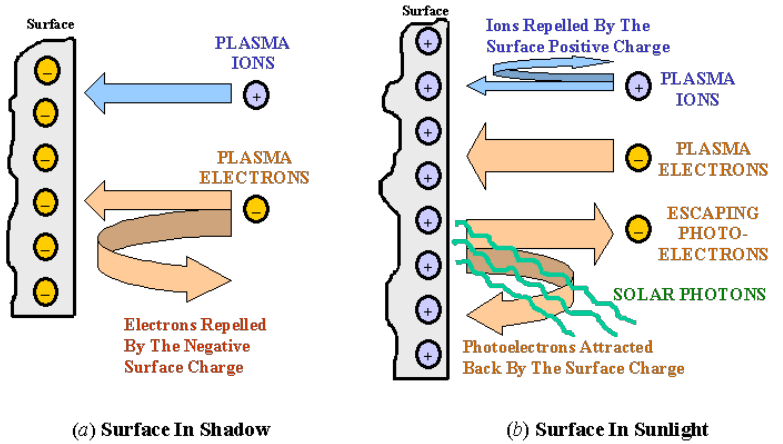
- **Total ionizing dose**
  - The combination of all ionizing radiation damages electronics and moves toward parts failure
- **Space systems have to design around this vulnerability**

NASA



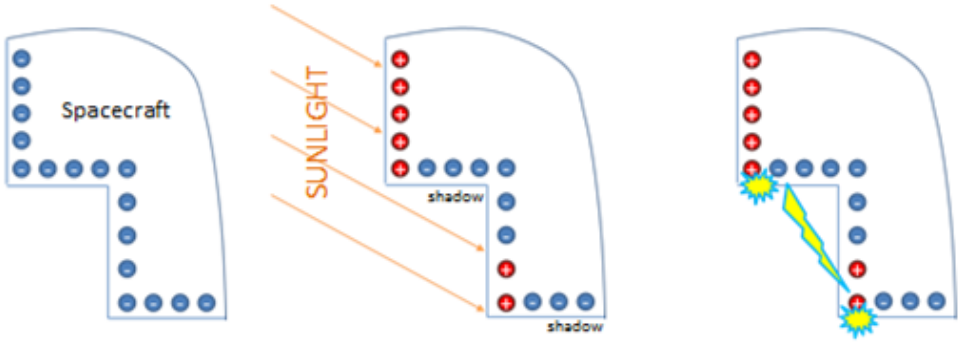
Space Weather Hazards

- **Surface charging**
  - Balance of plasma environment and photoelectron emission
  - Spacecraft charge charge up 1000s of volts relative to ambient plasma
    - Not by itself a hazard, becomes a hazard when design flaws allow differential changing and discharge
- **Space systems have to design around this vulnerability**



