Energetic Particles and Their Impacts Around the Heliosphere

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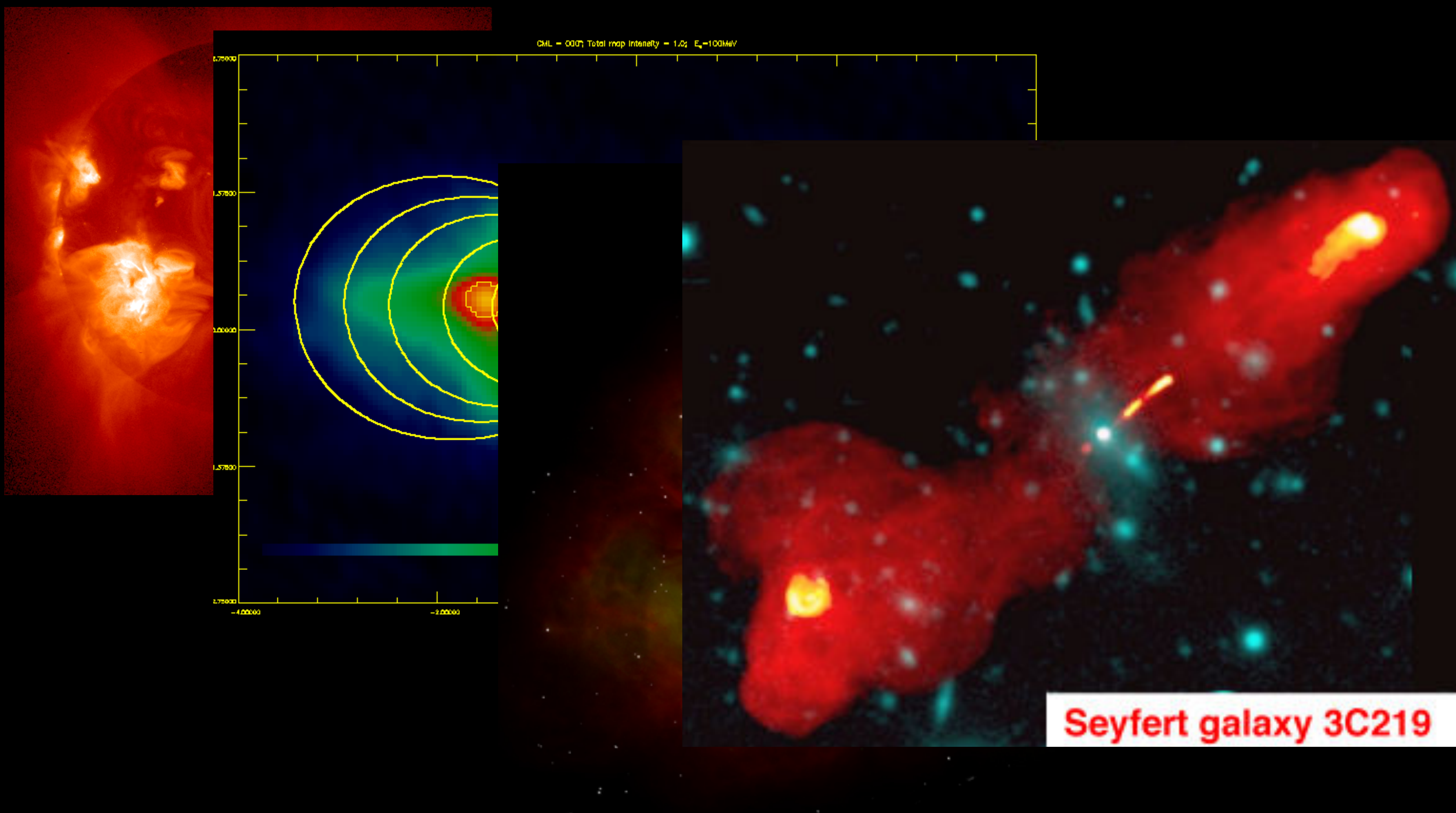
With thanks to countless others: NASA, NOAA, DOE….

Heliophysics Summer School 2013

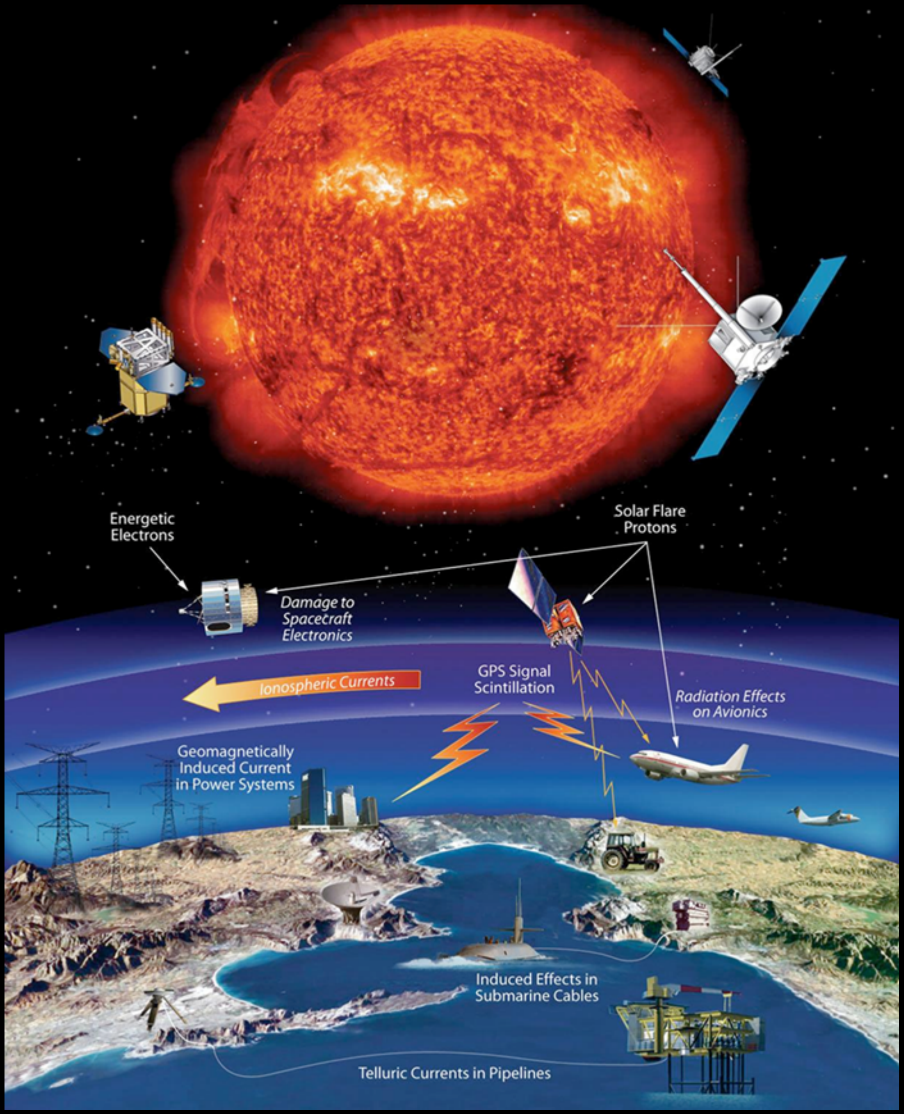
Boulder, CO

Why are energetic particles so important?



These cosmic systems are "visible" because of emissions from energetic particles in magnetic fields

"The Moon is a harsh mistress." – Robert Heinlein,1966
"Space is a hostile place." – Dan Baker, Heliophysics Summer School, 2010



Overview

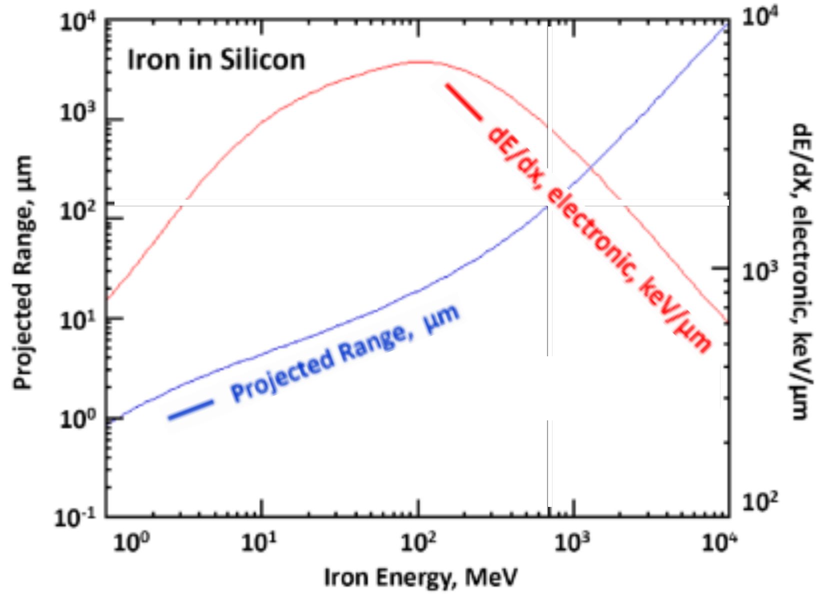
- Principles of Radiation Protection
- Sources of Ionizing Radiation
  - (Galactic) Cosmic Rays
  - Solar Particle Events
  - Trapped Energetic Particles
- Radiation in Past and Current Spaceflight Operations
  - Apollo-era
  - Shuttle and ISS
- Radiation and Future Spaceflight Operations
  - Moon
  - Mars and beyond
- Characterizing the Radiation Environment
  - Observations
  - Forecasting
- Summary

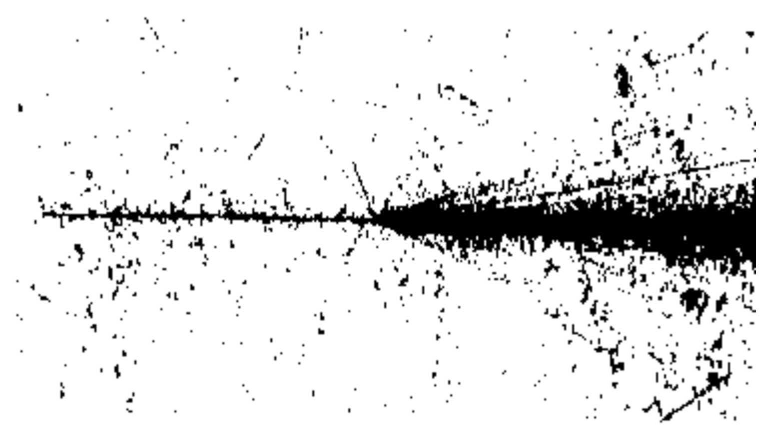
Principles of Radiation Protection

- Radiation of biological concern to the human spaceflight program is primarily "ionizing radiation"
- Ionizing radiation is produced by energetic particles (charged and neutral) or photons with sufficient energy to pass into and through human tissue; for protons, threshold energy is ~10 MeV
  - Protons, α-particles (helium nuclei), heavier ions, β-particles (electrons and positrons)
  - Neutrons
  - X-rays, γ-rays
- These sources ionize matter as they pass through it, and consequently damage human tissue in this interaction

Effects of Ionizing Radiation

- Charged particles loose energy by ionizing the matter they pass through
  - Rate of energy deposition dE/dx (Linear energy transfer LET); Vol II, Ch.3, Eq. 3.11 (the Bethe-Bloch equation)
  - Rate of energy deposition $dE/dx \propto z^2$
  - Also nuclear interactions, fragmentation, showers
  - Damage $\propto$ LET
- Protecting electronics
  - Memory corruption, CPU errors, part failure
- Protecting humans
  - Keep risk from chronic dose low, i.e. lifetime cancer risk due to integrated dose over mission(s) below mandated level
  - Protect against serious injury from acute dose due to prompt radiation from Sun





Iron ion travelling through plastic

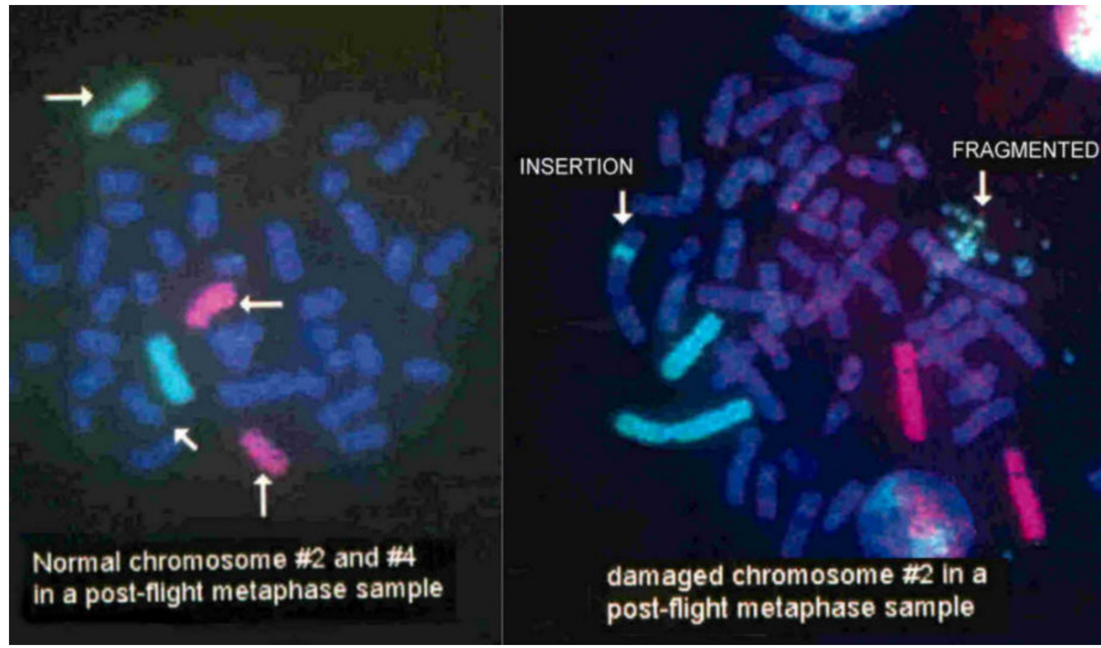
Radiation Units

- Gray (Gy) is the unit which characterizes amount of radiation absorbed by living tissues
- 1 Gy is defined to be 1 Joule of radiation energy absorbed per kilogram of matter (tissue, silicon, aluminum, etc.); 1 rad = 0.01 Gy
- Damage to matter depends on type of radiation (photon versus particle, light versus heavy ion, etc.)
- "Quality" factor (Q) used to quantify degree by which absorbed radiation produces damage, i.e., relative biological effectiveness (RBE) of any dose of radiation
- Dose equivalent is measured in sieverts (Sv) or rem (1 rem = 0.01 Sv) → rem = Q x rad; Sv = Q x Gy
- Q is determined empirically, normalized to damage produced by γ-rays (Q=1.0), for the same dose

Why Characterize Radiation Sources?

