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# Sun-Earth Connections: How the Sun Knocks Out My Cell Phone from 150 Million Kilometers Away

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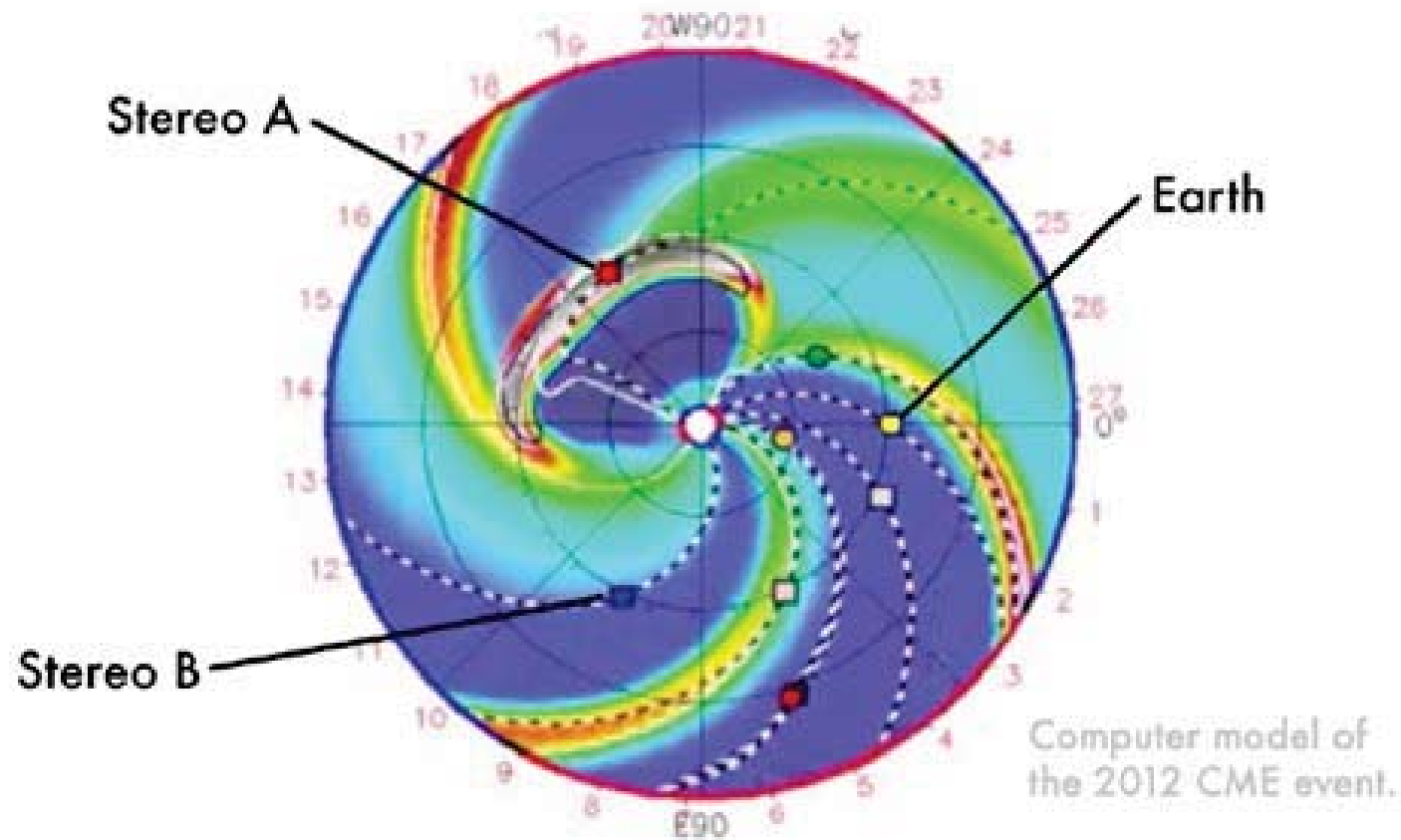
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# Abbreviations

- ACE—Advanced Composition Explorer
- CERN—Centre de Recherche Nucleaire
- CME—Coronal Mass Ejection
- DDD—Displacement Damage Dose
- GCR—Galactic Cosmic Rays
- GPS—Global Positioning System
- LET—Linear Energy Transfer
- PSYCHIC—Prediction of Solar particle Yields for Characterization of Integrated Circuits
- SEE—Single-Event Effects
- SPE—Solar Particle Event
- STEREO—Solar Terrestrial Relations Observatory
- TID—Total Ionizing Dose
- WC—Worst Case
- Z—Atomic Number

# Coronal Mass Ejection Simulation

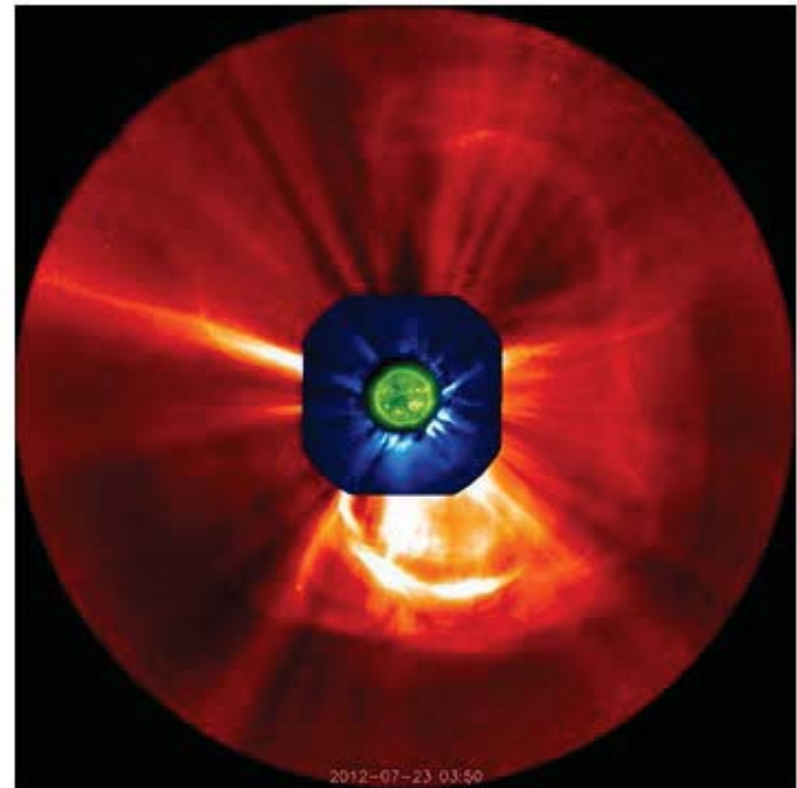


<http://iswa.gsfc.nasa.gov/iswa/iSWA.html>

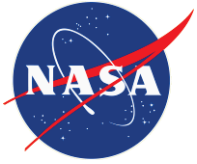


# Why Do We Care About Solar Weather?

- Carrington event (Sept. 1859) was largest solar particle event observed
  - Solar particle event reached Earth 4-5x faster than a normal event
  - Aurorae seen south to Havana and Hawaii, and North to Queensland
  - Colorado miners awakened by aurorae bright enough to read by
  - Telegraphs in Europe and America failed; operators got electric shocks
  - Minimal damage due to limited electrical and telecom infrastructure
- Atmospheric and Environmental Research and Lloyds of London estimate cost of Carrington-like event to current global economy of \$2.6 trillion
  - Entire Solar Cycle 24 caused \$2 billion in losses to space hardware



- Onset of Carrington-like event that missed Earth, July 23, 2012 as seen from STEREO A satellite



# Outline

- I. What are the threats posed by space weather?
- II. Earth-Sun interactions and threat mechanisms across 150 million km of empty(?) space.
- III. What is NASA doing to characterize space weather?
- IV. Mitigation
- V. Slower moving threats—long-term solar variation, climate change, etc.
- VI. Conclusions



# What Infrastructure Does Space Weather Threaten?



Energy, finance, water, health, transport and government infrastructure may also be compromised



**Satellites (GPS, telecom, weather, etc.) at risk due to charging, single-event effects, geomagnetic storm**

Electrical Power Grid and all it supplies at risk from geomagnetic storm.