(*a*) **Surface In Shadow** (*b*) **Surface In Sunlight**

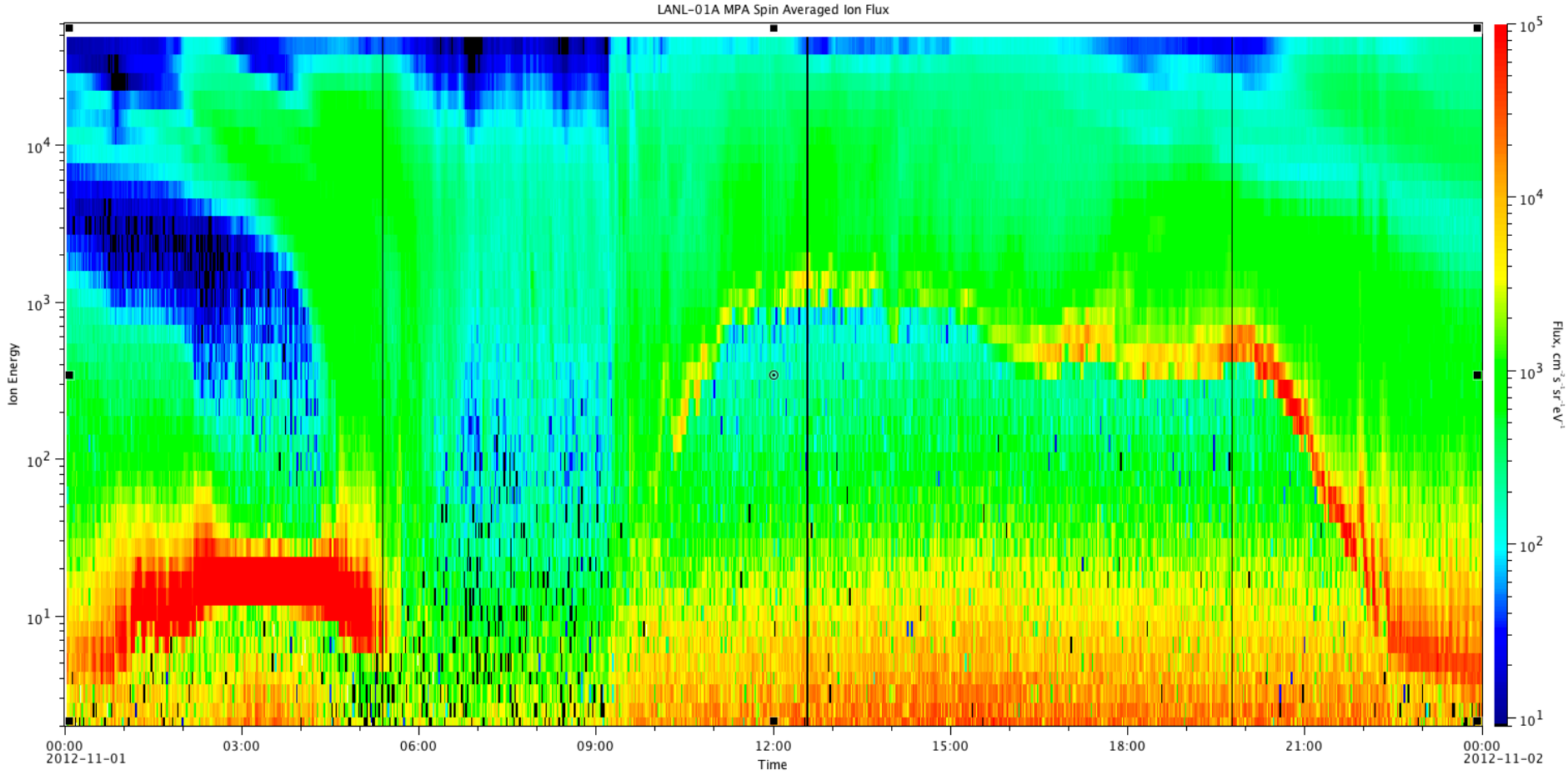
Leach1995



SIDC

Spacecraft charging example

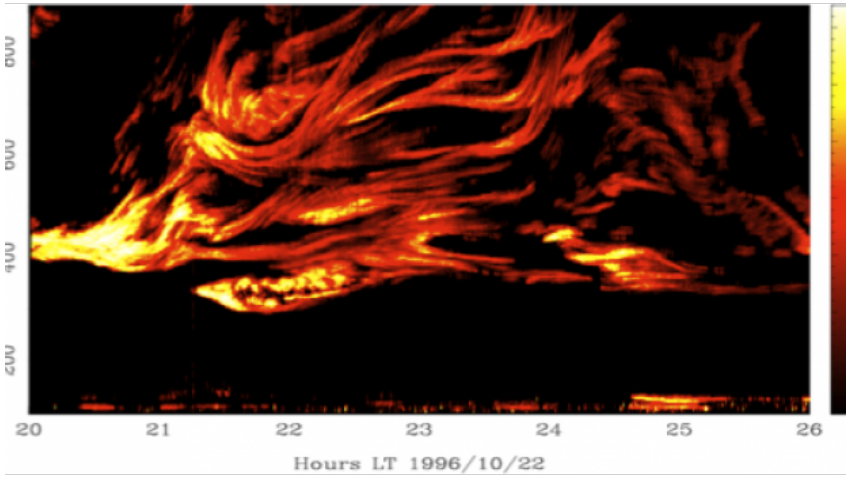
- **Ions are accelerated to a negatively charged spacecraft**
- **~9 hours of kV charging demonstrated by LANL-01A MPA instrument**
  - Ion spectrogram, 2012-11-01
  - No negative impact noted



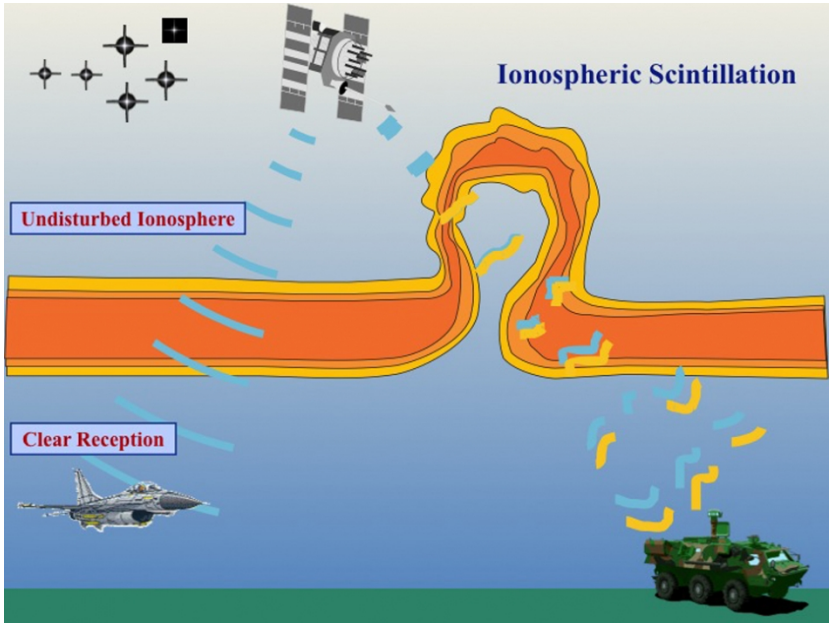
Space weather impacts

- **Ionospheric scintillation**
  - Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere
  - Changes path lengths and signal coherence as radio signals pass through the ionosphere
- **Space systems have to design around this vulnerability**