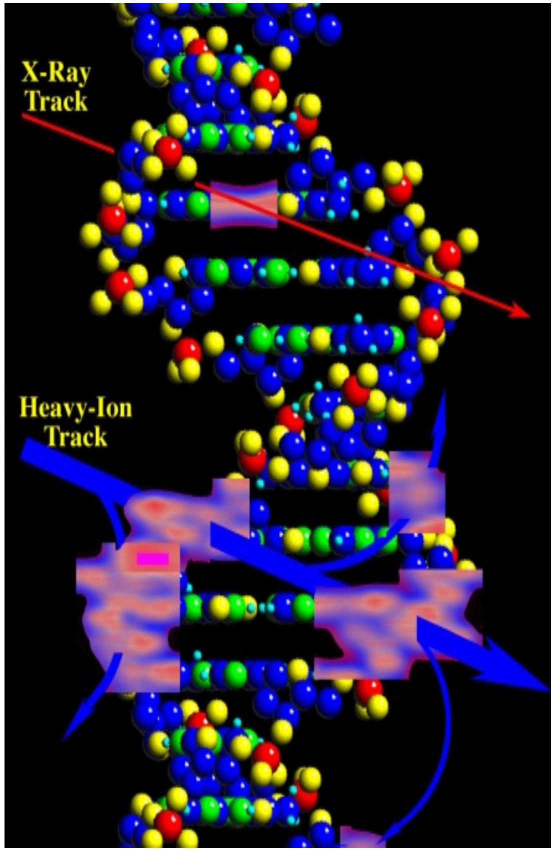
To understand risks to:

- Astronauts
  - Radiation Poisoning from sudden events
  - Heightened long-term risk
    - Cancer
    - Cataracts
- Spacecraft examples
  - Single event upsets
  - Attitude (Sun pulse & star tracker)
  - Radiation damage



Challenges to Radiation Protection

- Protect astronauts and equipment during transit to and habitation of lunar surface
  - Understand the lunar environment, optimize shielding design, accurate predictions of biological effect
- Primary spectrum of radiation is variable (time, energy, composition)
- Effect depends on properties of the radiation
  - Total energy deposited in the body
  - Rate of radiation dose
  - Particles with higher rate of energy deposition dE/dx may do more damage ($dE/dx \sim z^2$)
  - Particles fragment/scatter (focused damage)



(Courtesy, Mark Weyland, NASA Johnson Space Center, Space Radiation Analysis Group)

Threats of Radiation – “LNT”

- For large known radiation doses (i.e., Hiroshima and Nagasaki victims), linear statistical relationship exists between cancer mortality and dose
- Cancer occurs also naturally without specific large radiation dose, so establishing relationships at low dose difficult
- ICRP adopted Linear No-Threshold (LNT) model in 1959
  - Conservative model which extrapolates low dose threats linearly from high dose effects
  - Ignores statistical fluctuations which may dominate at low dose
  - Underscores the point that any amount of ionizing radiation poses a risk

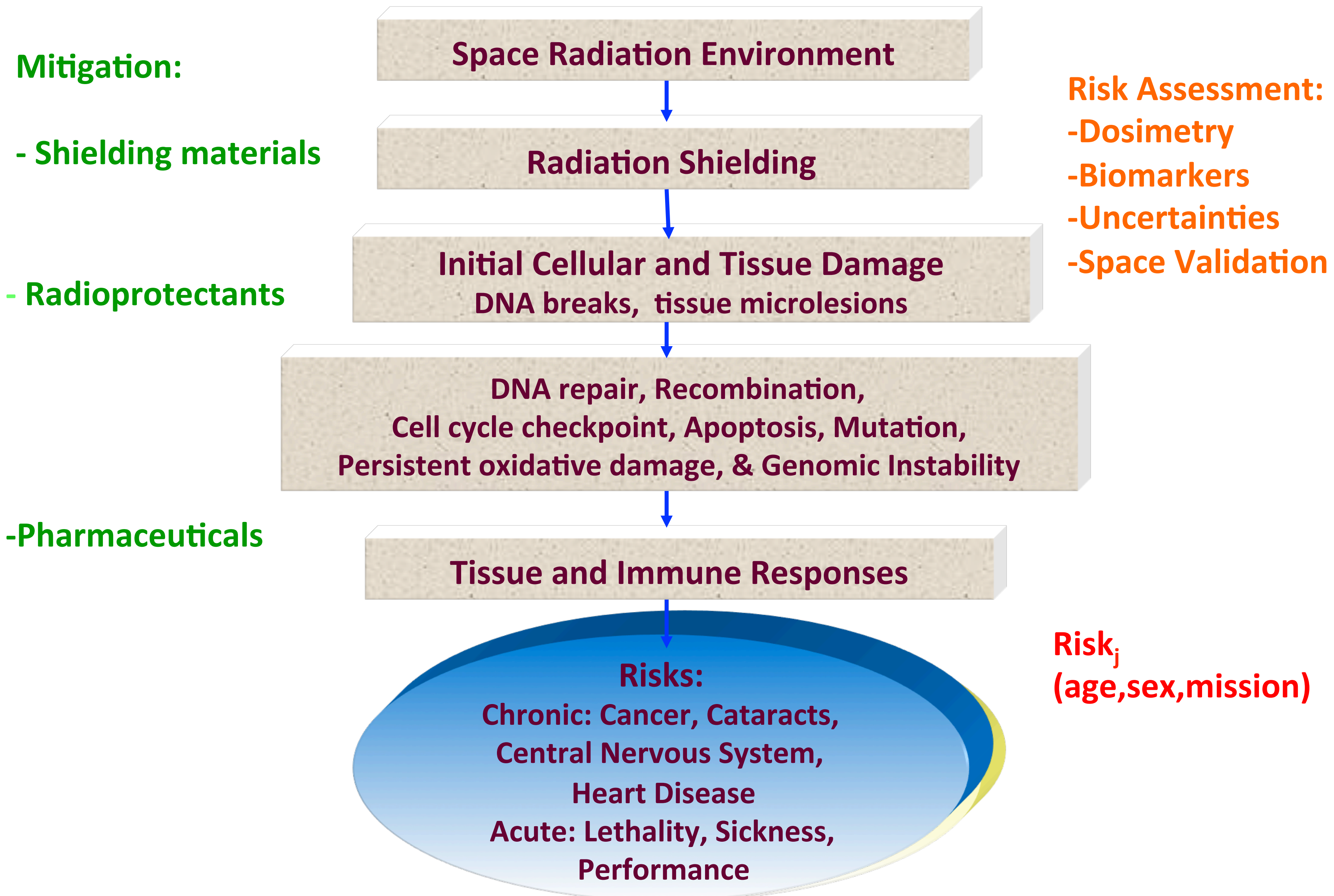
Threats of Radiation – Hormesis and ALARA

- Hormesis is controversial notion that is counter to LNT suggesting that some low doses of radiation are actually beneficial – generally not accepted
- Radiation exposure is prudently managed through the ALARA principle: As Low As Reasonably Achievable.
  - In the lab this means, for instance, limiting time of exposure, providing suitable shielding, and maximizing distance from a radioactive source
  - In space, this might mean limiting lifetime mission time, forgoing an EVA, or seeking shielding shelters
- NASA ALARA program seeks to prevent short-term flight risks and long-term risks to astronauts balancing moral obligations and financial realities

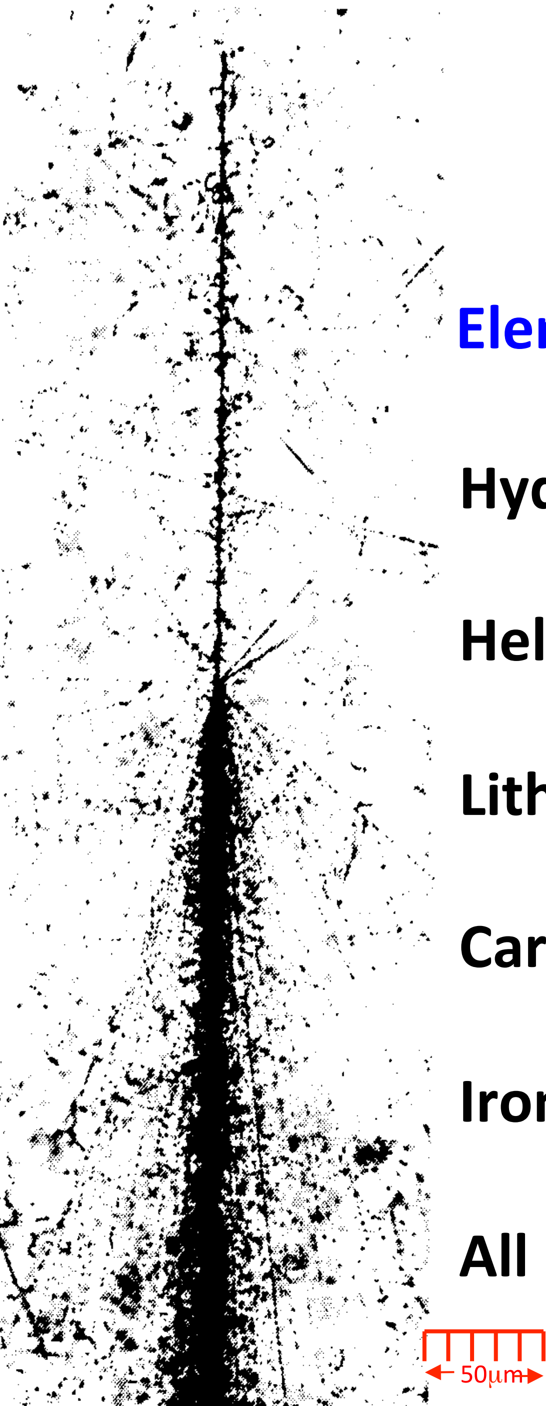
Threats of Radiation – National and International Regulatory Structures

- ICRP (International Commission on Radiological Protection)
- ICRU (International Commission on Radiation Units)
- NCRP (National Council on Radiation Protection)
- IEEE (Institute of Electrical and Electronics Engineers)
- NRC (US Nuclear Regulatory Commission)
- DOE (Department of Energy)
- OSHA (Occupational Safety and Health Administration)

Integrated Risk Projection

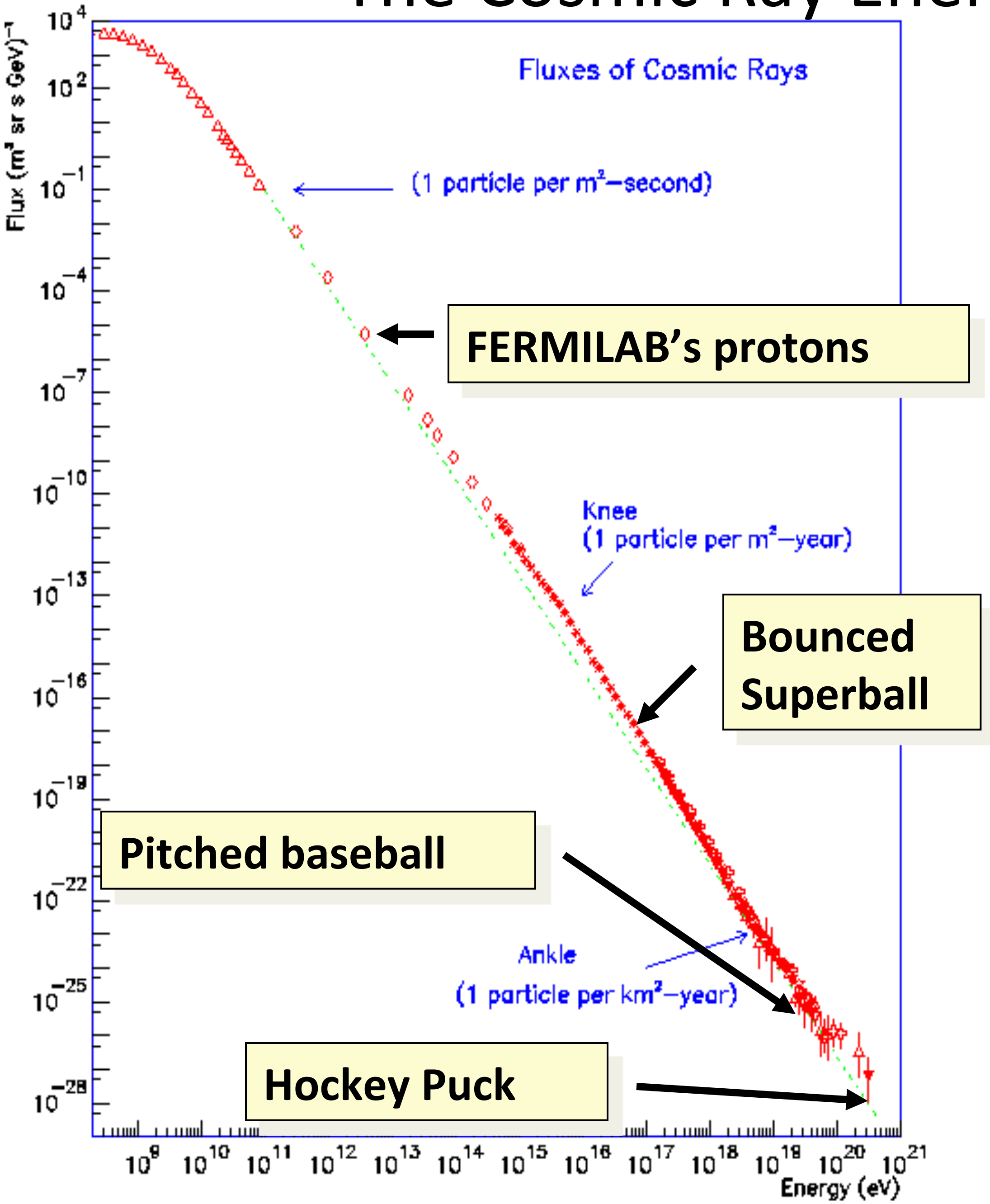


Energetic Charged Particles



Element	Atomic Number (Z)	Solar System Composition (relative #)	Primary Cosmic Ray Flux (#/m^{-2} sec)
Hydrogen (H)	**1**	**1.00**	**640**
Helium (He)	**2**	**6.8×10^{-2}**	**94**
Lithium, Beryllium, Boron		**2.6×10^{-9}**	**1.5**
Carbon, Nitrogen, Oxygen		**1.2×10^{-3}**	**6**
Iron (Fe)	**26**	**3.4×10^{-5}**	**0.24**
All heavier atoms		**1.9×10^{-6}**	**0.13**

The Cosmic Ray Energy Spectrum



The highest energy Cosmic Rays are SUBATOMIC particles carrying the energy of MACROSCOPIC objects!