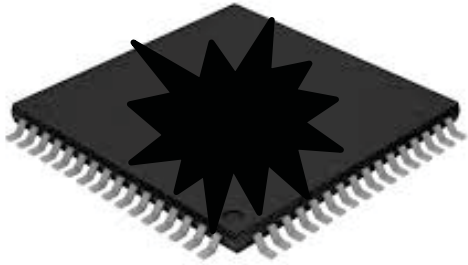
Electronics threatened by geomagnetic storm and secondary neutrons

Restoring some services could take years!

Telecommunications infrastructure damaged by geomagnetic storm.

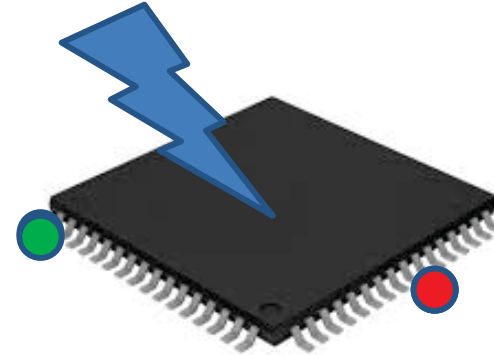
# Threats to Satellites

## Destructive Single-Event Effects



- Energetic particle hits sensitive node in part, causing complete functional failure.

## Nondestructive Single-Event Effects



- Energetic particle hits sensitive node in part, corrupting output or functionality.

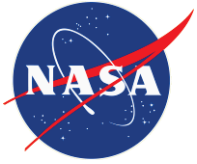
## Spacecraft Charging Effects

- Solar particle events inject charges into radiation belts, resulting in electrostatic discharge induced component failures .

- Highest risks likely to commercial telecommunication, satellite television
- Satellites with sensitive imagers likely vulnerable
- GPS less vulnerable because normal environment is already challenging

## Radiation Dose Effects

- Cumulative exposure to space radiation causes components to degrade and eventually fail.

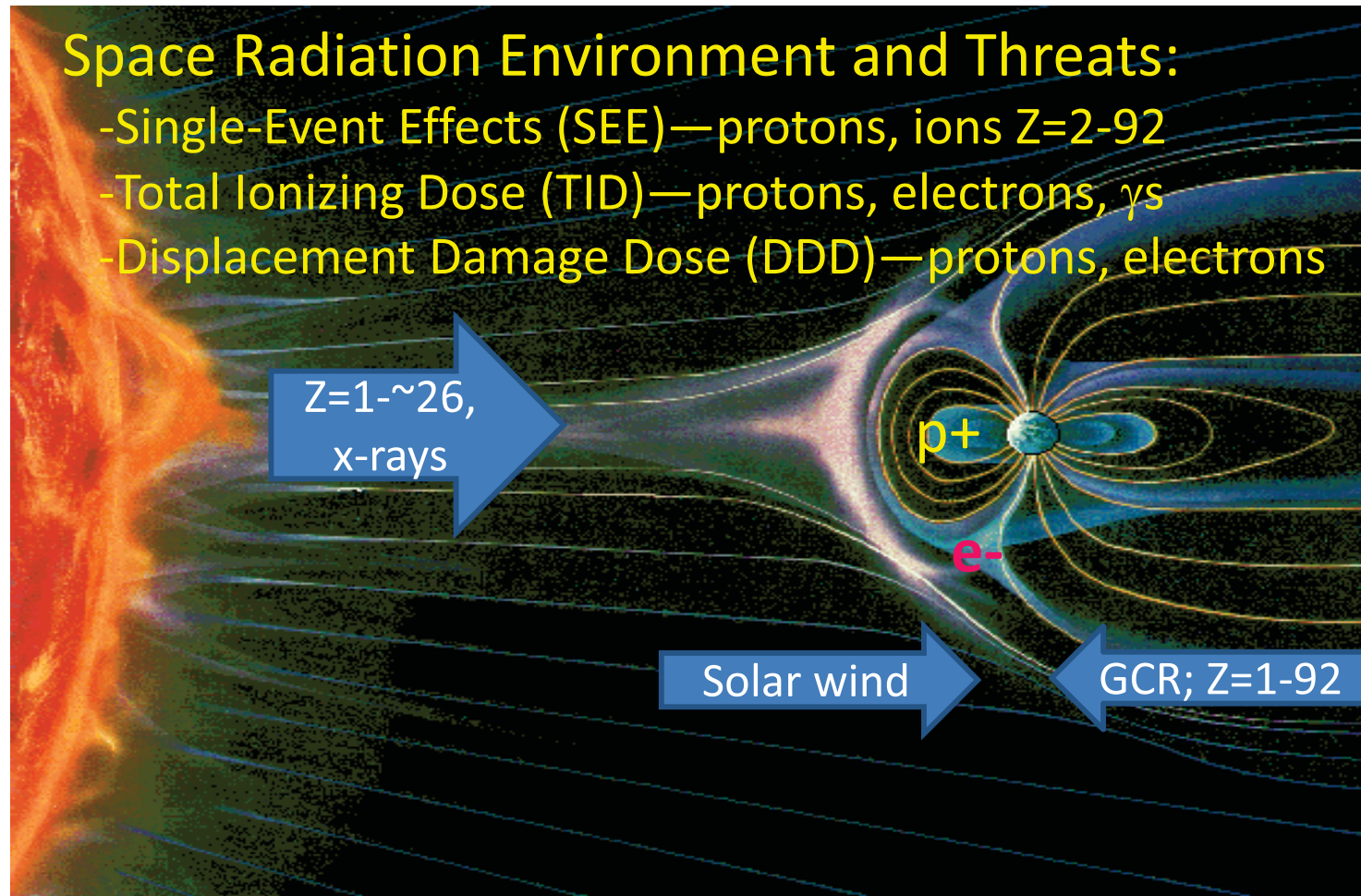


# Threats to Electrical Power Infrastructure

- Threats to electrical power
  - Space weather can cause current surges in electrical wires
  - Transformers can overheat and fail or be damaged by overvoltage/current
  - Current can flow even when power sources disconnected
- Factors affecting vulnerability
  - High magnetic latitude (North or South) increases risk
  - Long transmission lines exacerbate risks
  - High ground conductivity gives rise to higher induced currents
  - Proximity to salt water increases current levels
  - Single-phase transformers more likely to overheat
  - High voltage lines conduct higher currents
  - In US, most vulnerable area is US East Coast
- Mitigation
  - Networks of capacitors to smooth out current surges
  - Modernizing transformers and other infrastructure