NOAA



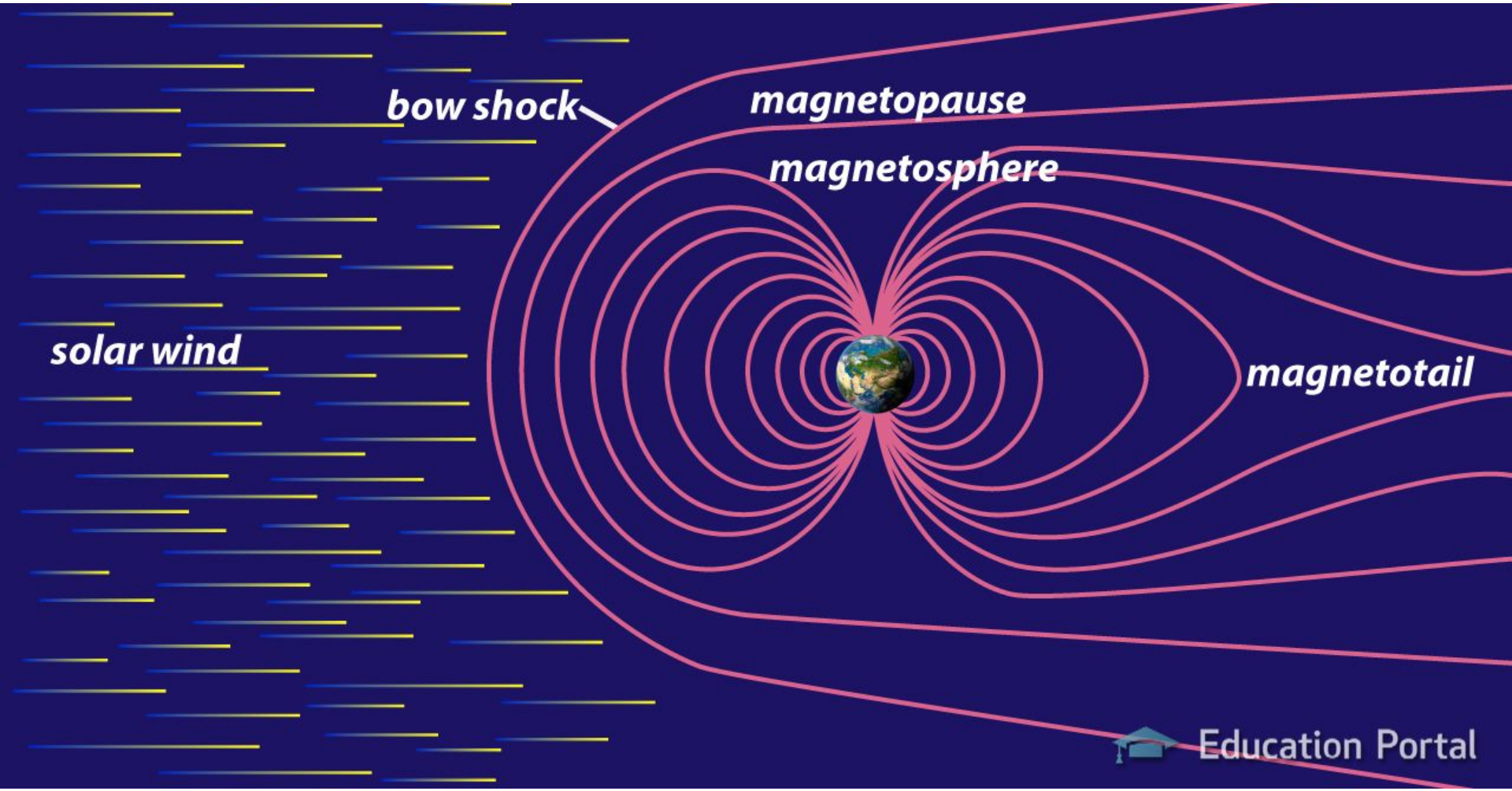
NASA



Geomagnetic Indices

- **We rely heavily on geomagnetic indices to give an overall state**
  - Dst – Disturbance Storm Time Index, 1-hour
    - Magnetic activity from near-equatorial magnetometer stations
    - Measures the depression of geomagnetic field by the symmetric ring current
    - Defines a geomagnetic storm
  - Kp – Planetary K-index, 3-hour
    - Magnetic activity from 13 magnetometer stations between 44-60 degrees latitude
    - Defines overall activity
  - AE/AU/AL/AO - Auroral horizontal indices, 1-minute
    - The magnetograms of the horizontal components from the AE stations are superimposed: the upper envelope defines the AU index, and the lower envelope define the AL index; then AE = (AU - AL) and AO = (AU + AL)/2.
  - Sunspot number
    - Number of sunspots on the sun, normally running average
  - F10.7 – Solar radio activity, daily
    - Solar radio flux at 10.7 cm (2800 MHz)
- **In general everything in the solar wind is correlated and everything in the magnetosphere is correlated – makes cause and effect challenging**