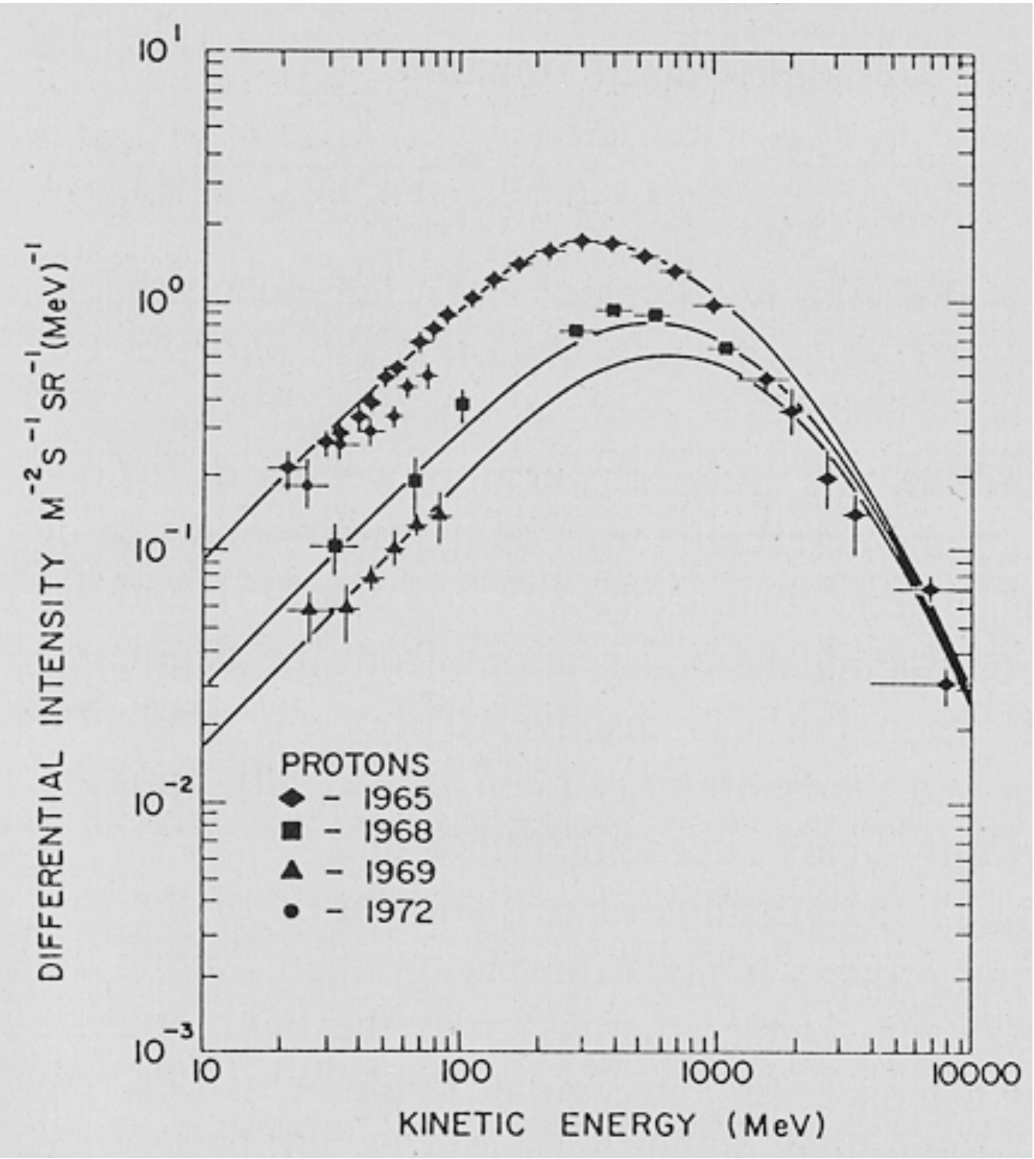
4×10^{21} eV = 60 joules

>***10 MeV p+'s*** penetrate typical s/c shielding and pose energy deposit risks in humans and machines

Galactic Cosmic Rays in the Heliosphere

Proton energy spectra observed at 1 AU (1965, solar minimum and 1969, maximum)

High-energy ions coming from the galaxy (thought to originate in association with supernovae remnants) penetrate the inner heliosphere.

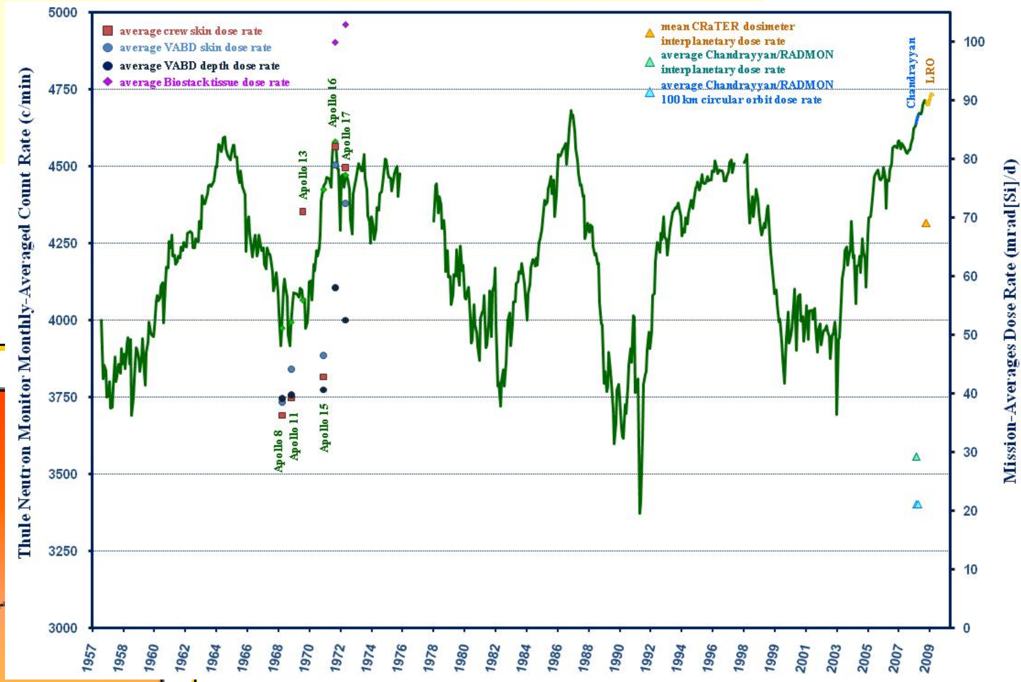


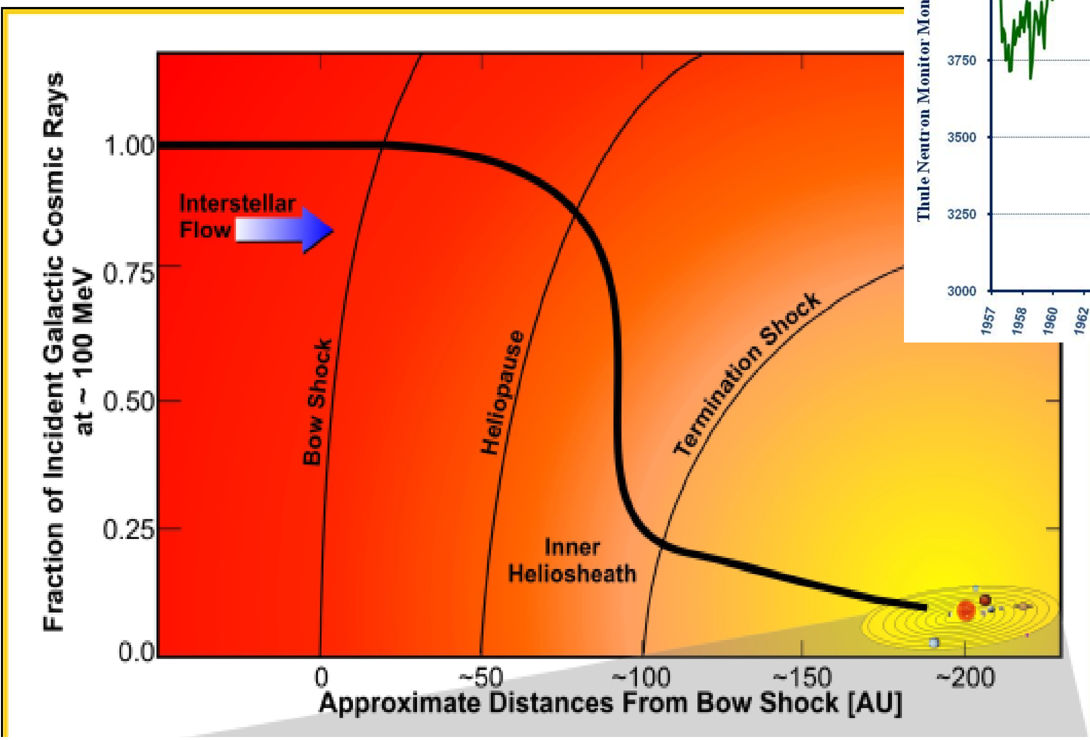
Fisk,1979

Galactic Cosmic Ray Modulation

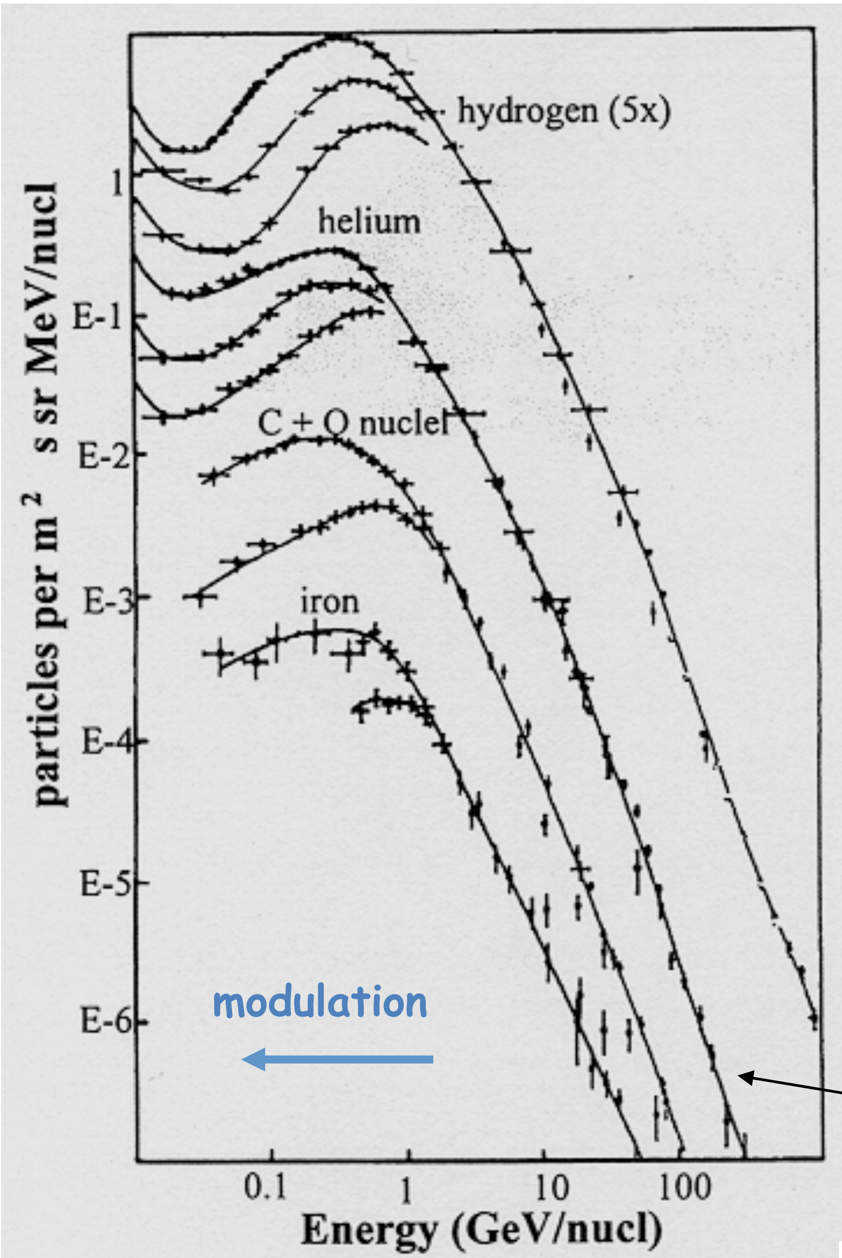
Interactions with solar wind and interplanetary magnetic field lead to:

- Radial intensity gradients
- Temporal variations



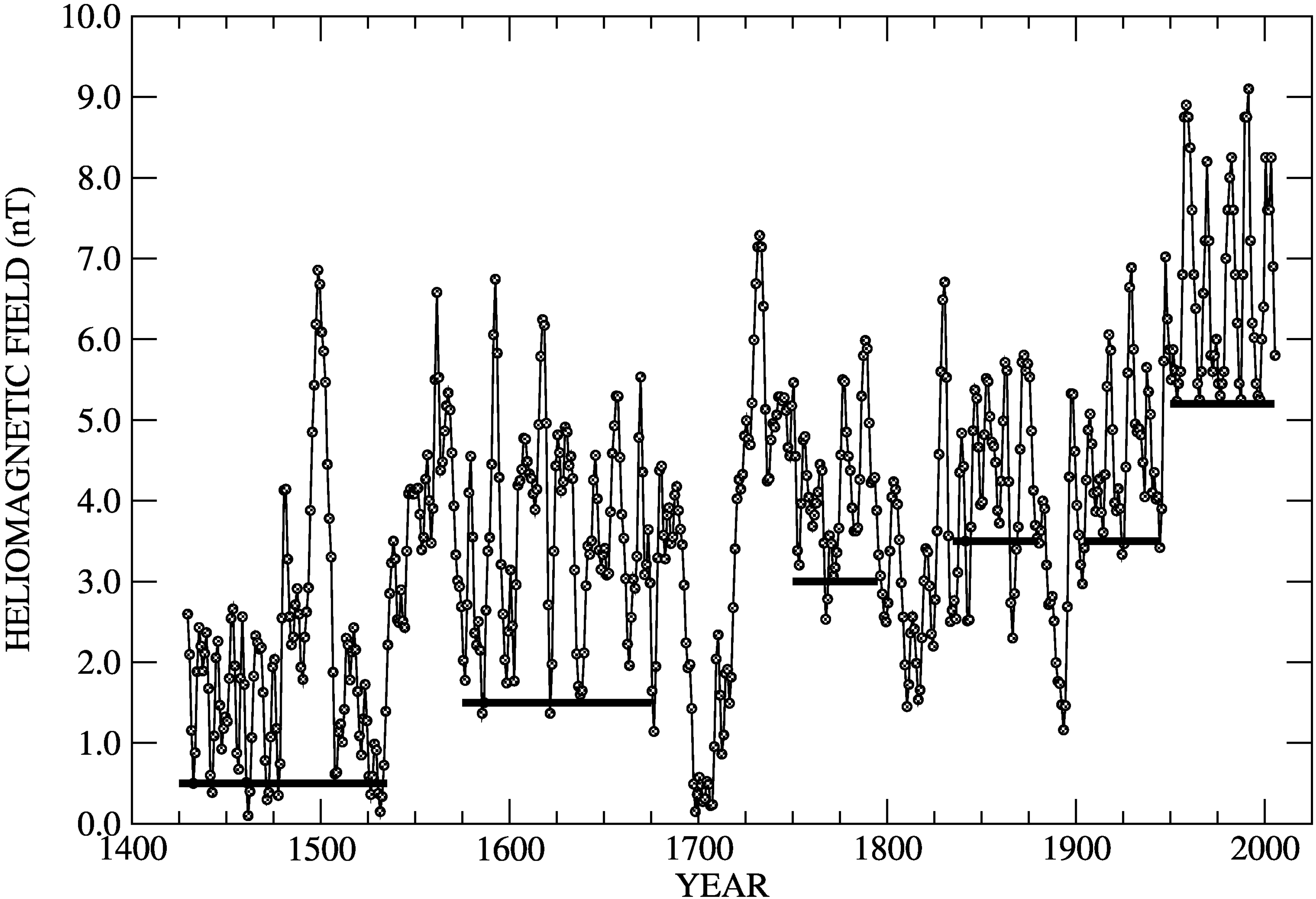


Galactic Cosmic Rays - composition

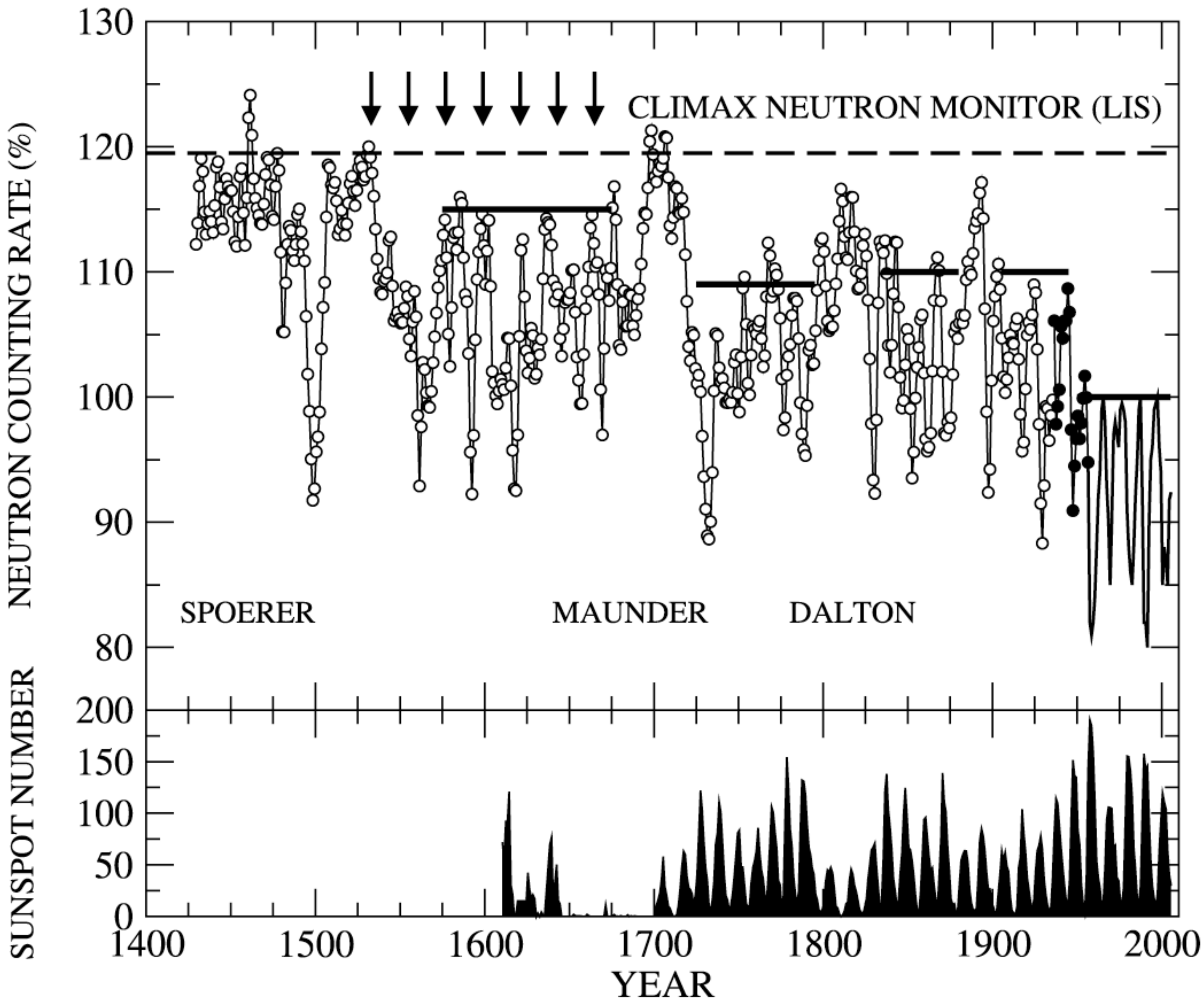


$J \sim E^{-\gamma}$ with $\gamma = -2.5$

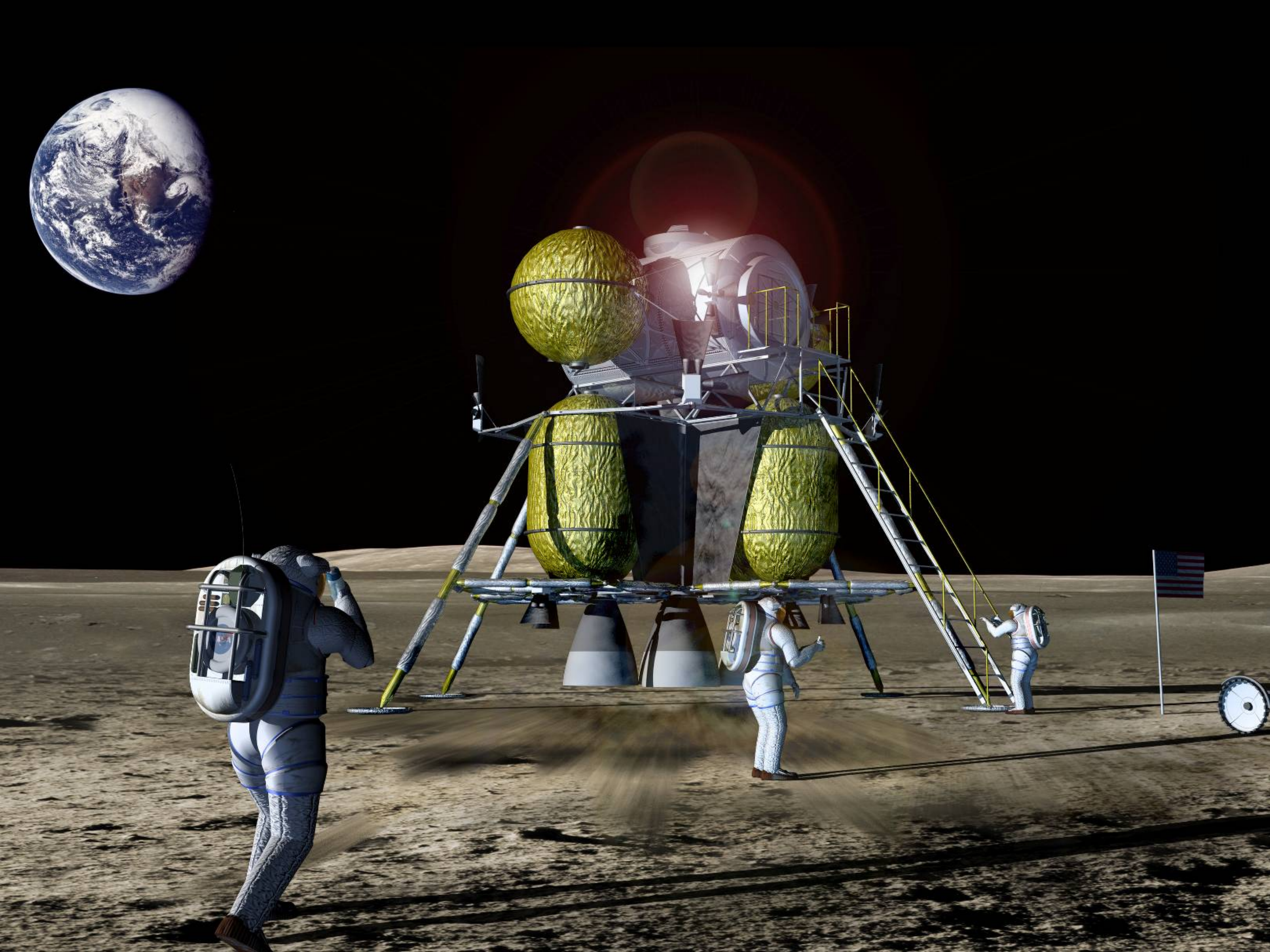
Meyer et al., 1974



- Heliospheric magnetic field helps limit access of cosmic rays to inner solar system
- Some studies show that we are at 500-year maximum of field strength
- Stronger fields provide greater shielding, hence 500-year minimum in GCR intensity



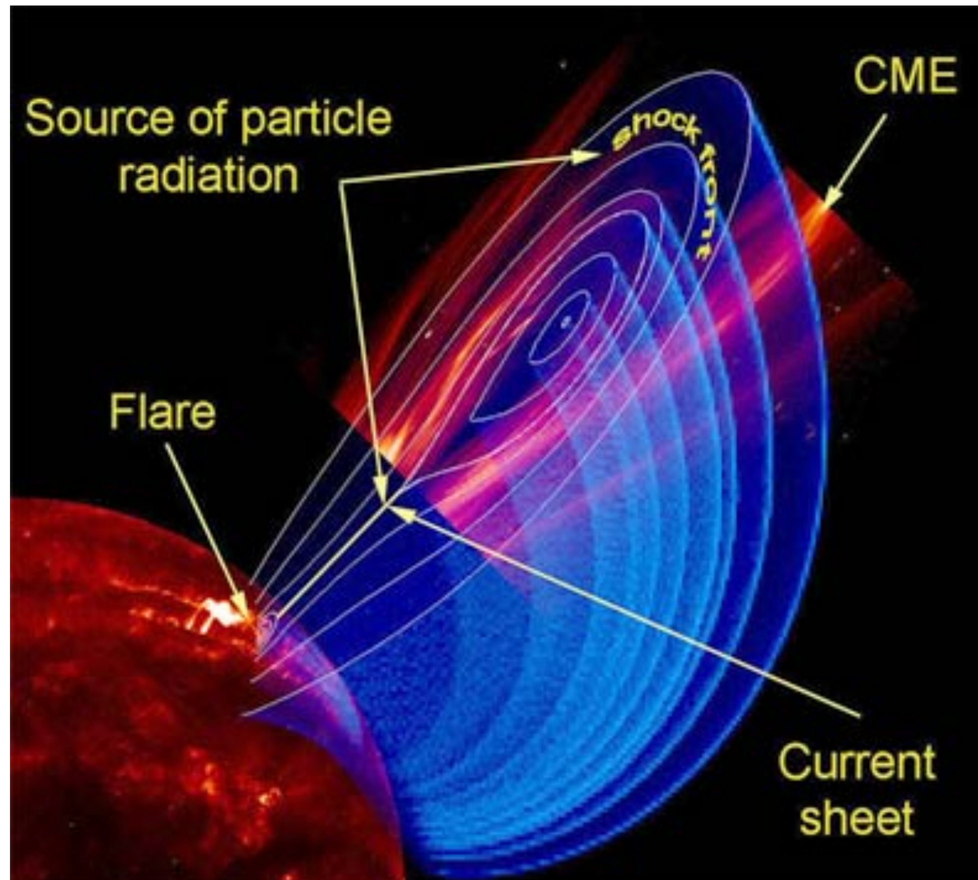
- Other studies based on ice core records suggest that we are indeed near a 500-year minimum in GCR intensity, with historic rates more than 20% greater than present



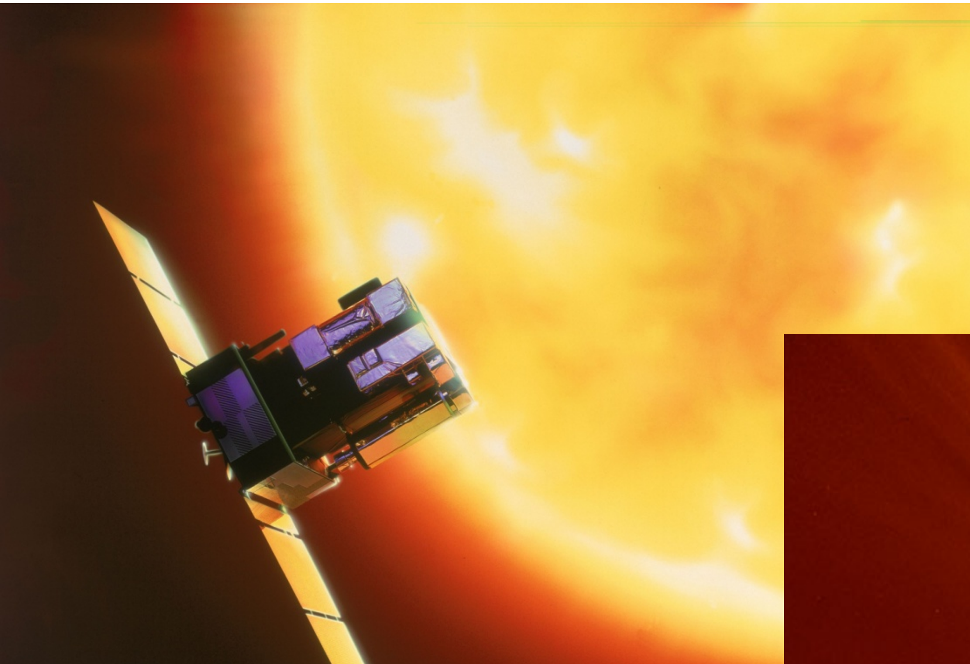
Sources of Ionizing Radiation: Solar Particle Events

- Solar Energetic Particles (SEPs) are energetic particles accelerated by processes associated with a solar source
- SEPs originate from:
  - acceleration near a solar flare site; and
  - acceleration through interactions with interplanetary shock waves propagating away from the Sun