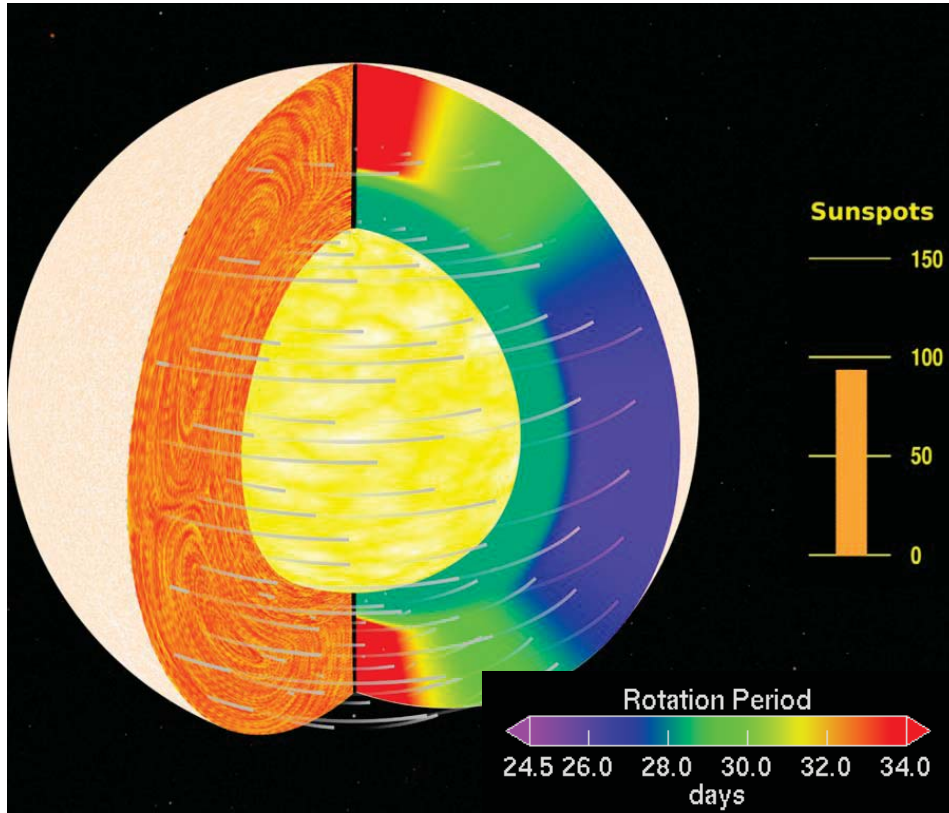


# Sun-Earth Connections

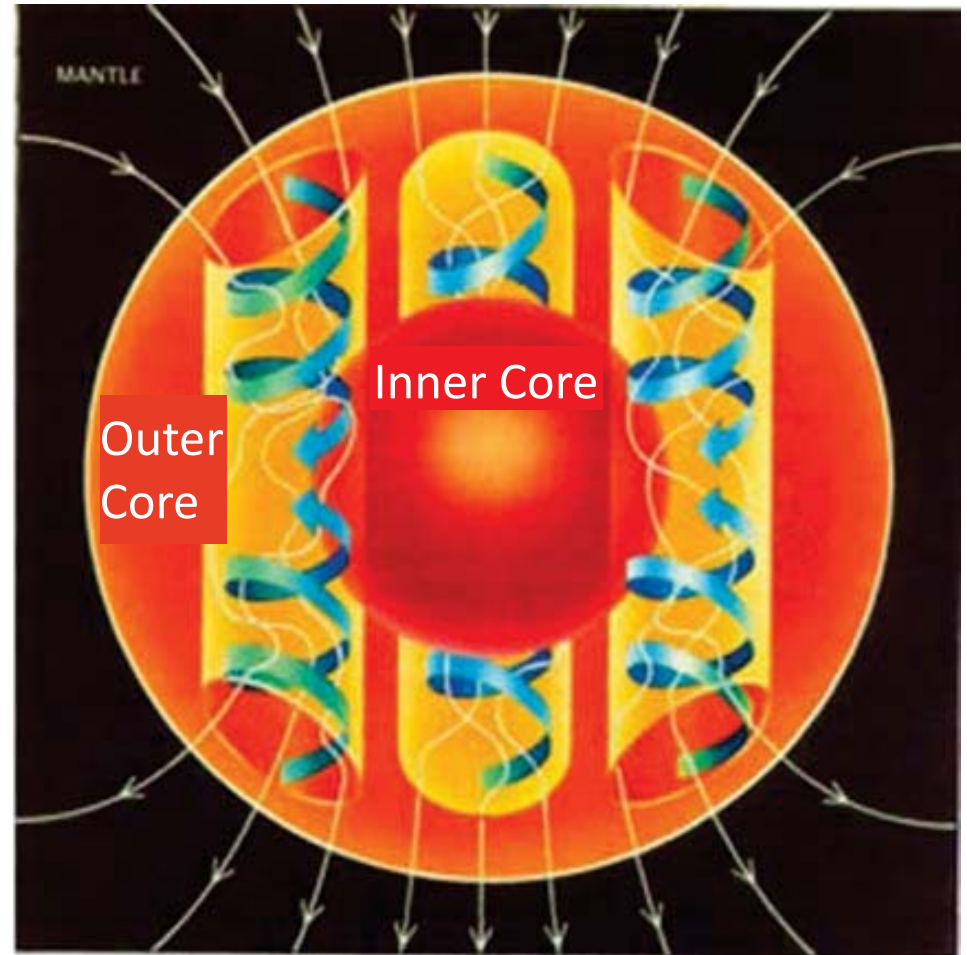


- Solar Particle Events (SPE) pose great threats to spacecraft, but solar wind also lowers GCR flux, so background threat may be lower
- Terrestrial threats from SPE induced geomagnetic storms, secondary neutrons
  - Geomagnetic storms induced by impulse given to geomagnetic field

# Solar and Earth Magnetic Fields



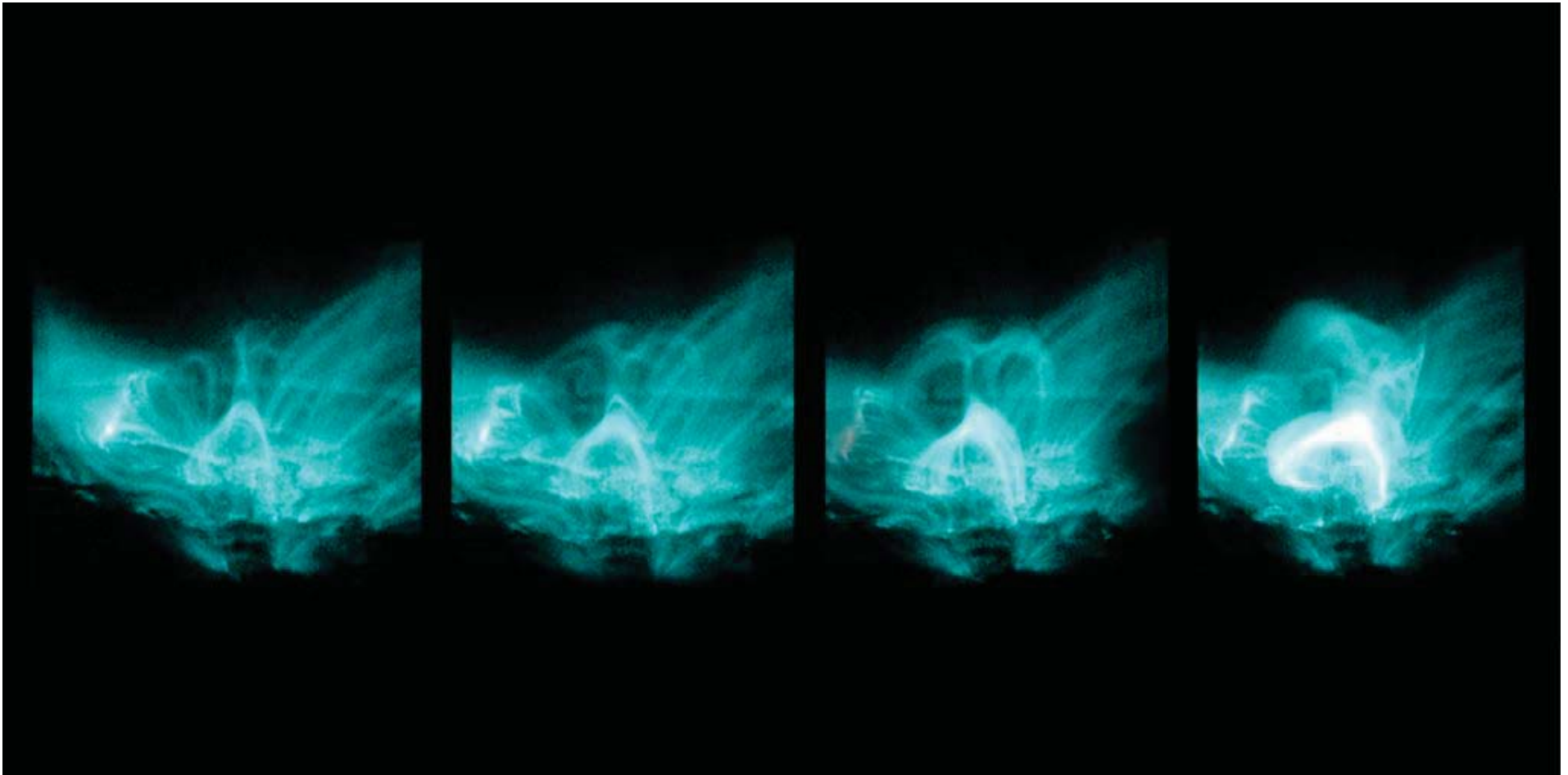
- Heliomagnetic field generated by convecting plasma near surface
  - Field flips every ~22 years giving rise to solar sun spot cycle



- Geomagnetic field generated by convection of liquid-iron outer core
  - Solid inner core stabilizes magnetic field, so flips occur every ~400000 years