A bit of vocabulary



A bit of vocabulary

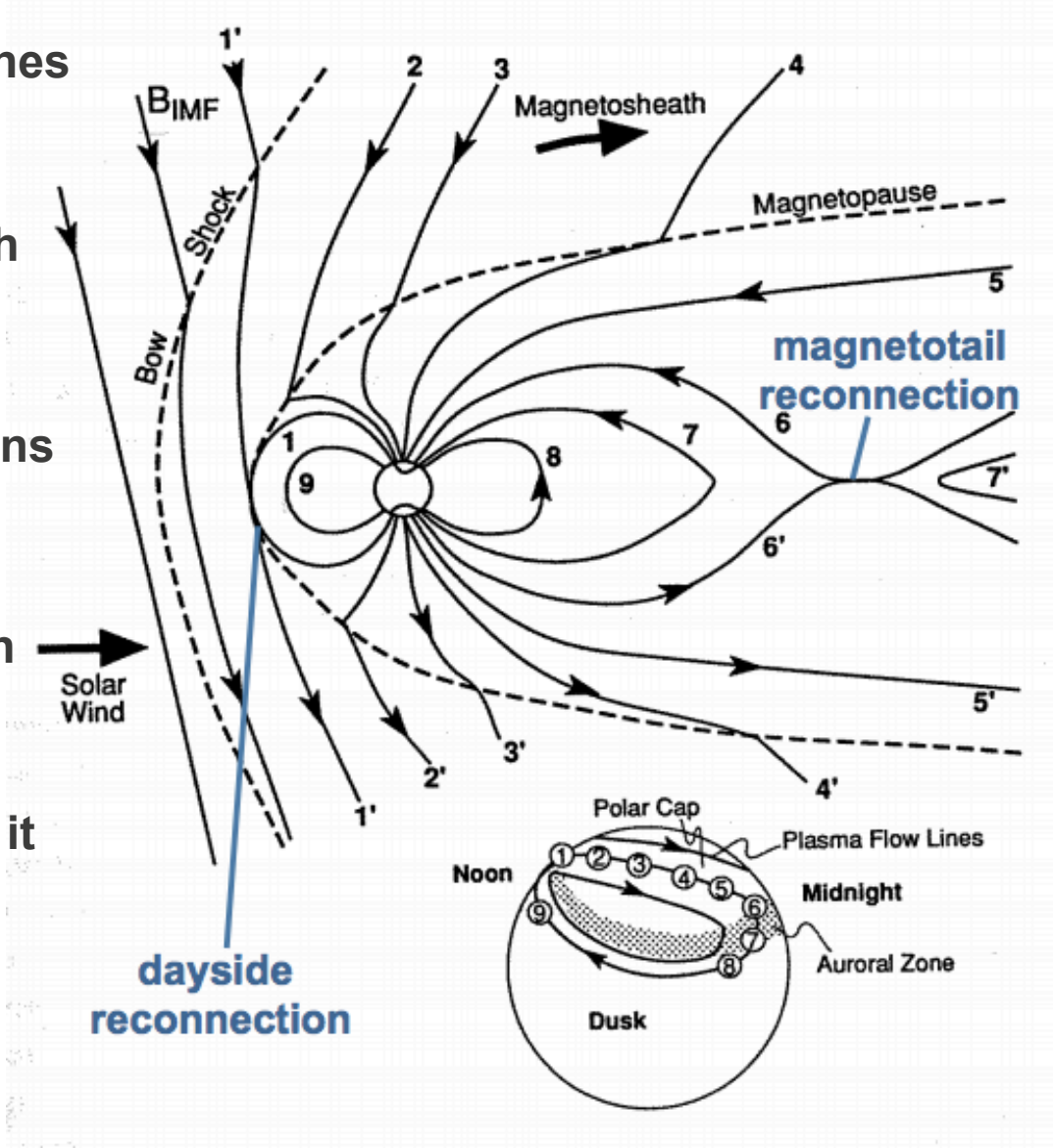
- **Solar wind – outward flow of magnetized plasma from the Sun**
- **Bow shock – shock at the front of magnetosphere where solar wind goes from supersonic to subsonic, 90,000 km from Earth**
- **Magnetopause – pressure balance boundary between magnetosphere and solar wind**
- **Magnetosphere – region of space dominated by Earth's magnetic field**
- **Magnetotail – elongated region of magnetic field dragged out by the solar wind**

- **Interplanetary Magnetic Field (IMF) – magnetic field in the solar wind**
- **Dipole tilt – the tilt of Earth's dipole compared to the Earth-Sun vector**
- **Geomagnetic storm – dip in the Dst index that lasts several days, accompanied by changes in particle and wave properties**
  - Primarily from "Ring Current" – ions and electrons injected form tail drift in different directions causing a current around the Earth

Dungey [1961] Cycle

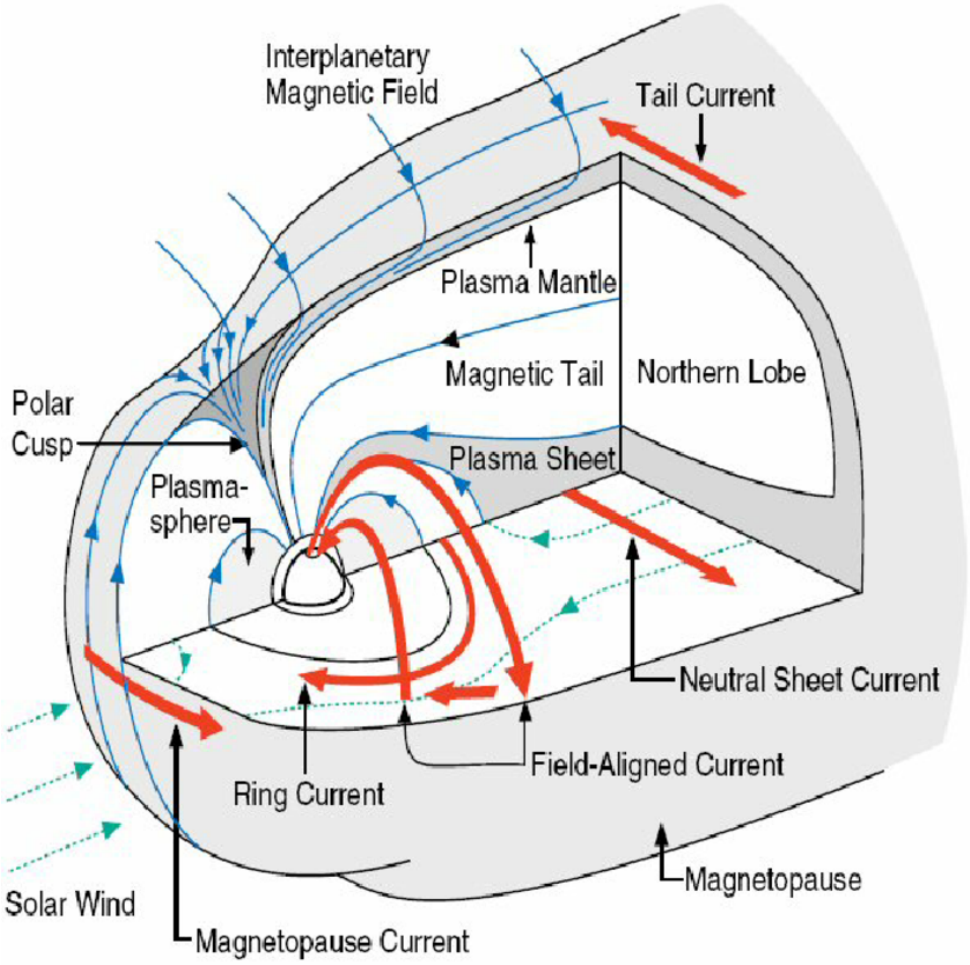
1. Solar wind magnetic field reaches the magnetosphere
2. Field line reconnects and split field line is pulled back on both sides of MS
3. Pulled further
4. Field line is stretched and begins to drape into the magnetotail
5. Magentotail formed
6. Field lines then reconnect at an "x-line"
7. Field line moves inward accelerating particles stuck to it
8. Return to dipole configuration
9. Rotates back to day side