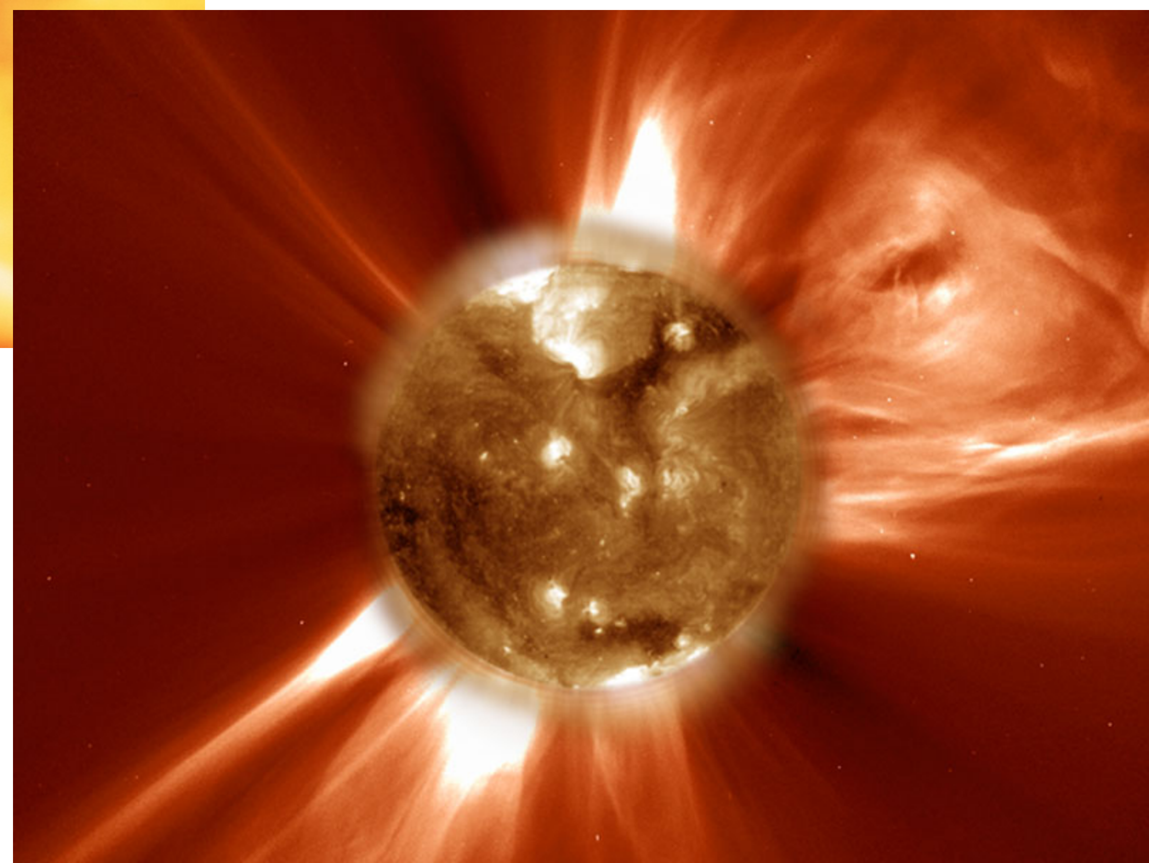
Sites of SEP Creation



Solar Heliospheric Observatory: SOHO

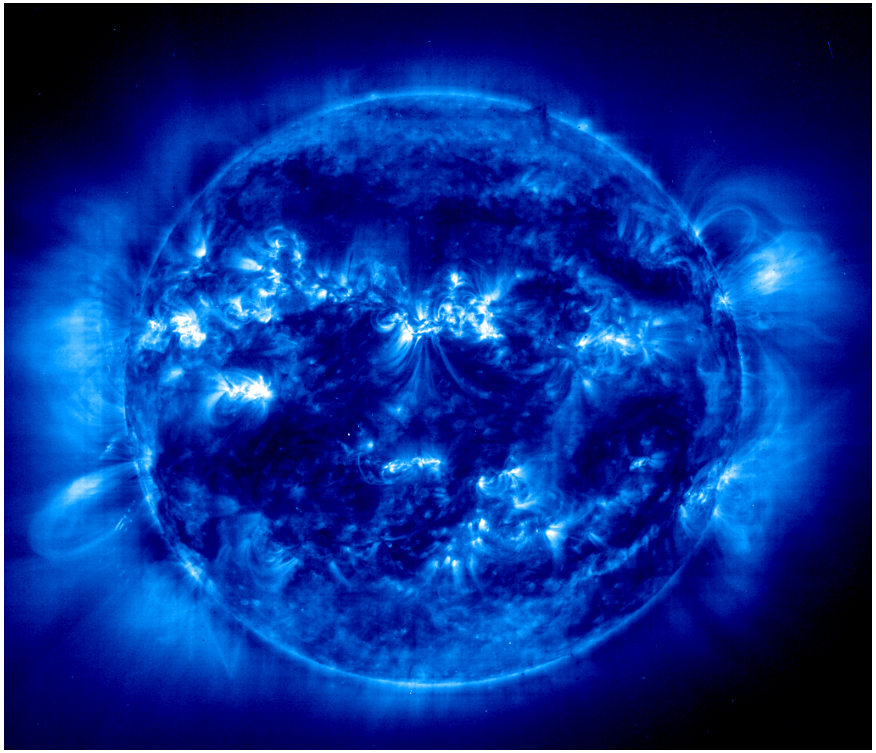


Transformative solar sentinel



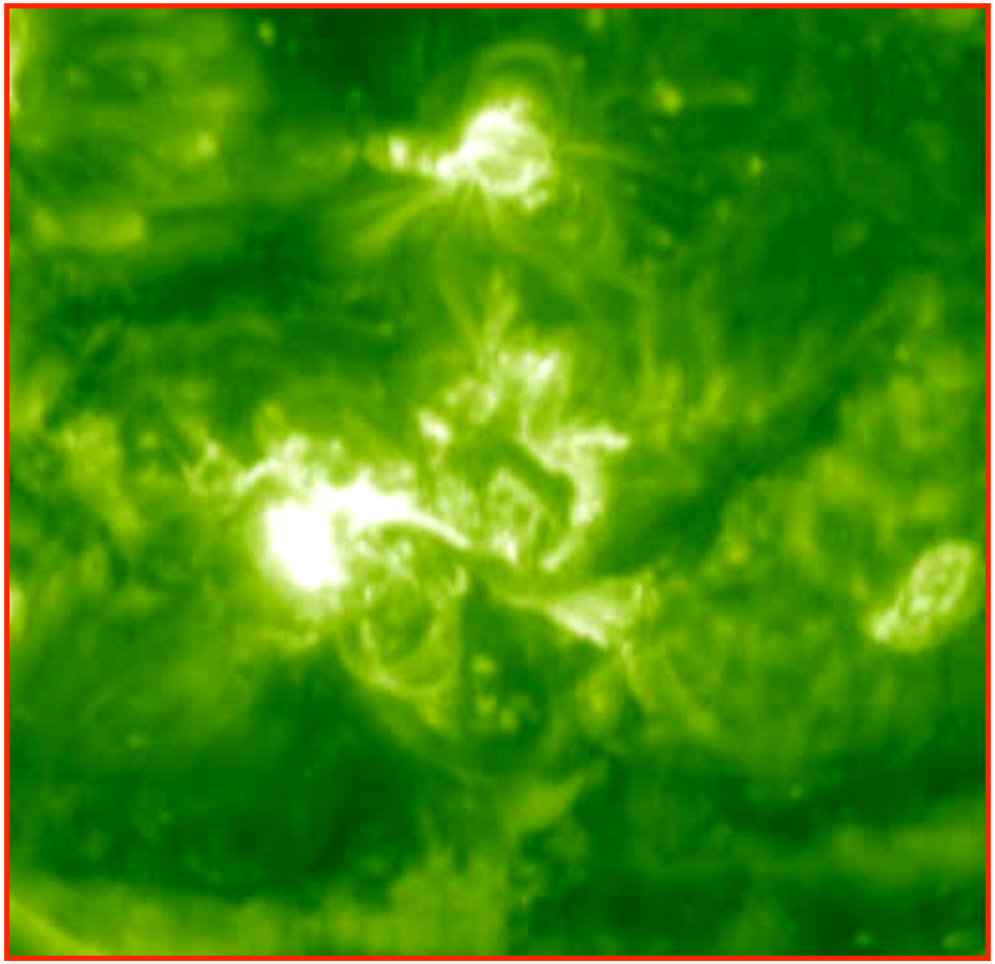
Mission period:
1995 - present

SOHO: The Active Sun



Solar Maximum:
15 July 2000

Halloween Storms
October 2003

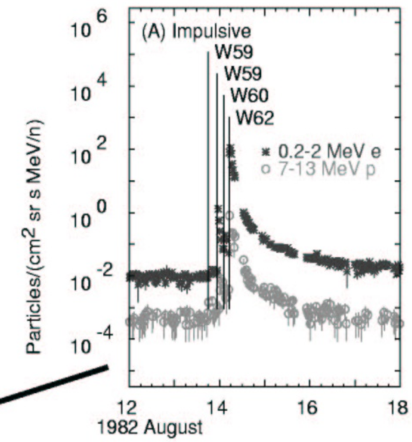


Coronal Mass Ejection - Earth Impact

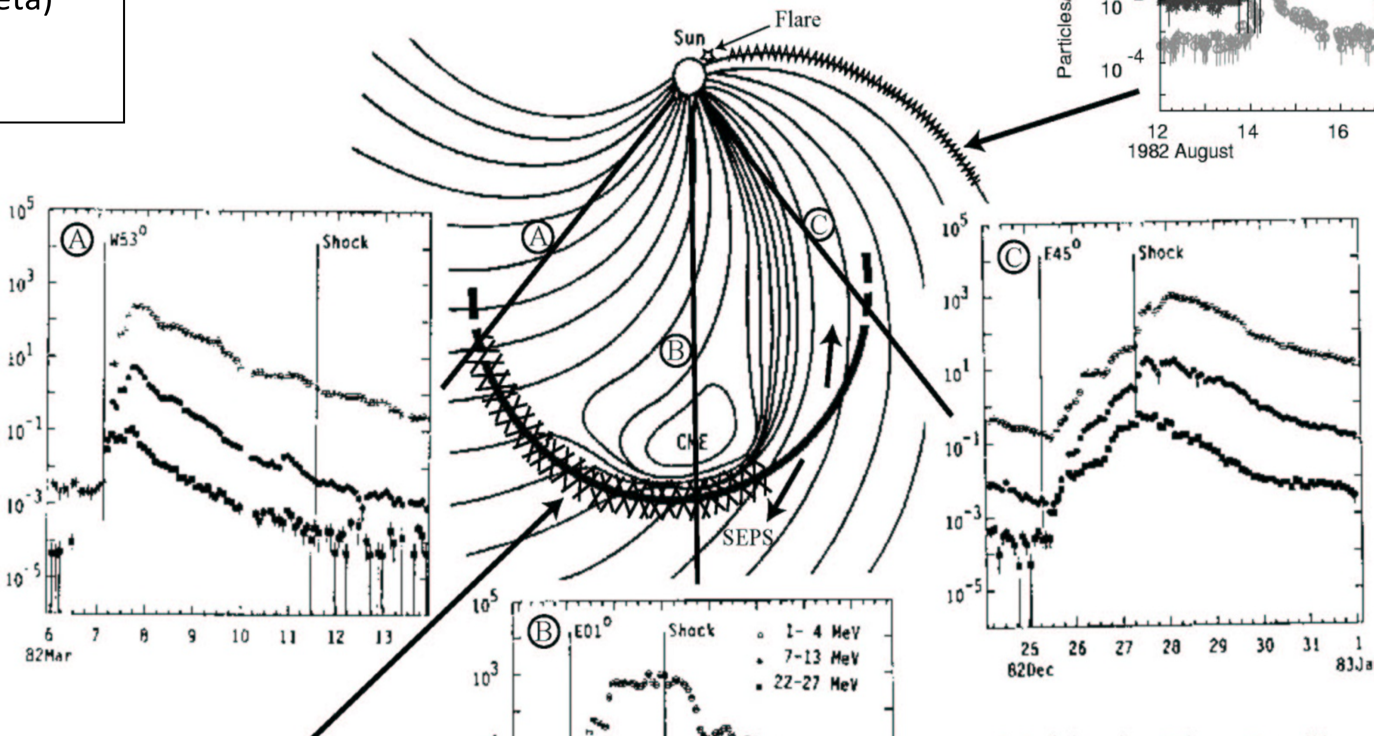
Courtesy of NASA

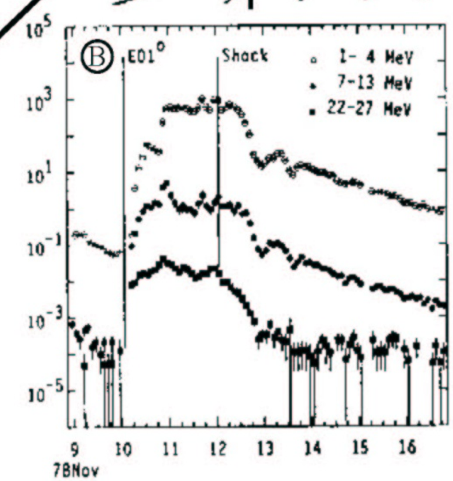
The timing of the peak flux depends on when the observer connects to the strongest part of the shock – need to know physical parameters of shock (Θ_{BN}, Mach #, plasma beta)

Locate ICME and/or Flare Acceleration Site(s) of SEP



Time of Arrival, Amplitude, and Duration of SEP critically important to users





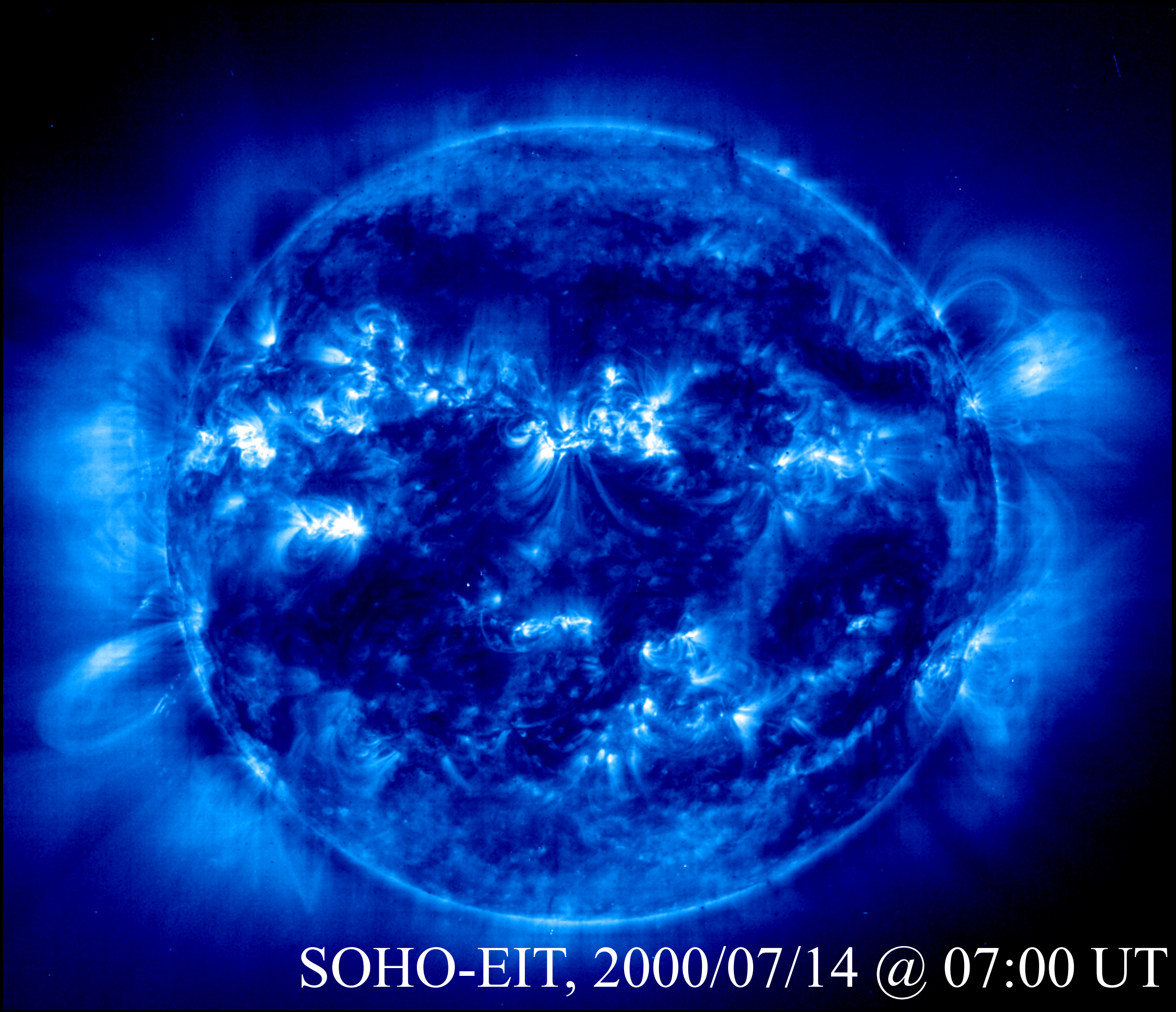
strongest ICME shock source region

- Multipoint Time Profiles (flare events are impulsive)
- Velocity Dispersions
- Composition (flare events are He^3, electron and heavy ion rich)