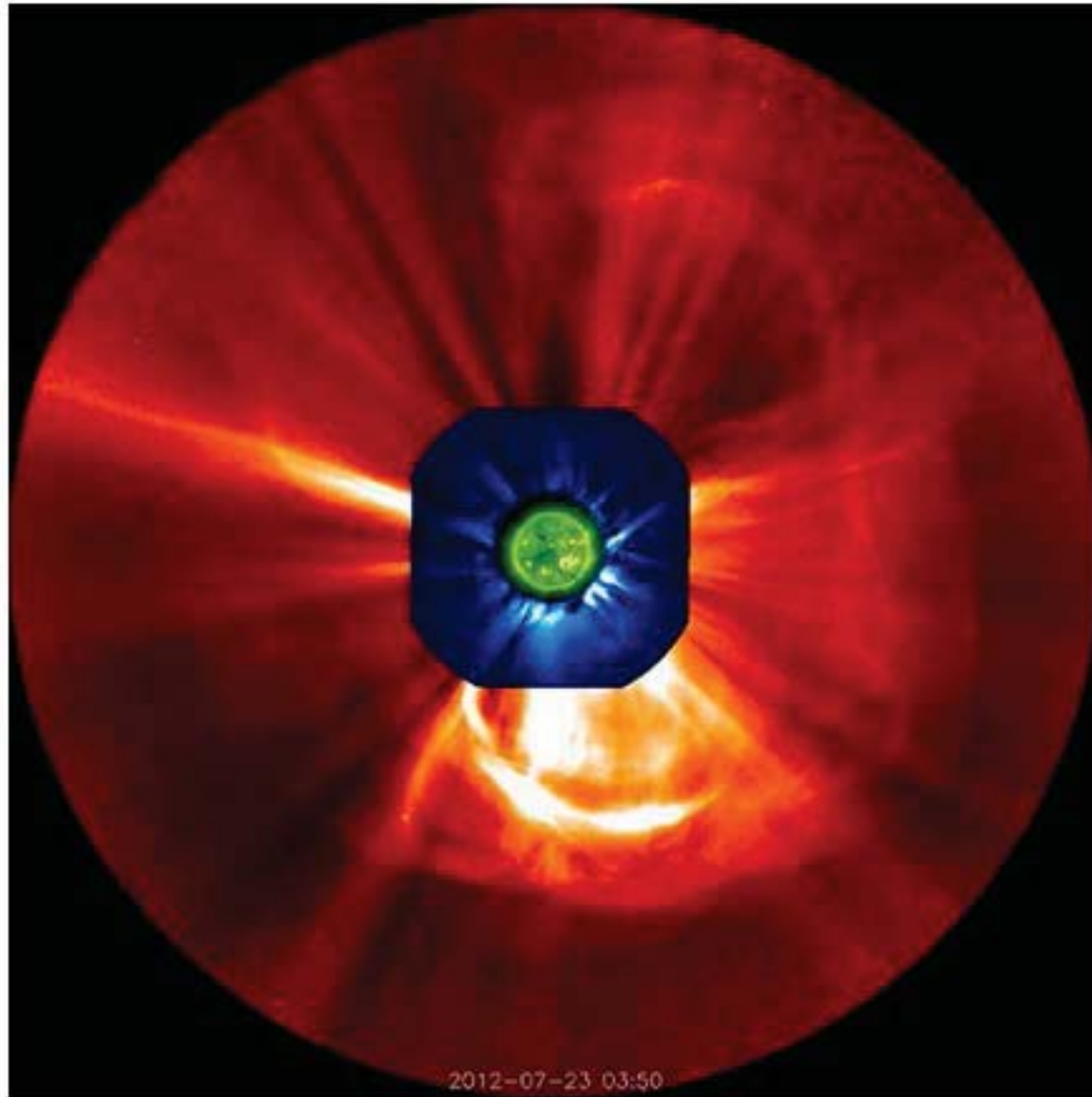


# Magnetic Reconnection



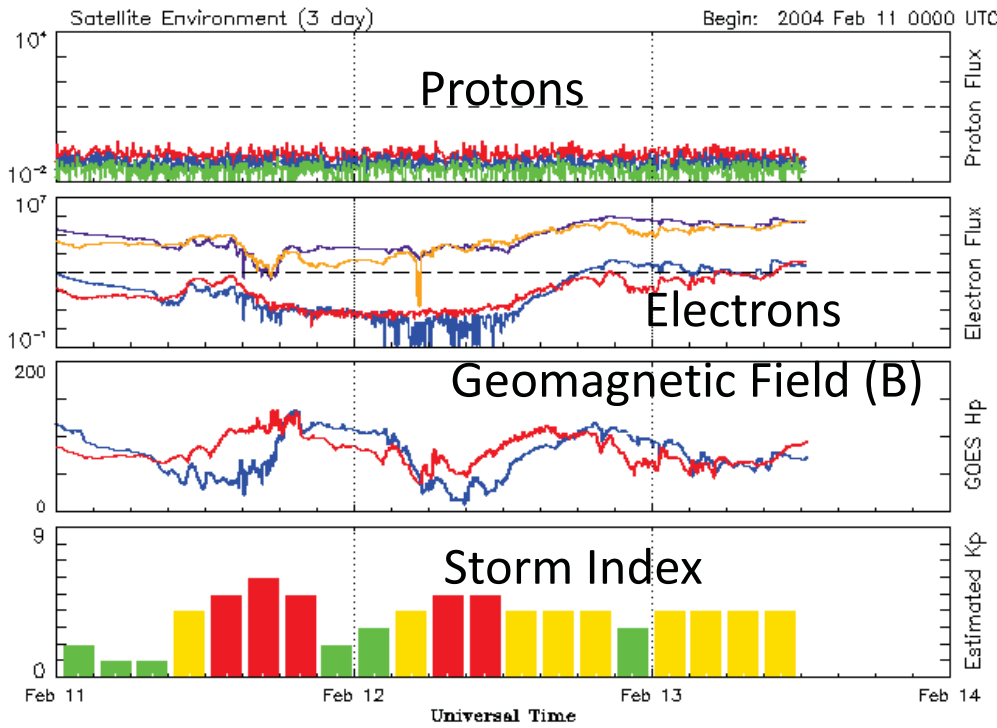


# Solar Particle Event



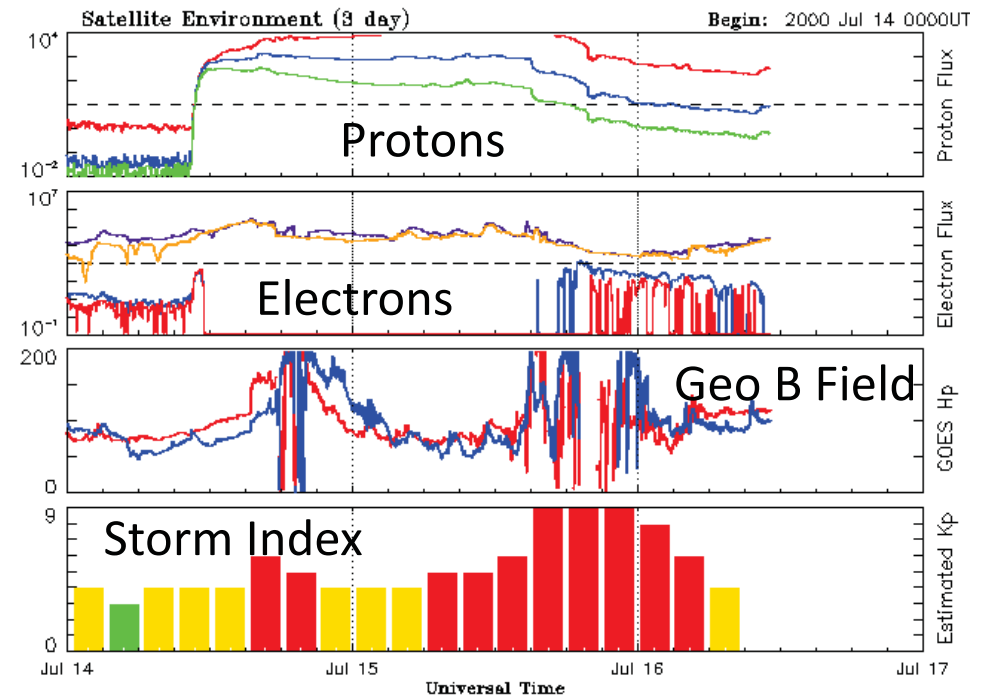


# Effects of Solar Particle Event at Earth



## Solar Quiet Conditions

- Proton and Electron Fluxes low
- Geomagnetic field fairly stable
- Solar storm Index moderate