Simplified but really gets the dynamics across



Magnetospheric regions

- Defined by particle and magnetic field properties
- Different regions have very different properties and pose different threats to spacecraft systems
- Most satellite orbits pass through many regions
- The region boundaries are dynamic and move significant amounts on minutes-to-hours timescales



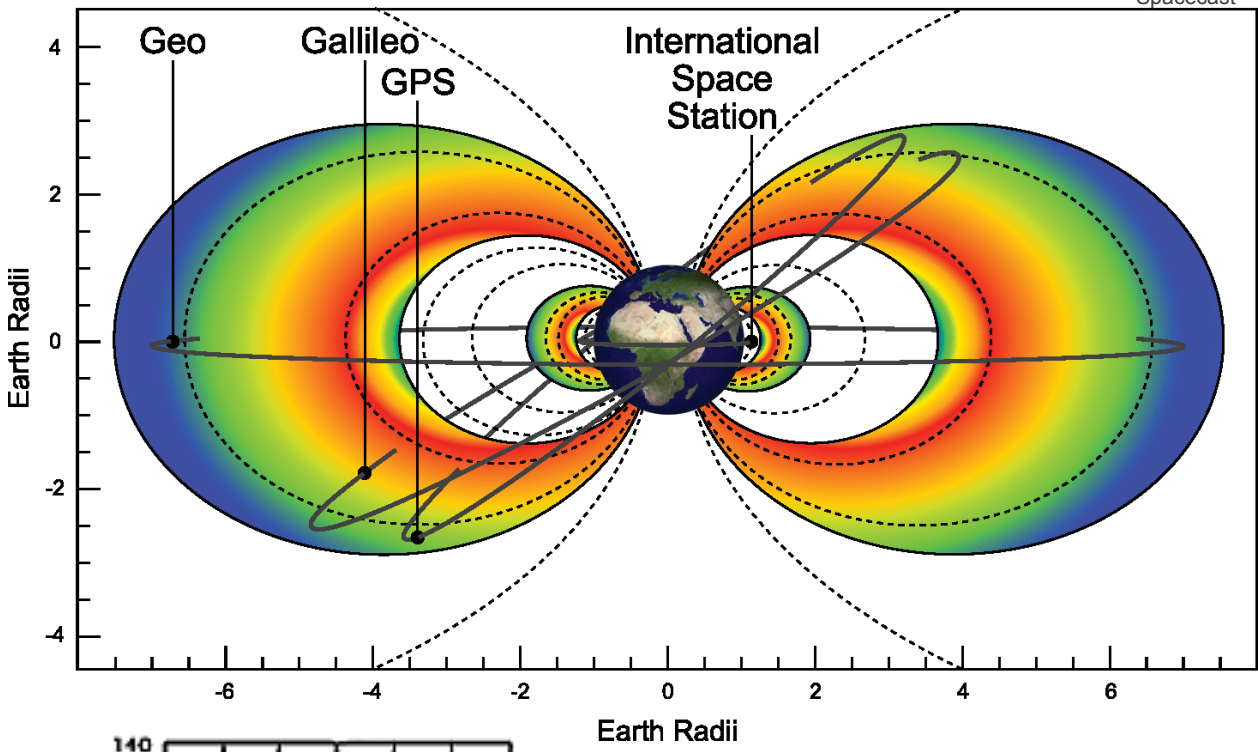
Plasma regions in the magnetosphere
Bulk properties – many orders of magnitude

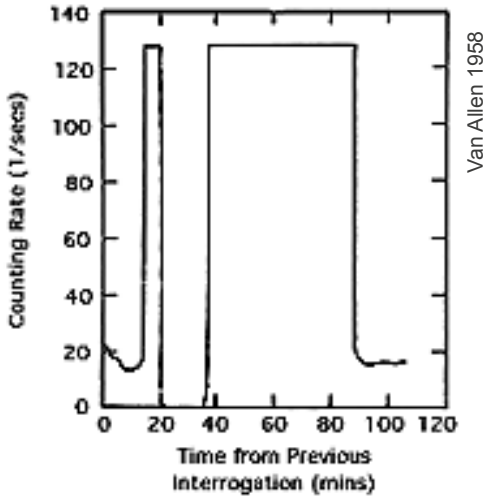
• Lobe: 0.01 ions/cm^3	1 – 20 keV
• Plasma sheet: 0.3-0.5 ions/cm^3	0.1 – 20 keV
• Inner magnetosphere: 1 ions/cm^3	10 – 100 keV
• Plasmasphere: 100 ions/cm^3	eV
• Solar wind near earth: 6 ions/cm^3	1.5 – 10 keV
• Radiation belt: 0.01 electrons/cm^3	100 – 10,000 keV
• Inner zone: 0.01 protons/cm^3	10,000 – 1,000,000 keV