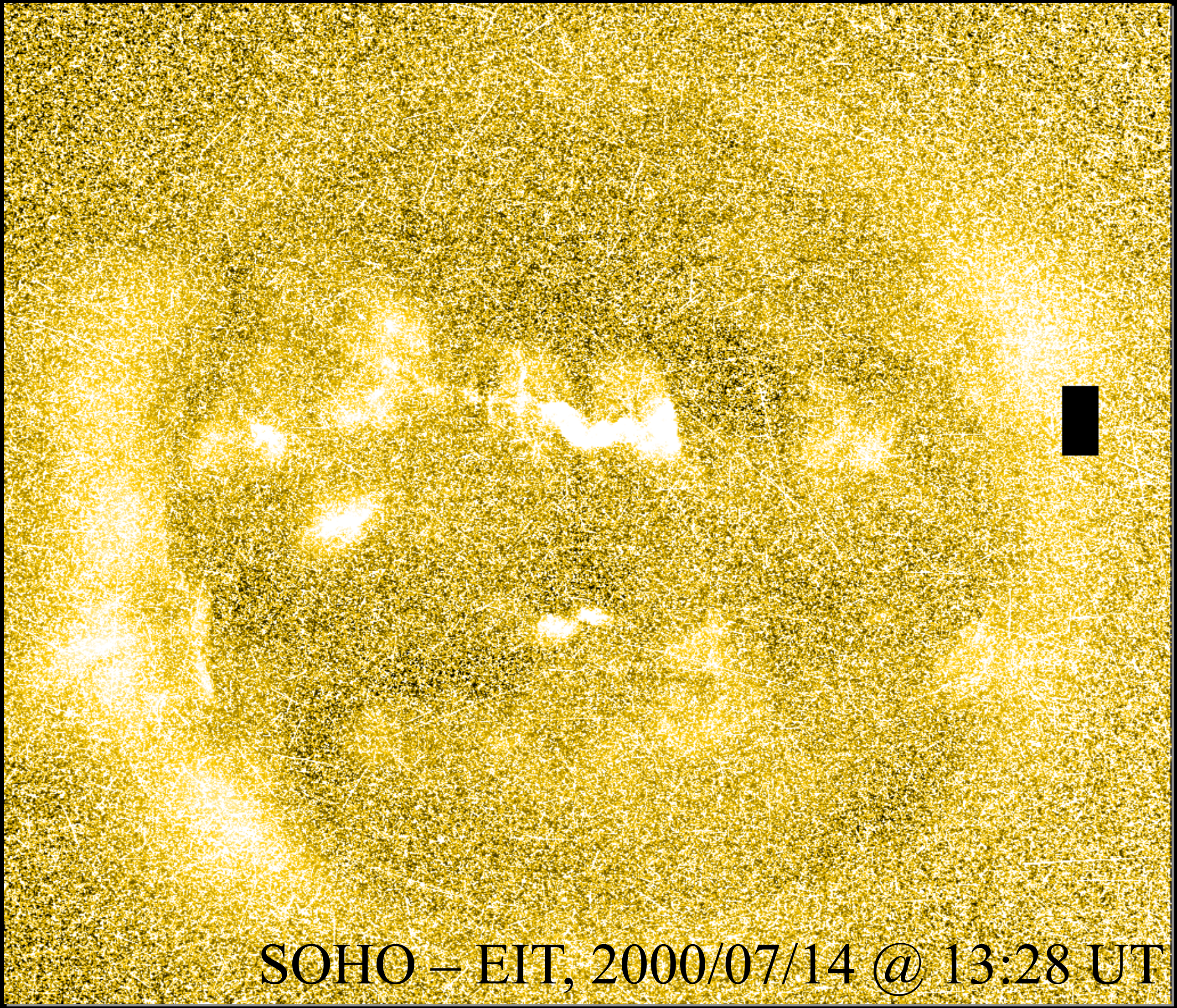
Solar Radiation Storms (Energetic Particles)

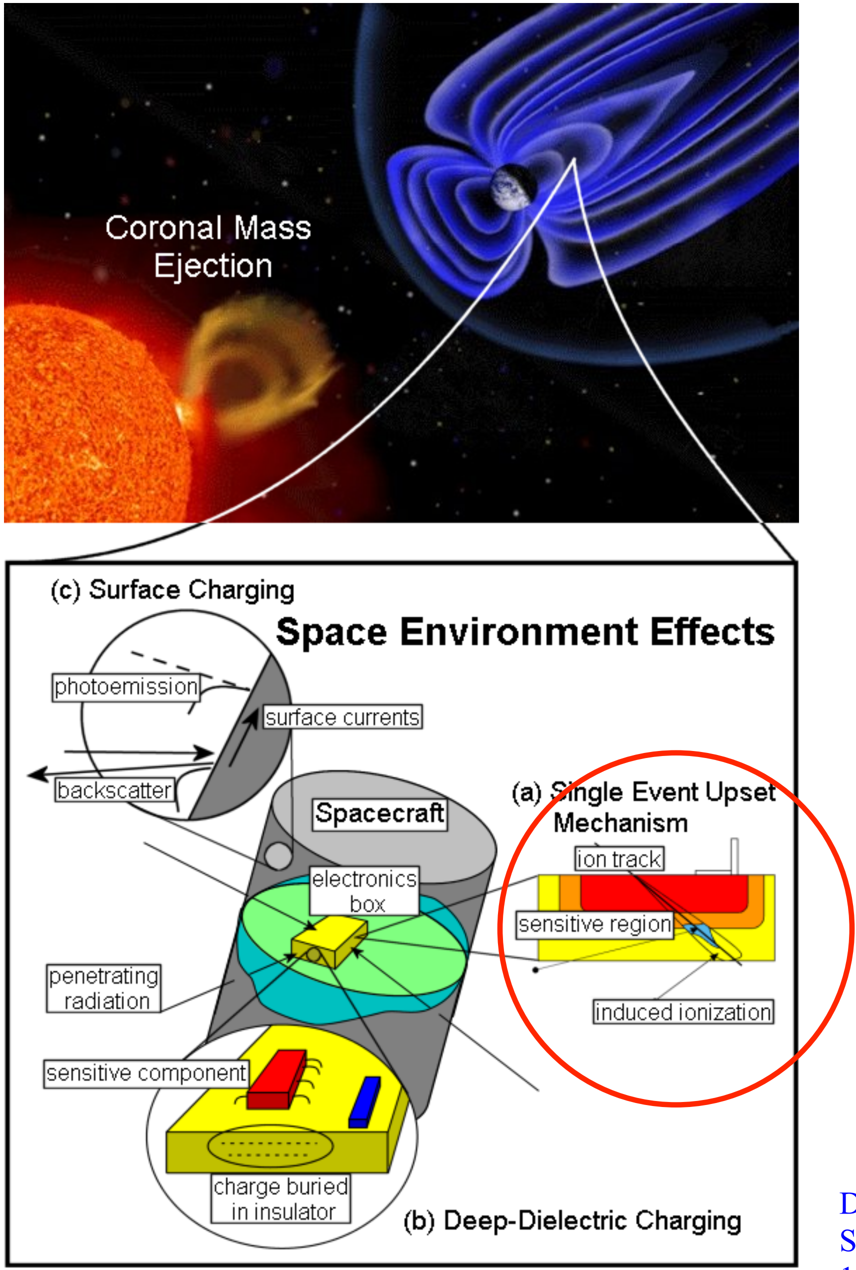
	Solar Radiation Storms	Flux level of >10 MeV protons $(cm^2 \ s \ sr)^{-1}$	Frequency of Occurrence
Extreme **S5**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
Severe **S4**	**Biological:** unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
Strong **S3**	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
Moderate **S2**	**Biological:** none. **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
Minor **S1**	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

The Active Sun: July 2000



Background Due to Solar Particles





High-Energy Ion Effects

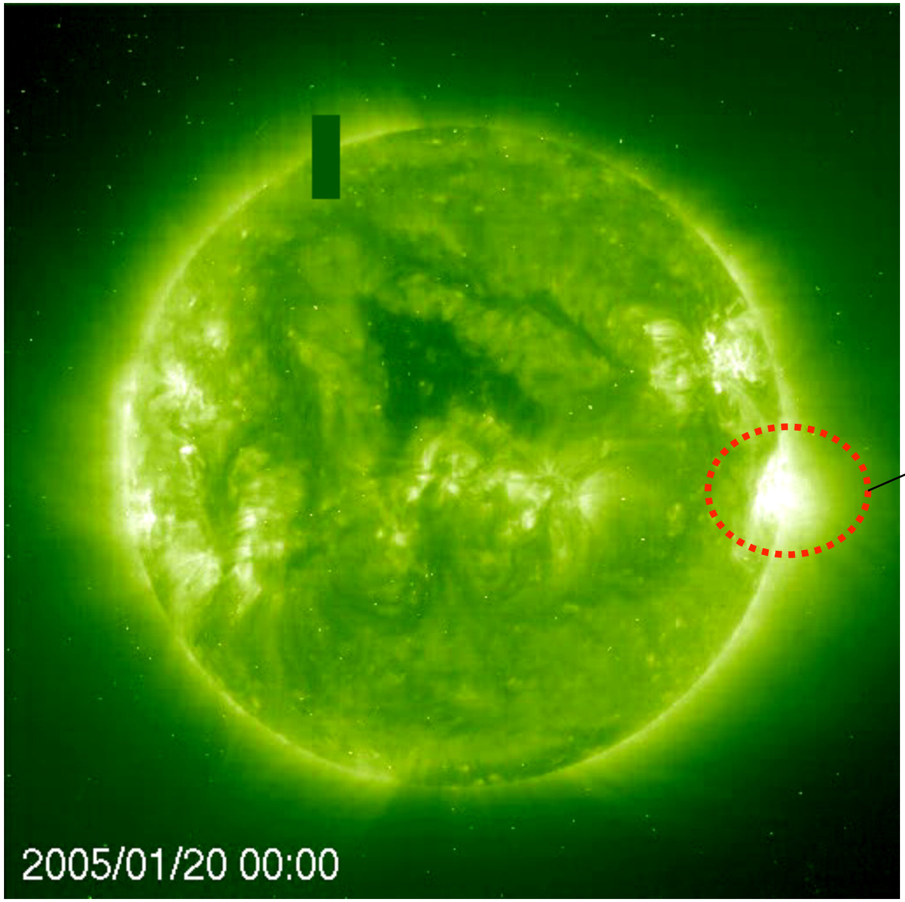
D.N. Baker "How to Cope with Space Weather," *Science*, *297*, 1486, 2002

So What? Powerful Solar Variability.

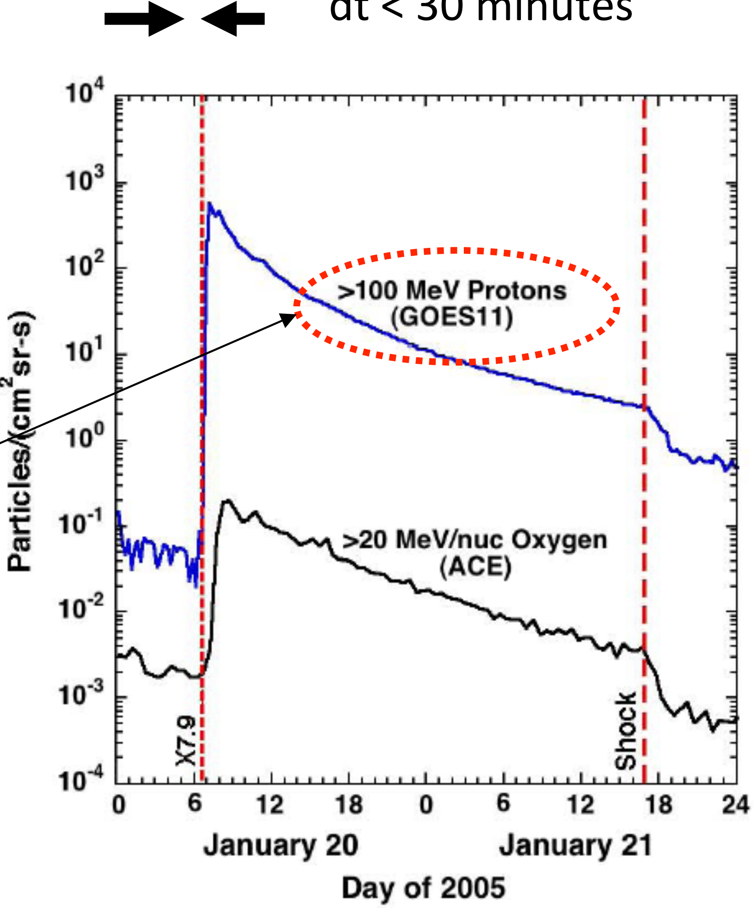
Image credit: J. Koeman

- Near solar minimum
  - Few sunspots
  - Few flares
  - Quiet corona
- Giant sunspot 720
  - Sudden appearance
  - Strong magnetic field
  - Very large
  - On west limb by January 20

Who Cares? Astronauts, s/c Operators



dt < 30 minutes




Space Radiation Hazards
and the Vision for Space
Exploration
Report of a Workshop
Ad Hoc Committee on
the Solar System Radiation Environment
and NASA's Vision for Space Exploration: A Workshop
Space Studies Board
Division on Engineering and Physical Sciences
National Research Council of the National Academies

Magnitude and Scope of Effects?