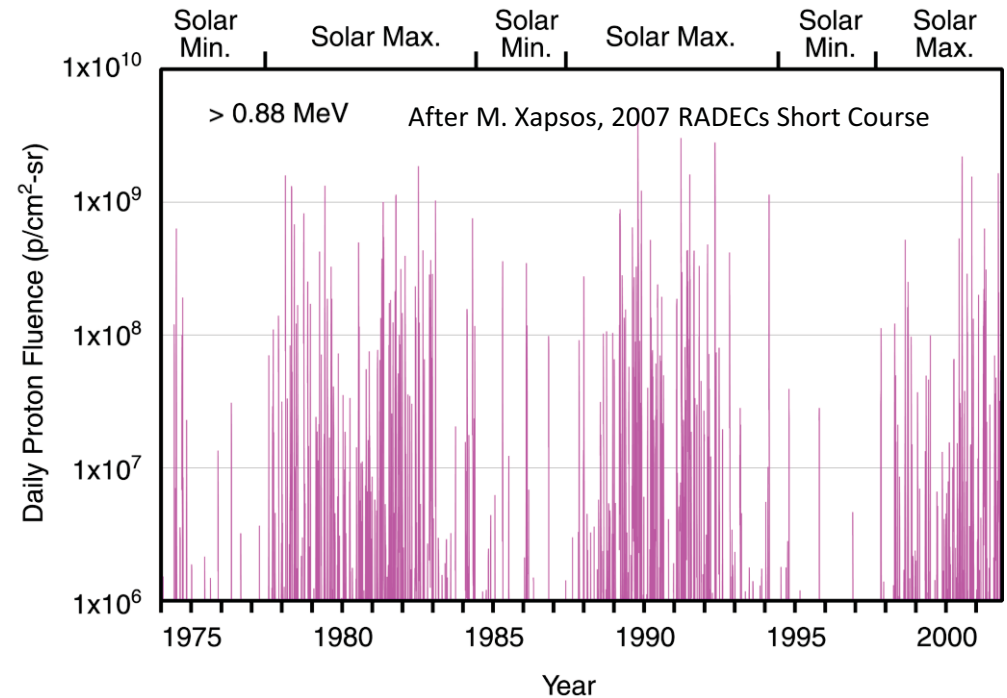
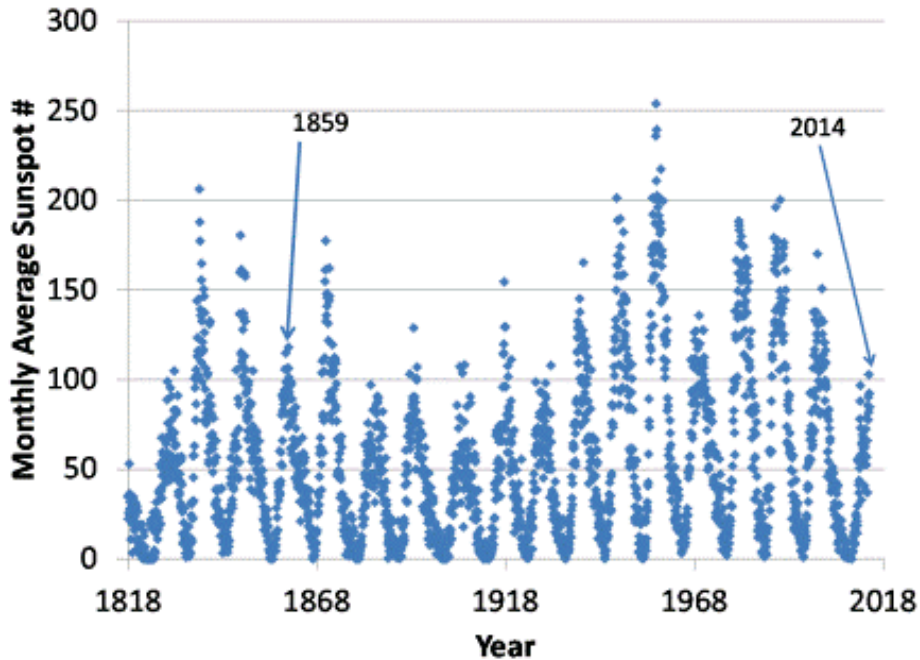
## Bastille Day SPE, July 14, 2000

- Solar proton flux rises  $>10^5$  x
- Large geomagnetic oscillations
- Solar Storm Index maxed out.

NOAA Space Weather Prediction Center, <http://www.swpc.noaa.gov/>



# The Solar Cycle



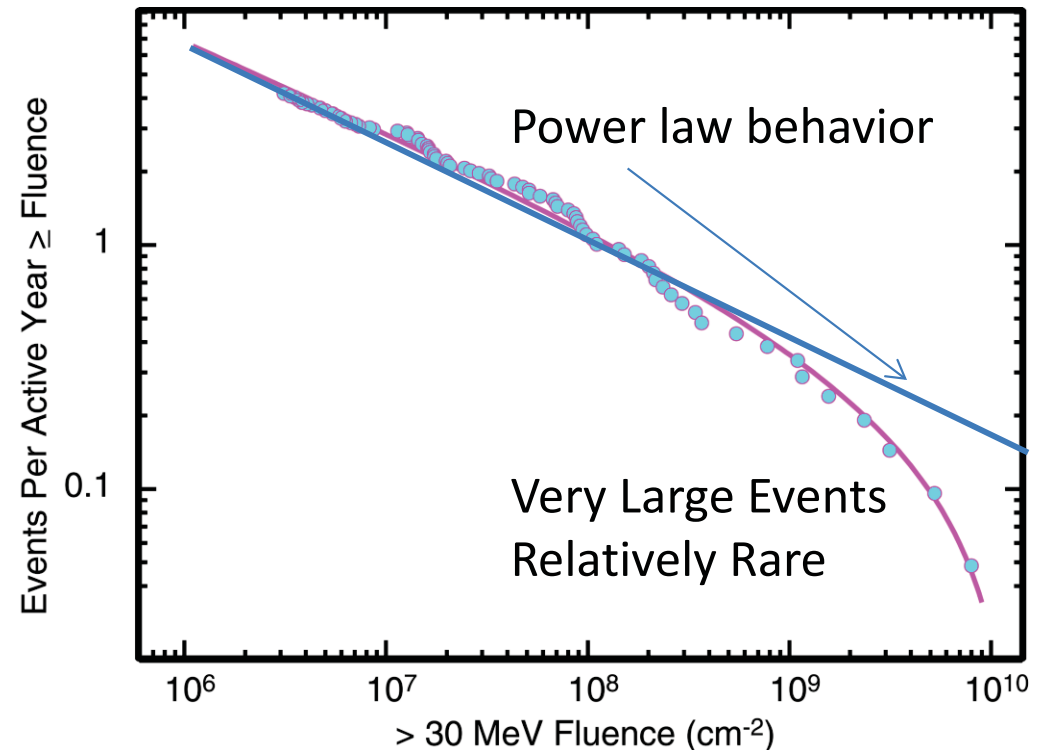
- Solar magnetic and energetic particle activity correlates with sunspot number.
- These follow a roughly 11-year cycle
  - 7 years active and 4 years inactive.
  - Large solar particle events can occur any time but most likely in solar max

- Solar Maximum has highest particle fluxes
  - 96.4% protons
  - 3.5% alpha particles
  - 0.1% heavier ions (not to be neglected!)
  - One CME yields  $>10^9$   $>30$  MeV protons/cm<sup>2</sup>
  - Fluxes  $10^5$   $>30$  MeV protons/cm<sup>2</sup>/second