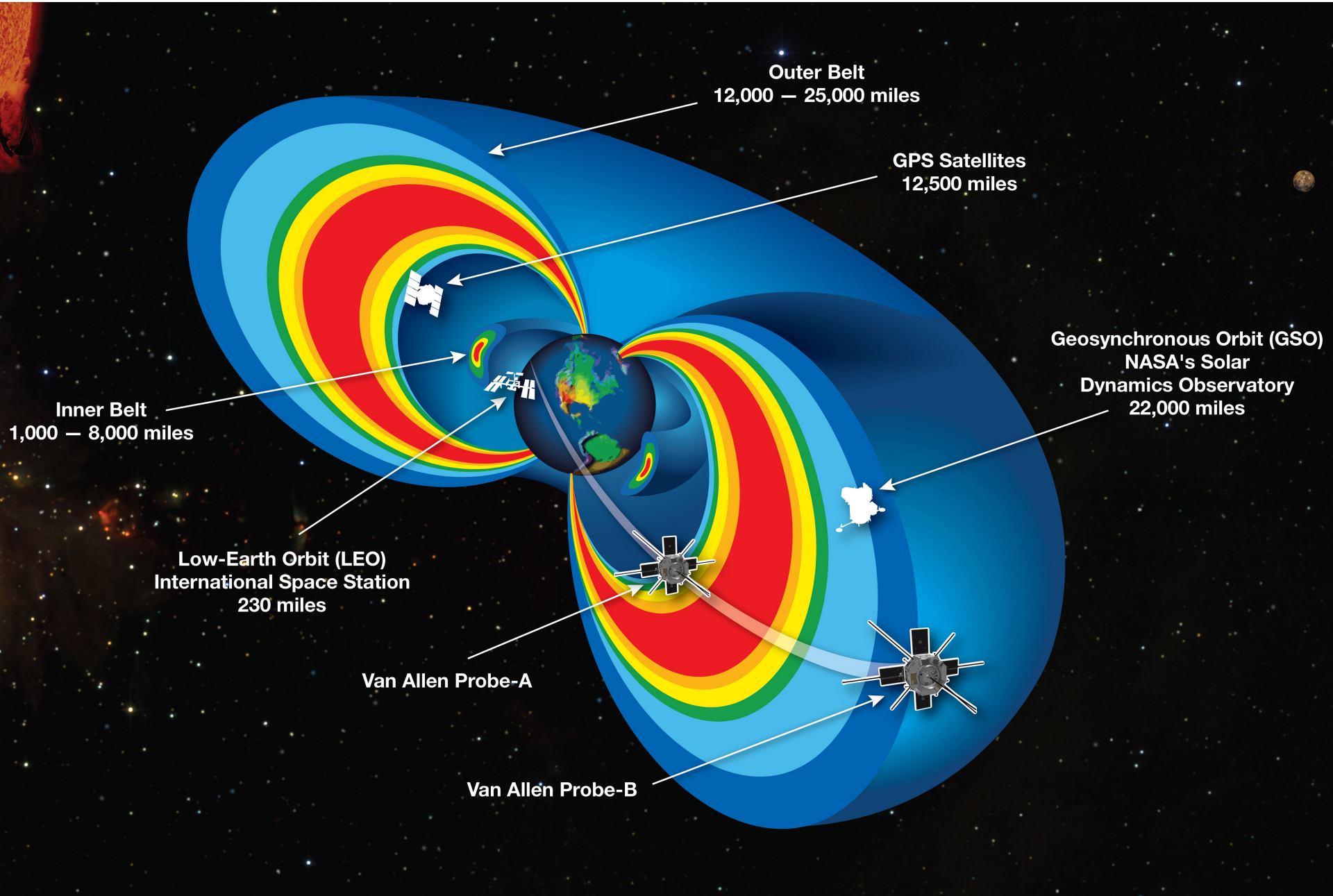
Van Allen Radiation Belts

- **Discovered by first US satellite, Explorer-1**
  - January 31, 1958

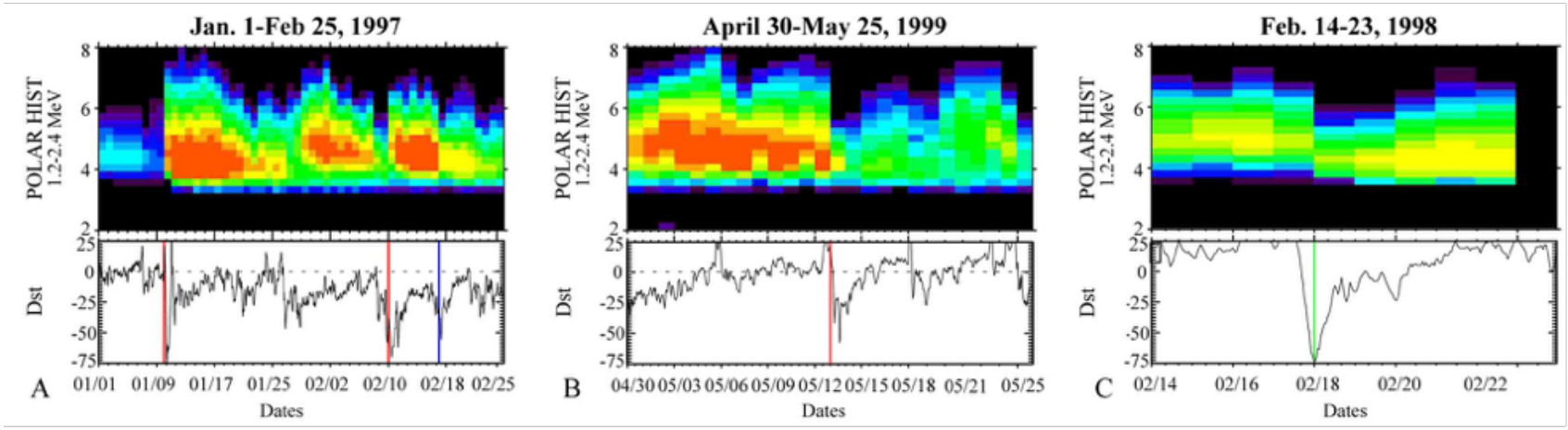
Spacecast



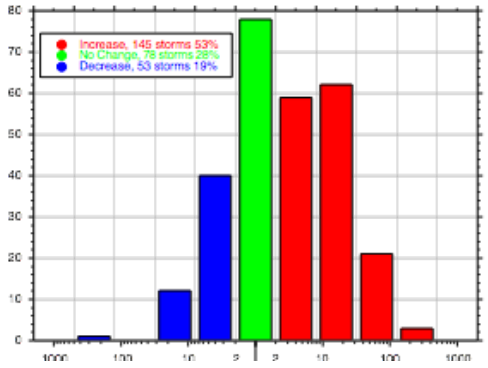



Outer Belt
12,000 — 25,000 miles
GPS Satellites
12,500 miles
Geosynchronous Orbit (GSO)
NASA's Solar
Dynamics Observatory
22,000 miles
Inner Belt
1,000 — 8,000 miles
Low-Earth Orbit (LEO)
International Space Station
230 miles
Van Allen Probe-A
Van Allen Probe-B

We still can't predict radiation belt response

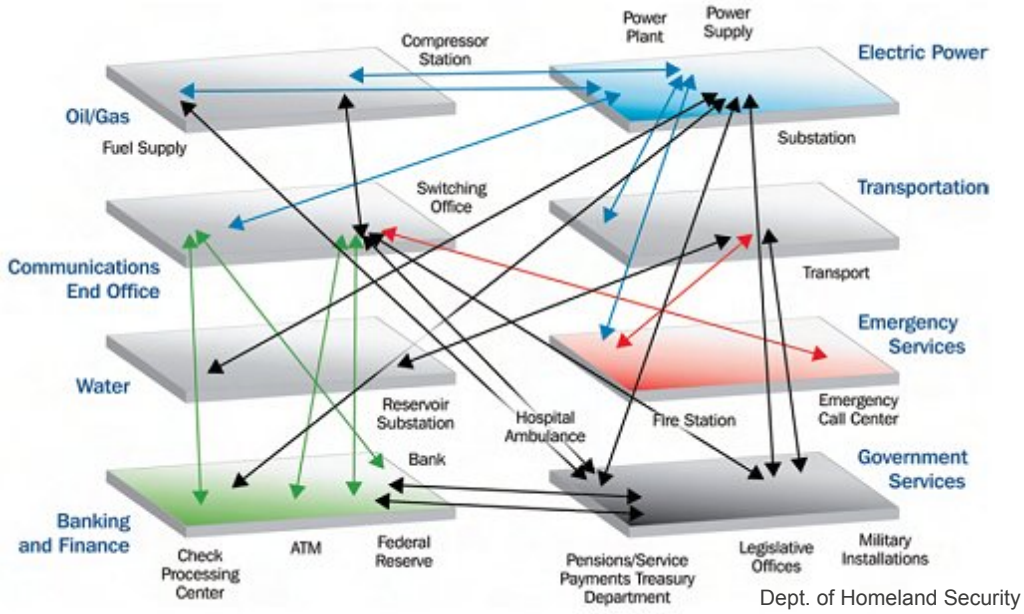


- The radiation belts respond to geomagnetic storms