- ISS: 1 REM (Roentgen Equivalent Man, 1 REM ~ 1 CAT Scan)
  - Scintillations
  - Hardened shelter
- Spacesuit on Moon 50 REM (Radiation sickness)
  - Vomiting
  - Fatigue
  - Low blood cell counts
- 300 REM+ suddenly
  - Fatal for 50% within 60 days
- Also
  - Two communication satellites lost
  - Airplanes diverted from polar regions
  - Satellite tracking problems, degradation in solar panels

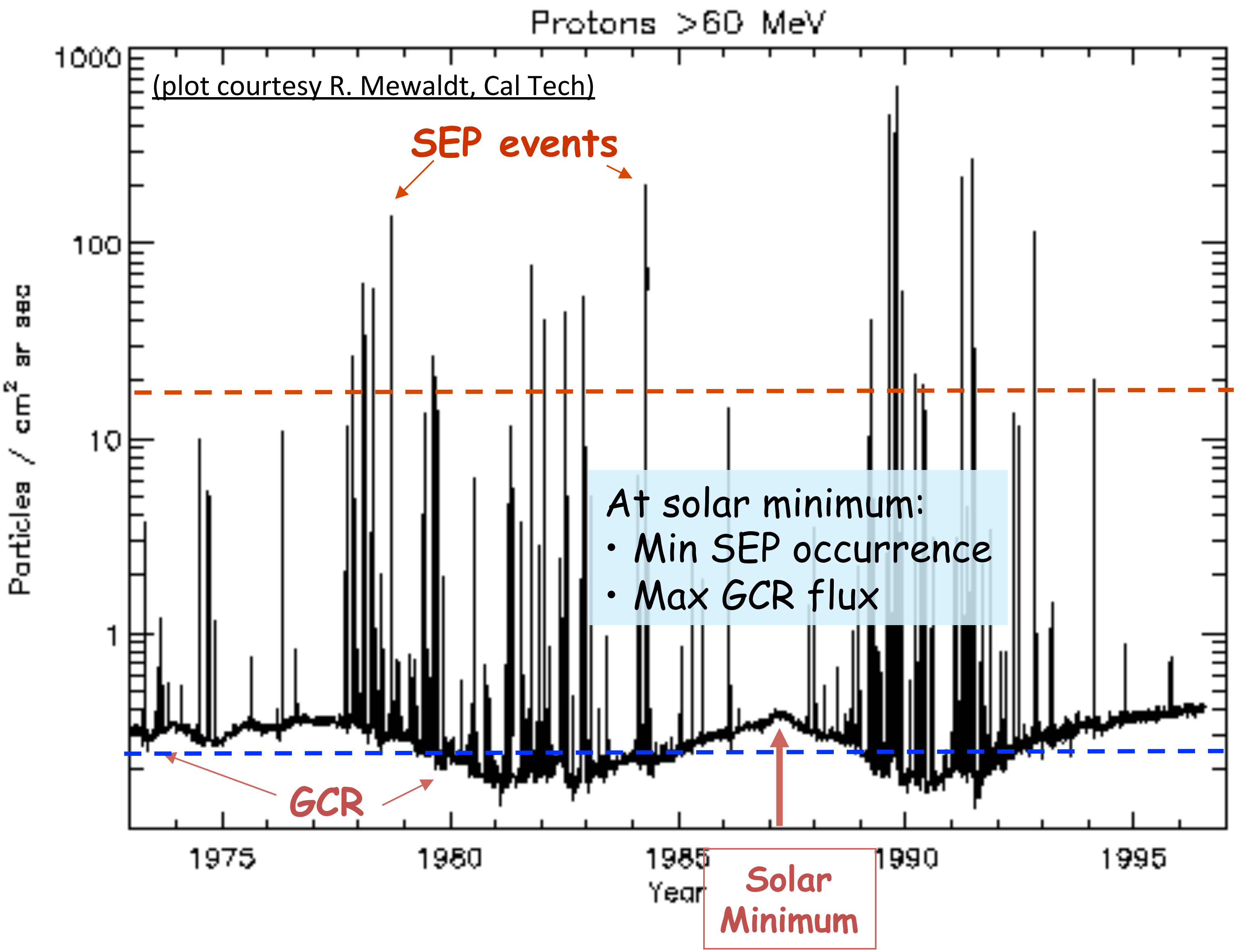
How Big is Big? Potentially Fatal.

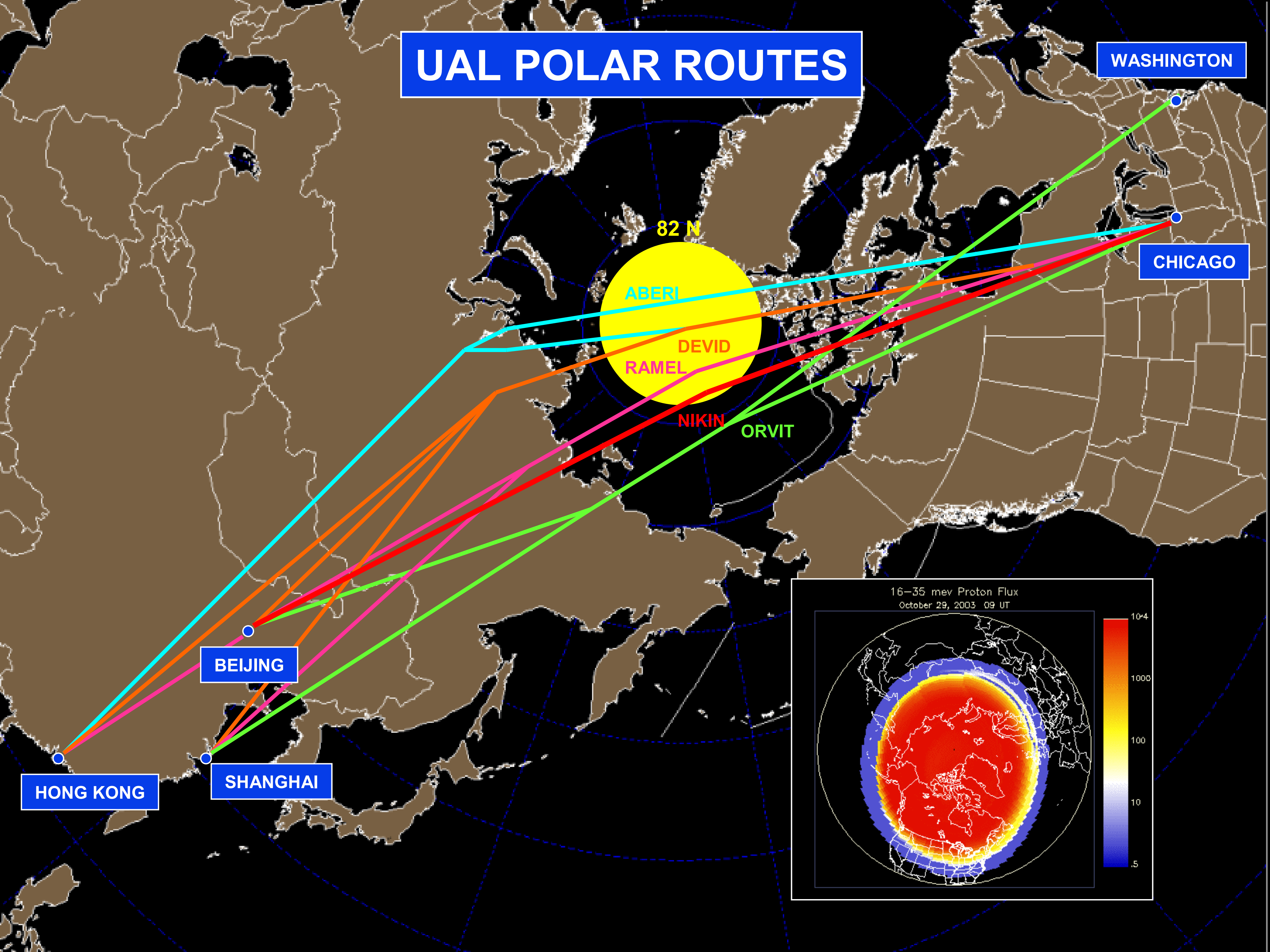
Big Bear Solar Observatory

- Apollo 16 in April 1972
- Flare on August 7, 1972
- Apollo 17 that December
- Derived dosage 400 REM
- Michener’s “Space” is based on this event

SEP event occurrence varies with the solar cycle in anti-phase with weaker but persistent galactic cosmic ray fluxes

When is it safe for space travel? Never!!

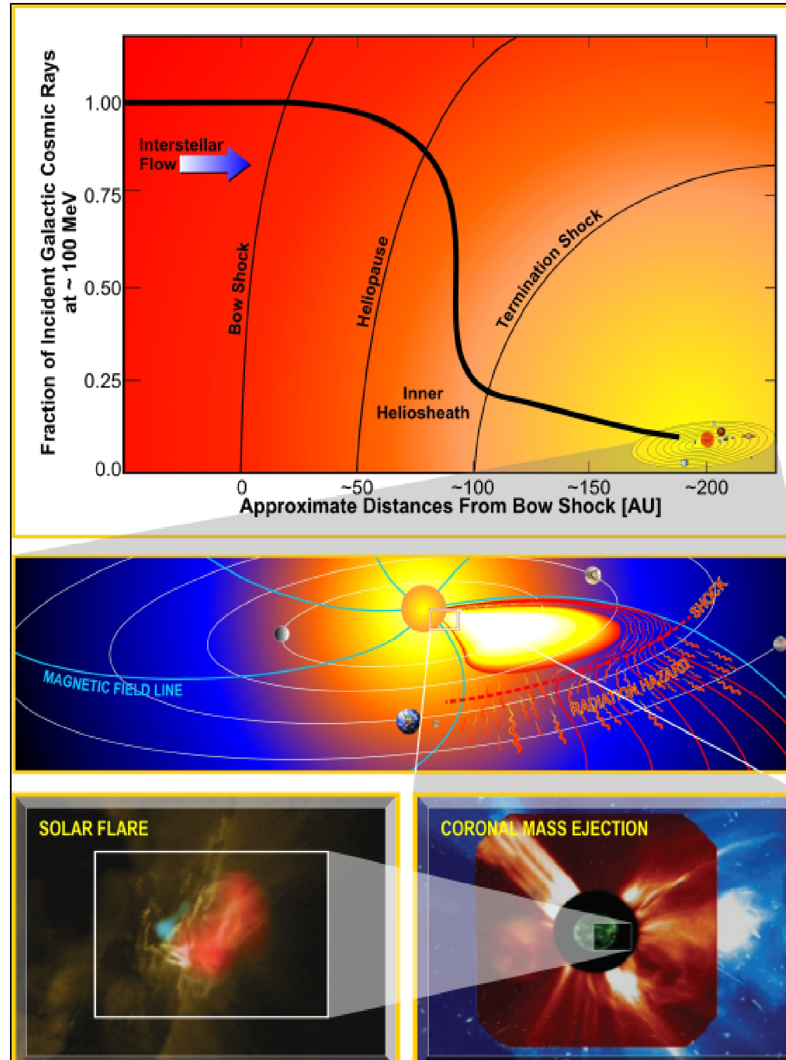




UAL POLAR ROUTES
WASHINGTON
CHICAGO
82 N
ABERI
DEVID
RAMEL
NIKIN
ORVIT
BEIJING
HONG KONG
SHANGHAI
16–35 mev Proton Flux
October 29, 2003 09 UT
10^4
1000
100
10
.5

Summary: Radiation Hazards

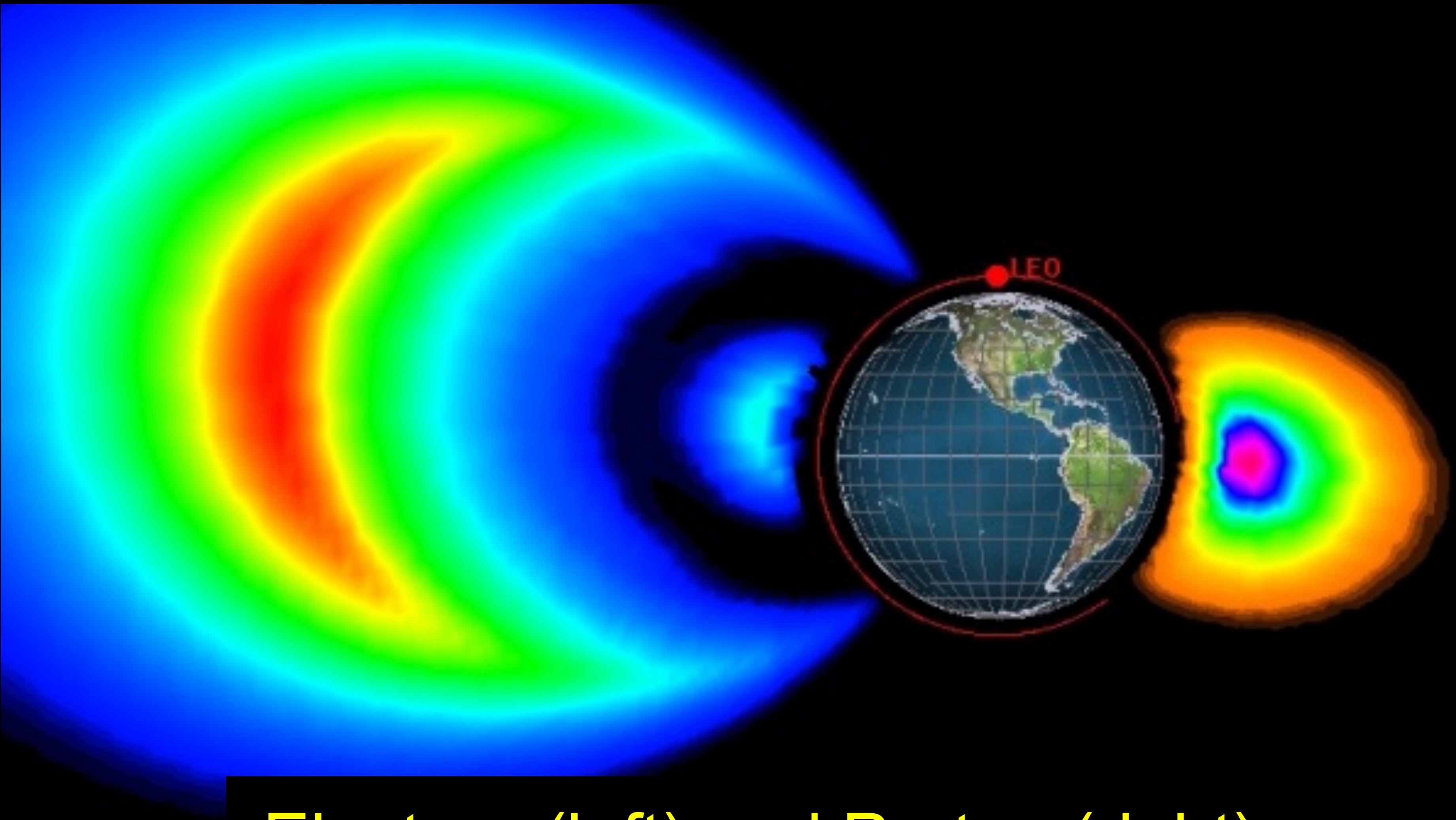
- Galactic Cosmic Rays (GCRs)
  - Steady Background
  - Career limit in ~ 3 years
  - Some predict that 50% of an astronauts DNA would be shattered during a round-trip mission to Mars
- Solar Energetic Particles (SEPs)
  - Acute Sources
  - ESPs versus impulsive component
  - Time-dependent response
  - Difficult to predict