# Solar Particle Event Size Distribution

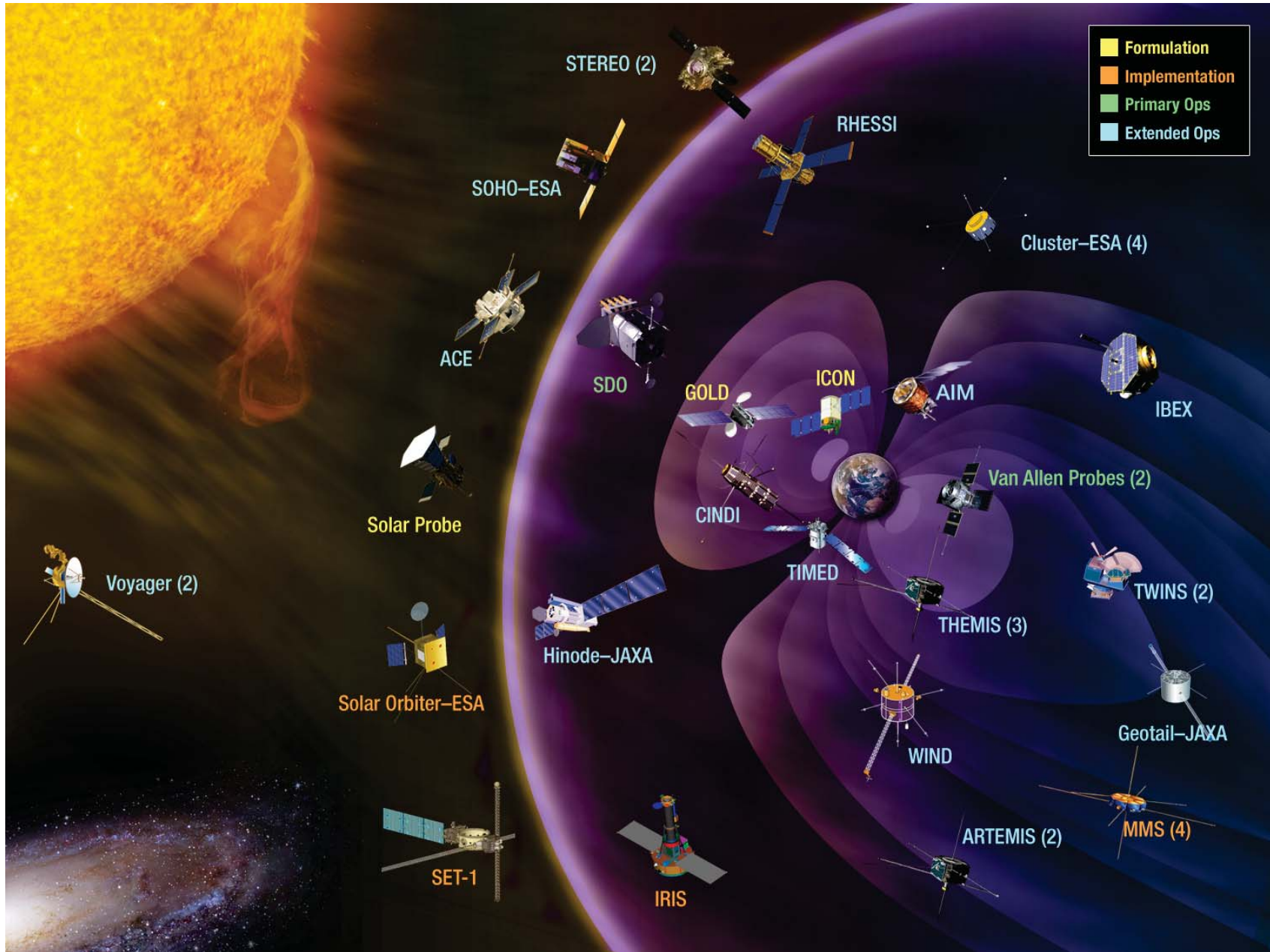
- Event Sizes span more than 4 orders of magnitude in energy and particle fluence
  - Smaller event sizes follow power law function
  - Larger event sizes fall off much more rapidly than power law
- Carrington-type event is extremely rare
  - Statistics too poor to predict frequency
  - July 2012 event doubled sample size of such events
  - Demonstrates advantage of a robust heliospheric observatory



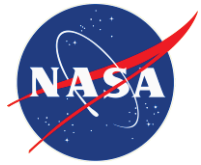
M.A. Xapsos et al., IEEE TNS, Dec. 1999



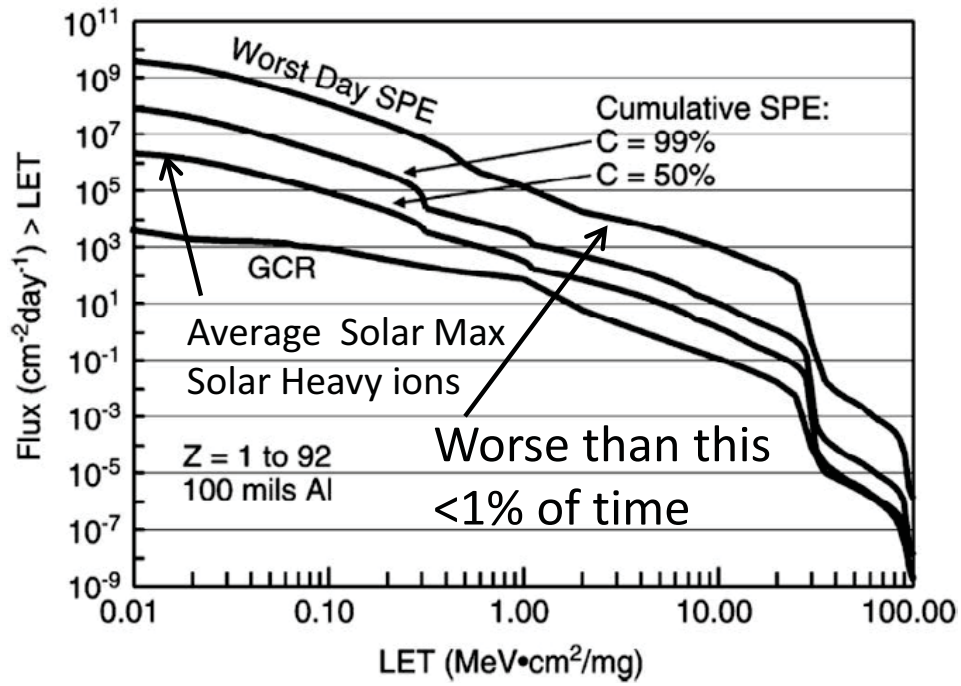
# What is NASA Doing? Heliospheric Observatories





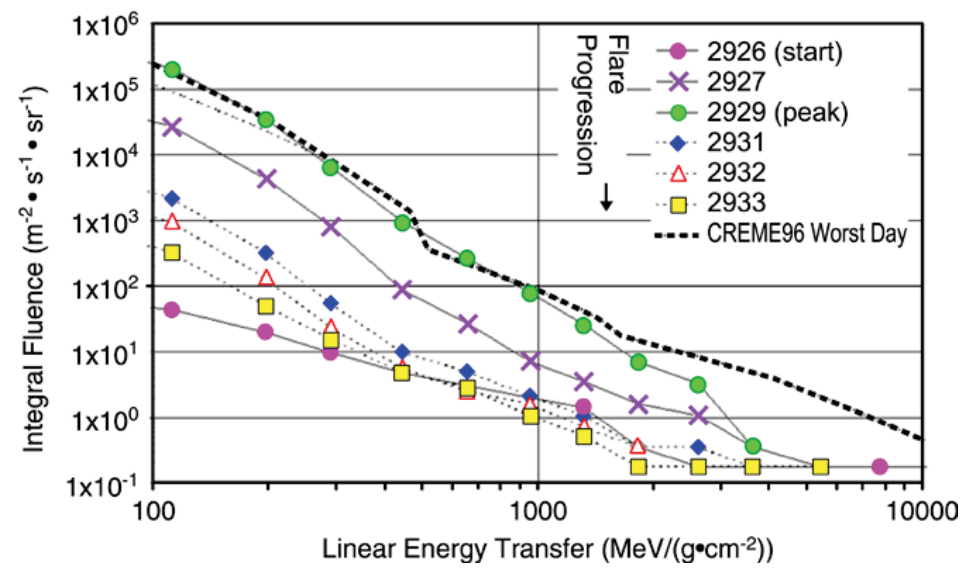


# What Is NASA Doing? Modeling and Validation



After M. Xapsos, IEEE TNS 2007, p. 1985  
Results include elements from atomic number Z = 1 to 92.