- Strong storms to not imply strong radiation belt intensity
- Storms don't always produce intensifications at all



Reeves et al GRL 2003

Carrington Event (Solar storm of 1859)

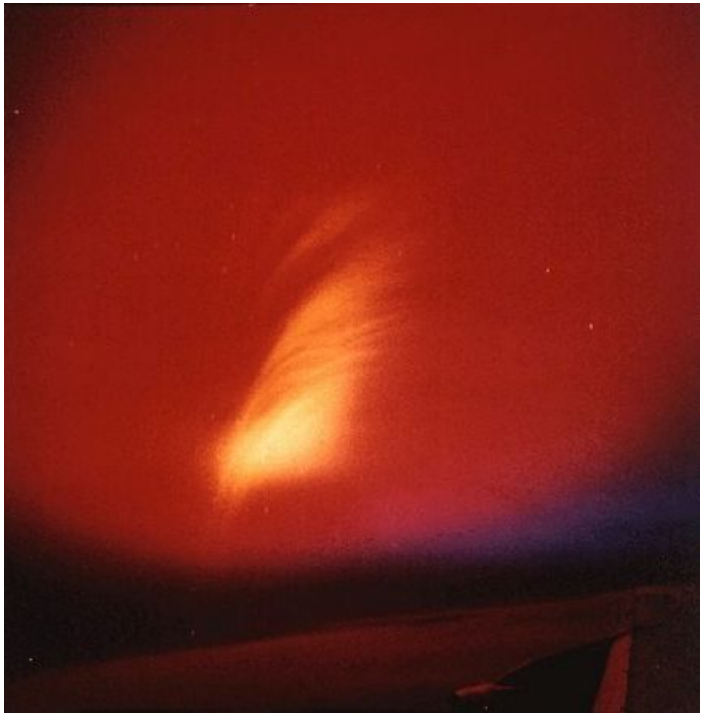


Dept. of Homeland Security

- **The aurora was visible:**
  - Sub-Saharan Africa
  - Mexico
  - Queensland
  - Cuba
  - Hawaii
- **Dst estimates are -800 to -1750 nT (big is -400nT)**
- **National Academies report "Severe Space Weather Events—Understanding Societal and Economic Impacts"**
  - $2 trillion impact possible in the first year
- **Everything is interconnected today, ripple effects**