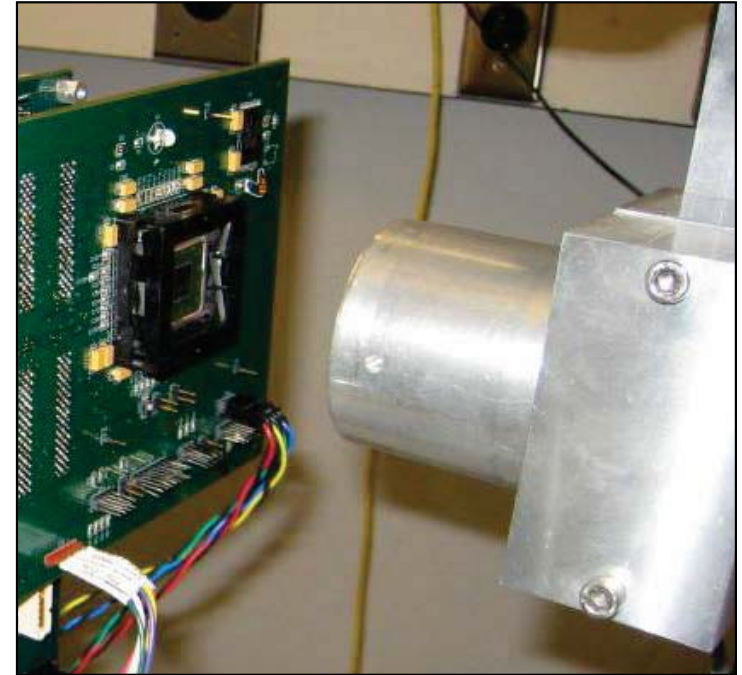
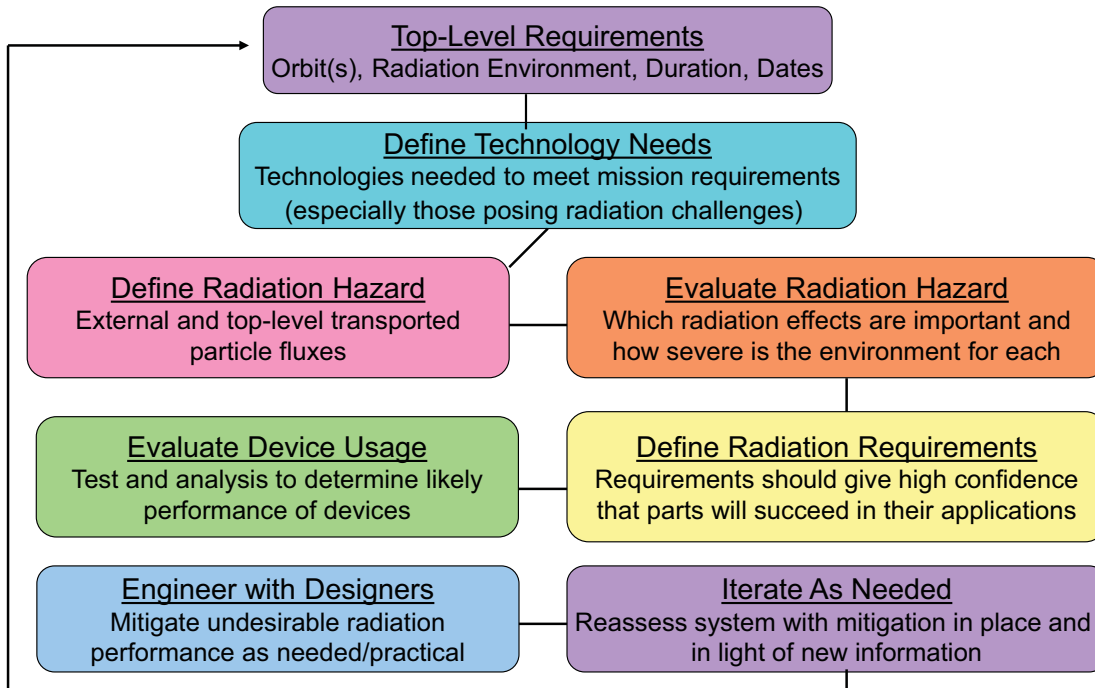
- Linear Energy Transfer (LET) measures how much charge an ion track leaves in a semiconductor device
  - Depends on ion species (heavier is worse) and energy
- PSYCHIC model by M. Xapsos estimates heavy-ion fluxes for any confidence



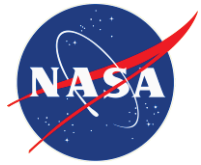
C.S. Dyer et al., IEEE TNS, Dec. 2002

- Study of Solar Cycle 23 showed 3 events approaching standard “worst-case” (WC) solar heavy-ion model
  - Model is not overly conservative
  - Events comparable to WC expected every solar cycle
- Carrington-like events over 2 orders of magnitude higher fluxes

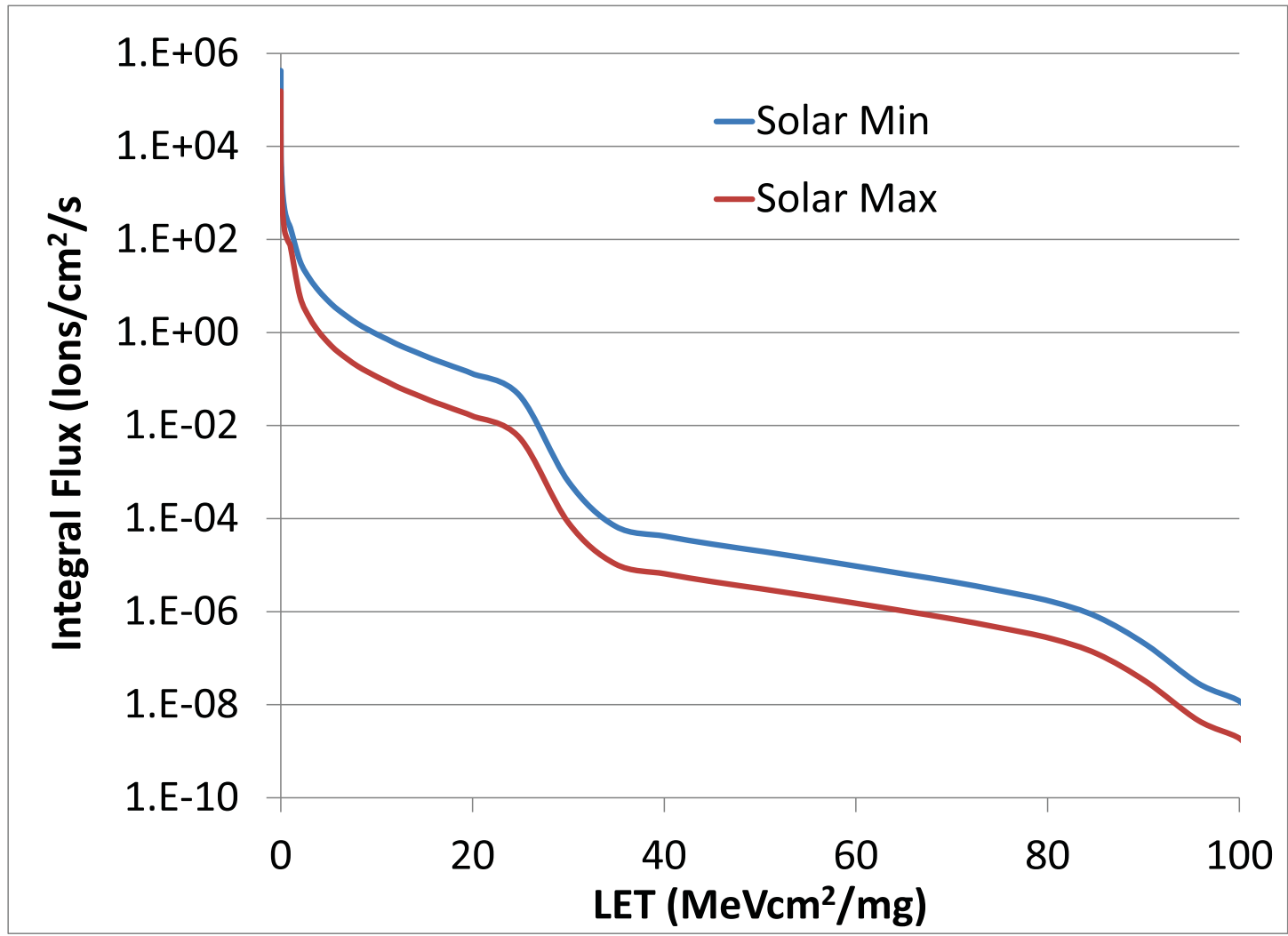
# What is NASA Doing? Testing and Radiation Hardening