Man made space weather

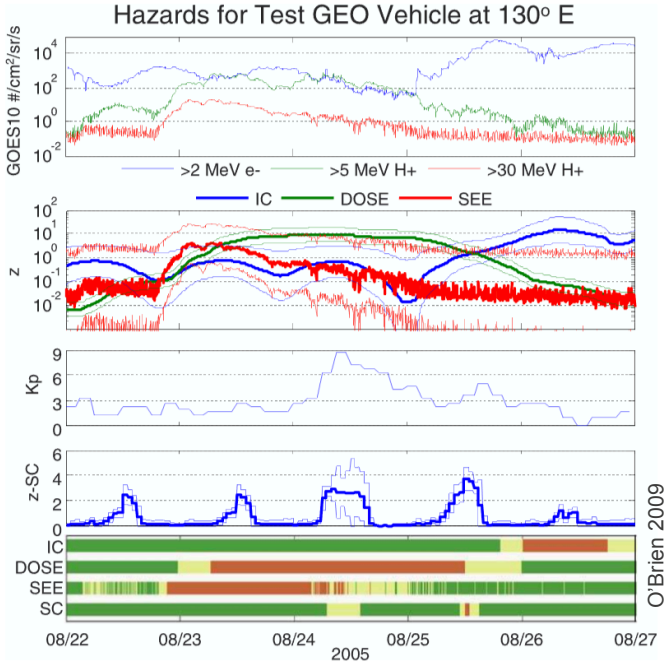
- **July 9th, 1962**
- **Starfish Prime nuclear test, 1.4 MT**
- **Some studies claim resulting MeV electrons lasted for 5-years**
- **Damaged 2/3 of satellites in low Earth orbit**
  - There were not that many at that time… (6)



T+3 minutes

What can space weather understanding and prediction provide?

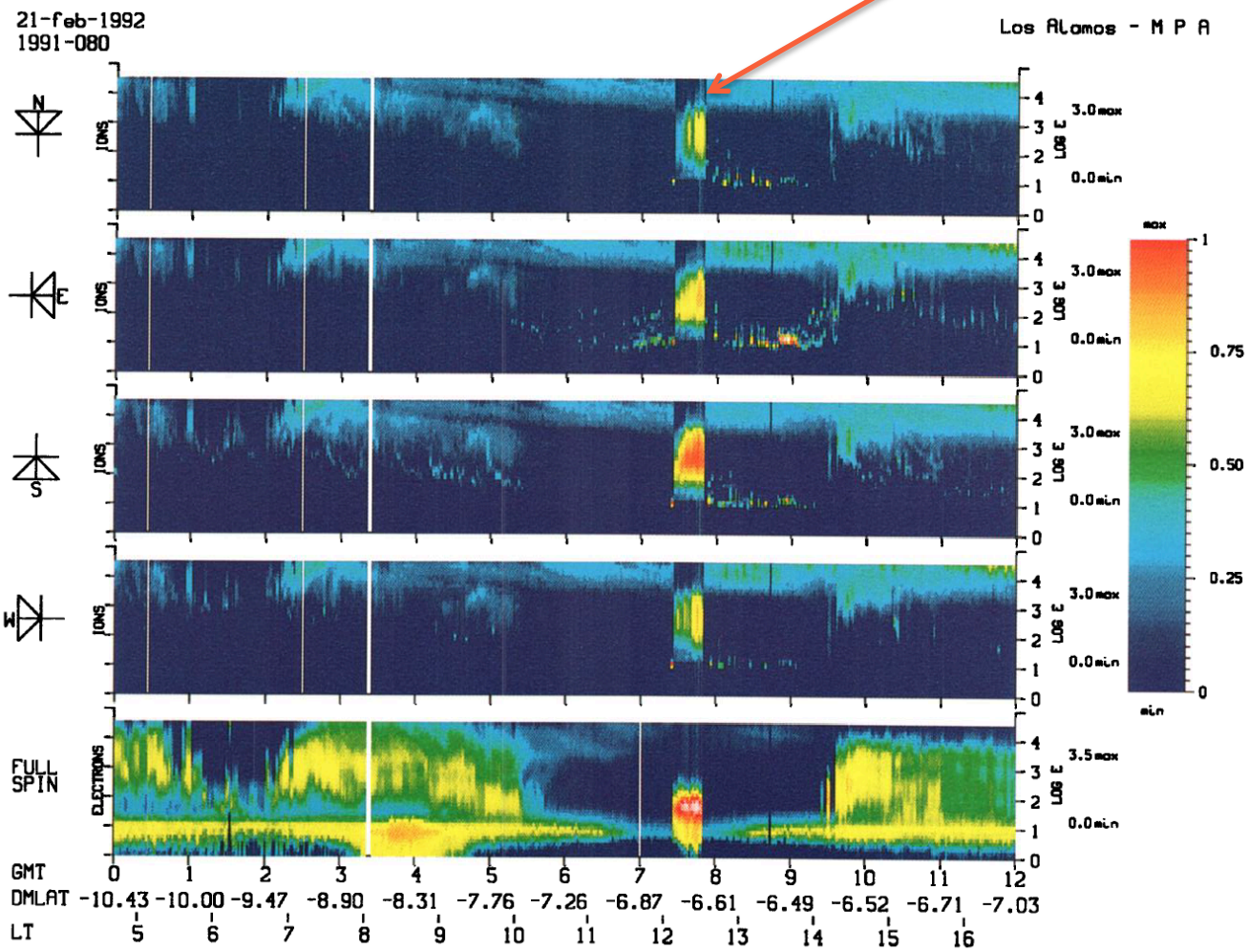
- **Better understanding of environments and impacts aids design**
  - Less money, fewer failures, more sensor uptime
- **Operational impacts**
  - When are my sensors/systems likely to be compromised?
  - When do I have to staff my ground station outside of 8-5?
  - My system just failed, could this be space weather?
    - Am I under attack?
  - What is my sensor sensitivity/SNR during this event?
- **True for both space and ground assets**



BACKUP

Examples of regions From LANL-Geo

Magnetosheath or LLBL



McComas JGR 1993