- Satellites most vulnerable to space weather
- NASA's radiation hardening approach emphasizes collaboration with designers
  - Goal is to achieve robust operation, high performance and economical design
  - Involves part selection and system design
  - Approach iterates until requirements met
- Testing done at accelerators and other radiation sources
  - Goal is to make test as realistic as economically possible
- Models used to extrapolate and bound application performance

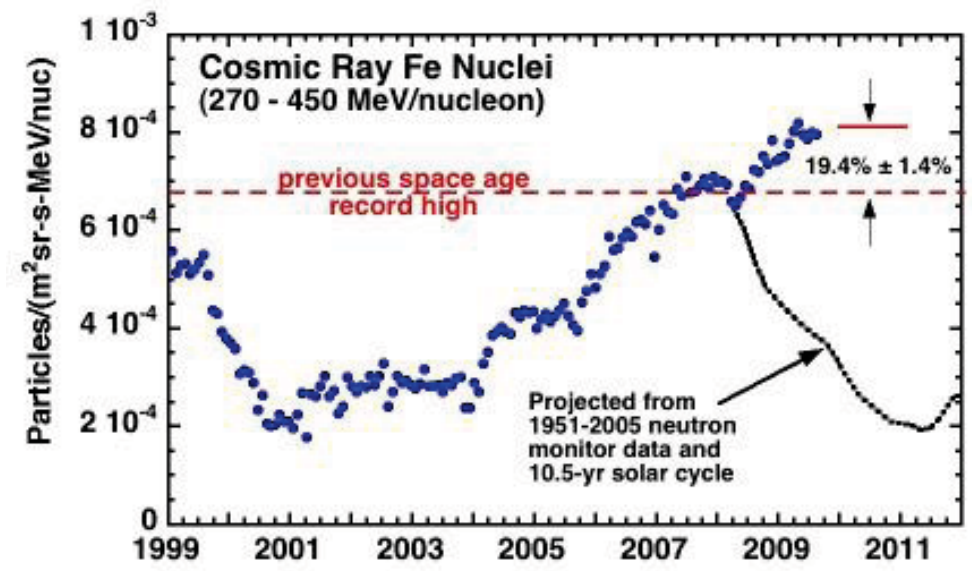
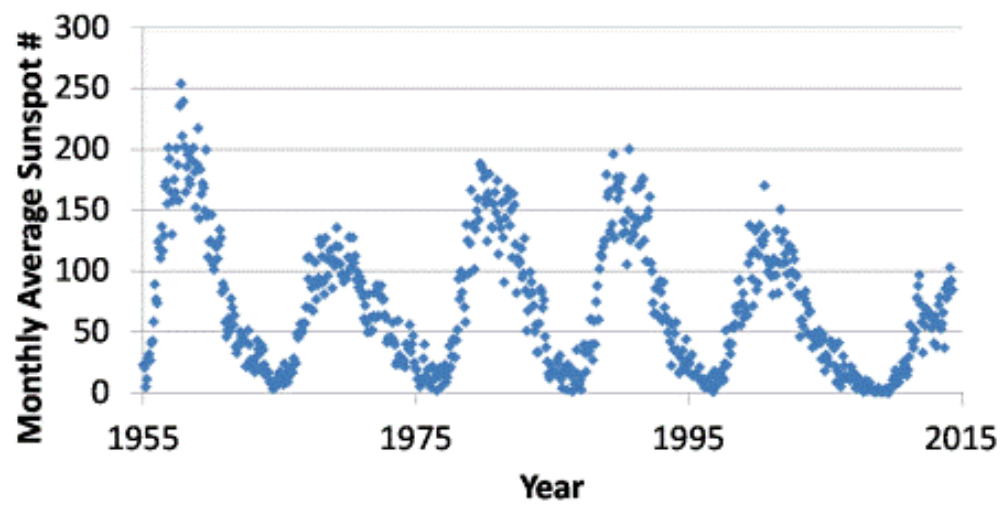


# Other Threats Affected by Solar Cycle

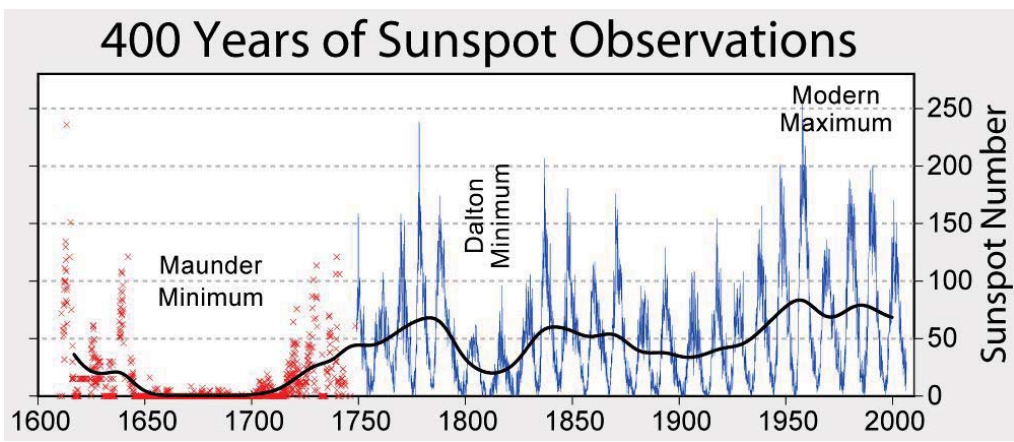


- Solar Cycle Affects Galactic Cosmic Ray Flux
  - Stronger solar wind keeps out GCR during solar Max
  - GCR flux and background SEE rates are highest during Solar Min

# This Solar Cycle is Different

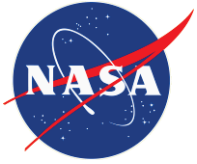


From [http://www.nasa.gov/topics/solarsystem/features/ray\\_surge.html](http://www.nasa.gov/topics/solarsystem/features/ray_surge.html)



[http://www.globalwarmingart.com/wiki/File:Sunspot\\_Numbers.png](http://www.globalwarmingart.com/wiki/File:Sunspot_Numbers.png)

- Last Solar Min ~50% longer than normal
- Current Solar Max also weak
- Deep solar Min → higher GCR fluxes
  - NASA's Advanced Composition Explorer (ACE) showed up to 20% increase
- Are we starting a Grand Solar Minimum?
  - Past Minima had cold temperatures
  - Probably not: more active than Dalton or Maunder Minima



# Does Space Weather Explain Climate Change?

- Total solar irradiance has not changed since the 1950s—that won't work
- Can solar modulation of galactic cosmic rays do the job?
  - Mechanism: galactic cosmic rays create more cloud condensation nuclei (CCN)
    - Clouds reflect sunlight , lowering temperatures
    - Solar Cycles 22 and 23 resulted in low GCR fluxes, increasing temperatures?
- What does the evidence say?
  - High GCR fluxes in 2009-2010 should have cooled temperatures, but 2010 was the warmest year on record (statistical tie with 1998 and 2005)
  - Mechanism is questionable—not clear if lack of CCN is a limiting factor for clouds
  - CLOUD experiment at the Centre European de Recherche Nucleaire (CERN) found that GCR fluxes probably play a very limited role in cloud formation
- Best evidence suggests anthropogenic CO<sub>2</sub> increases best fit the data
  - Mechanism is well understood (and known since 1850)
  - Linear regression of temperature versus  $\ln[\text{CO}_2]$  explains >74% of variation
- Research continues, but unlikely to affect current models



# Conclusions

- Space weather poses increasing risks to critical infrastructure
  - Satellite assets , power grid, information technology, communications and through these sectors nearly every other aspect of the economy
  - Carrington-type event occurring now could cause \$2.6 trillion in damages
- Very large solar particle events are rare, but have high impact
  - Estimating frequency of occurrence is problematic due to poor statistics
  - Multiple Satellites observing the Sun from multiple angles increases the probability of seeing such events, greatly improving the statistics
- NASA addressing the issue by
  - Observing and modeling the space radiation environment
  - Hardening critical space assets
- Understand of Sun-Earth connections is still evolving
  - Current weak solar cycle provides new interesting understanding
  - Latest research suggests climate connection likely not significant
- What will the 6<sup>th</sup> solar cycle of the space age bring?