Sources of Ionizing Radiation: Trapped Particles

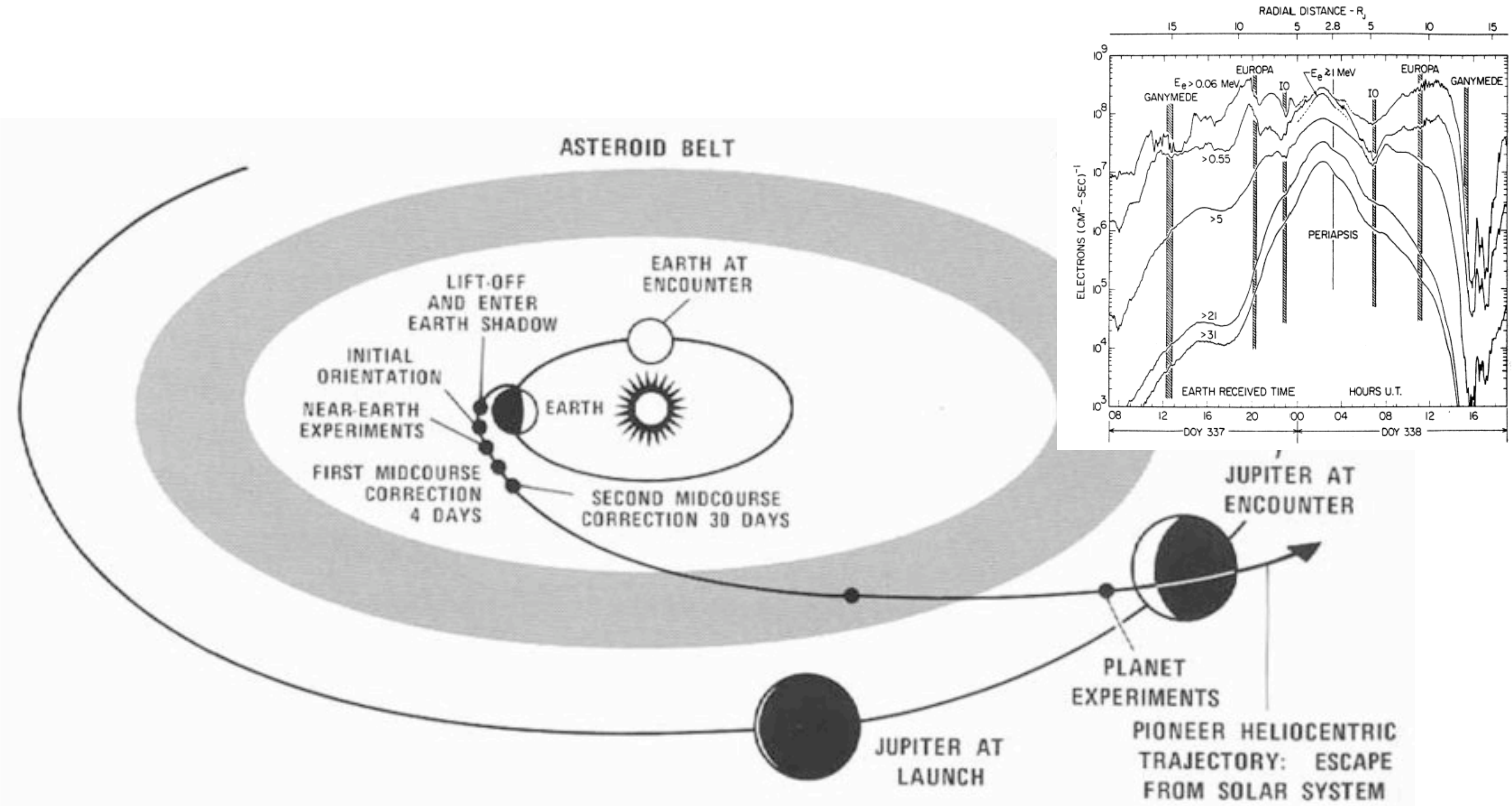
- Planetary magnetospheres with strong dipolar magnetic fields (i.e., Earth, Jovian planets) can trap charged particles (bottle) as well as deflect them (shield); ordered by magnetic field geometry
- Trapped energetic particles (principally protons and electrons, but also heavy ions) fill vast regions of the inner magnetosphere in the Van Allen "Radiation" Belts
  - Belts are not "radioactive", rather, they contain particles capable of producing ionizing radiation
  - Protons dominate inner belt; electrons outer belt
- Earth's offset tilted dipole brings radiation belts closest to surface off Brazil and produces region called the South Atlantic Anomaly (SAA) – a region where inner belt protons affect LEO missions
- Beyond LEO, missions going to Moon and beyond pass rapidly through radiation belts (ALARA) , thus minimizing radiation risks


TWENTY-FIVE CENTS
MAY 4, 1959
SPACE and the RADIATION BELT
TIME
E WEEKLY NEWSMAGAZINE
PHYSICIST
JAMES VAN ALLEN
$7.00 A YEAR
VOL. LXXIII NO. 18

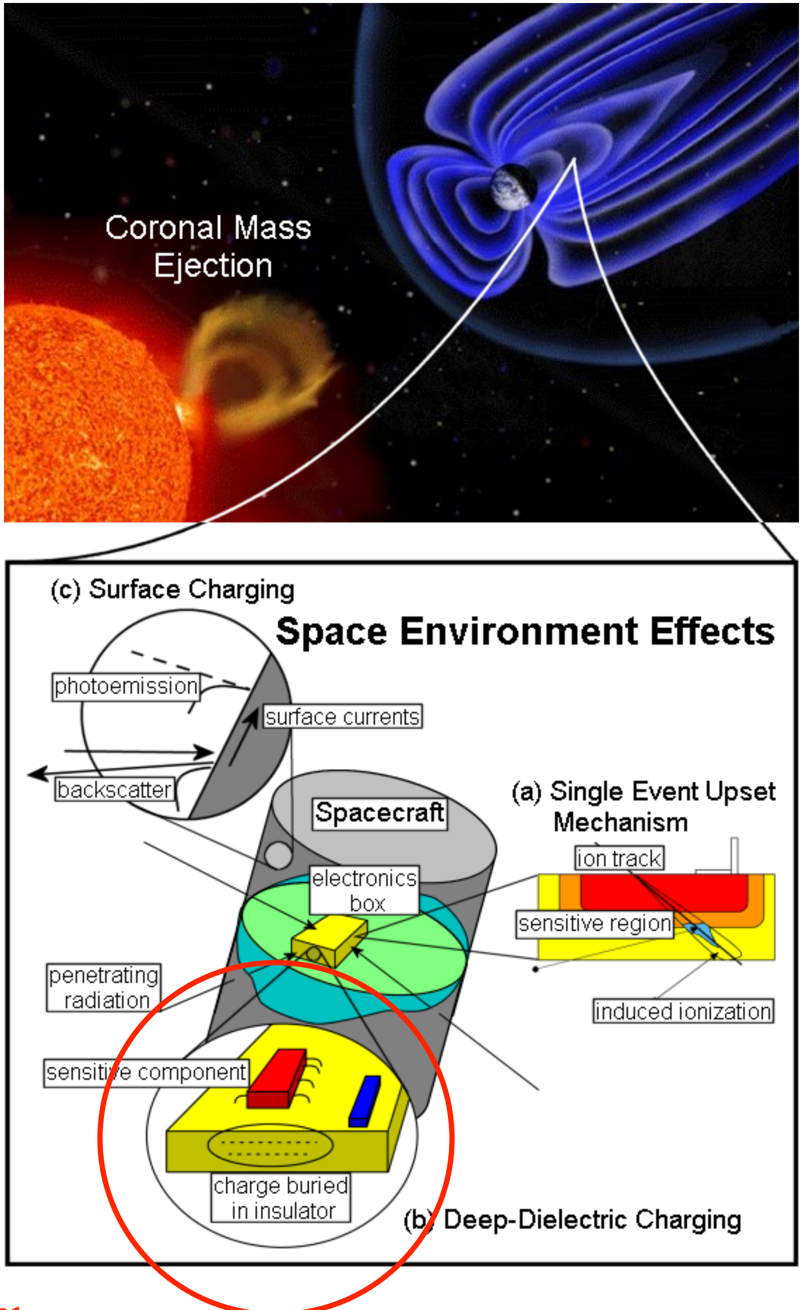



Electron (left) and Proton (right)
Radiation Belt Models

Exploration of the 1970s: Amazing Era



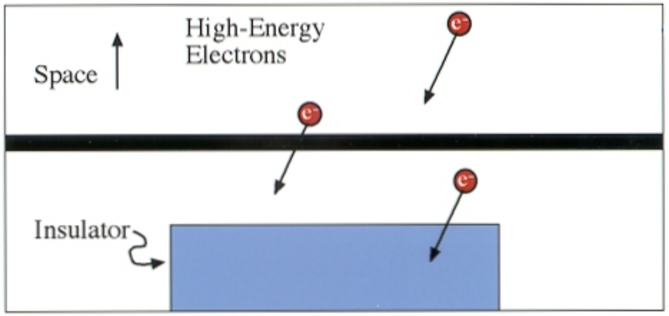
Pioneer 10 (and 11) to Jupiter, Saturn and Beyond



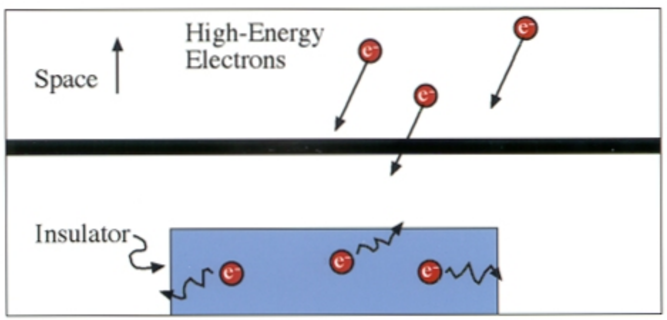
High-Energy Electrons

[Baker, *Science*, 2002]

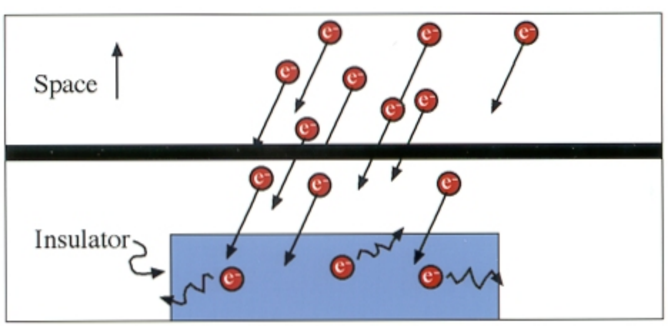
Energetic Electrons: Deep-Dielectric Charging



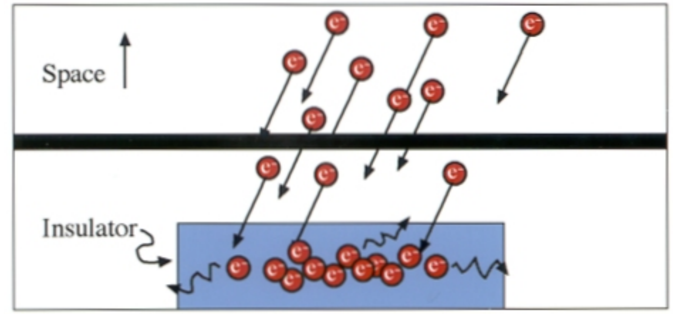
1. Electrons bury themselves in the insulator



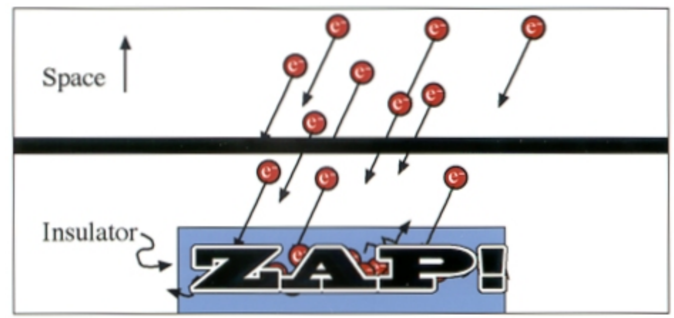
2. Electrons slowly leak out of the insulator



3. Influx of electrons increases to levels higher than the leakage rate



4. Electrons build up faster than they leak off



5. Discharge (electrical spark) that damages or destroys the material

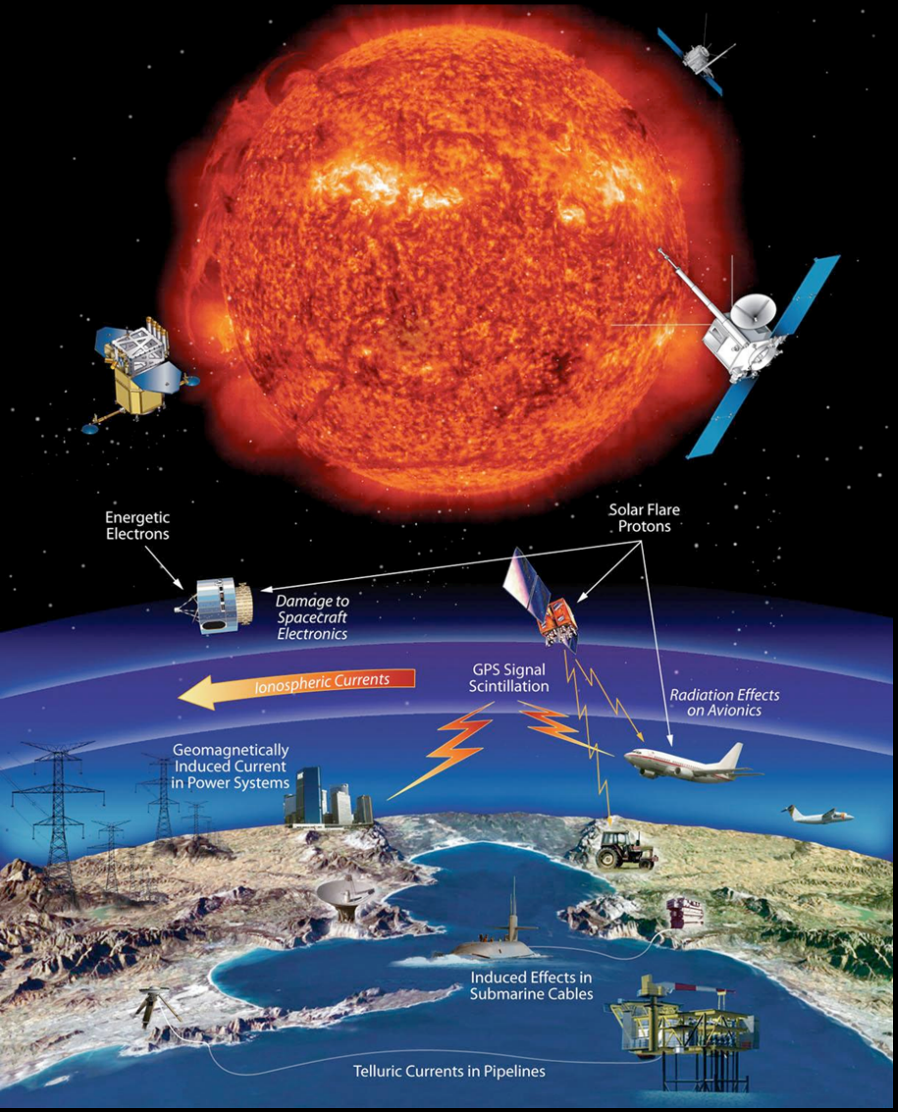
Practical Motivation: Drivers of Space Weather

Coronal Mass Ejections (CMEs):
- Arrive 1- 4 Days later
- Last a day or two
- Produce Geomagnetic Storms at Earth
- Systems Affected
  - Radio Communications
  - Navigations
  - Electric Power Grids
  - Pipelines

Solar X-Rays:
- Arrive in 8 Minutes
- Last minutes to hours
- Increases ionosphere density
- Systems Affected:
  - Radio Communications
  - Navigation

High-Speed Solar Wind:
- Common During Solar Minimum
- Enhances Radiation Belts
- Systems Affected
  - Satellite Charging
  - Astronouts

Solar Energetic Particles:
- Arrive in 30 Minutes to 24 hours
- Last several days
- Systems Affected:
  - Astronauts
  - Spacecraft
  - Airlines
  - Radio Communications

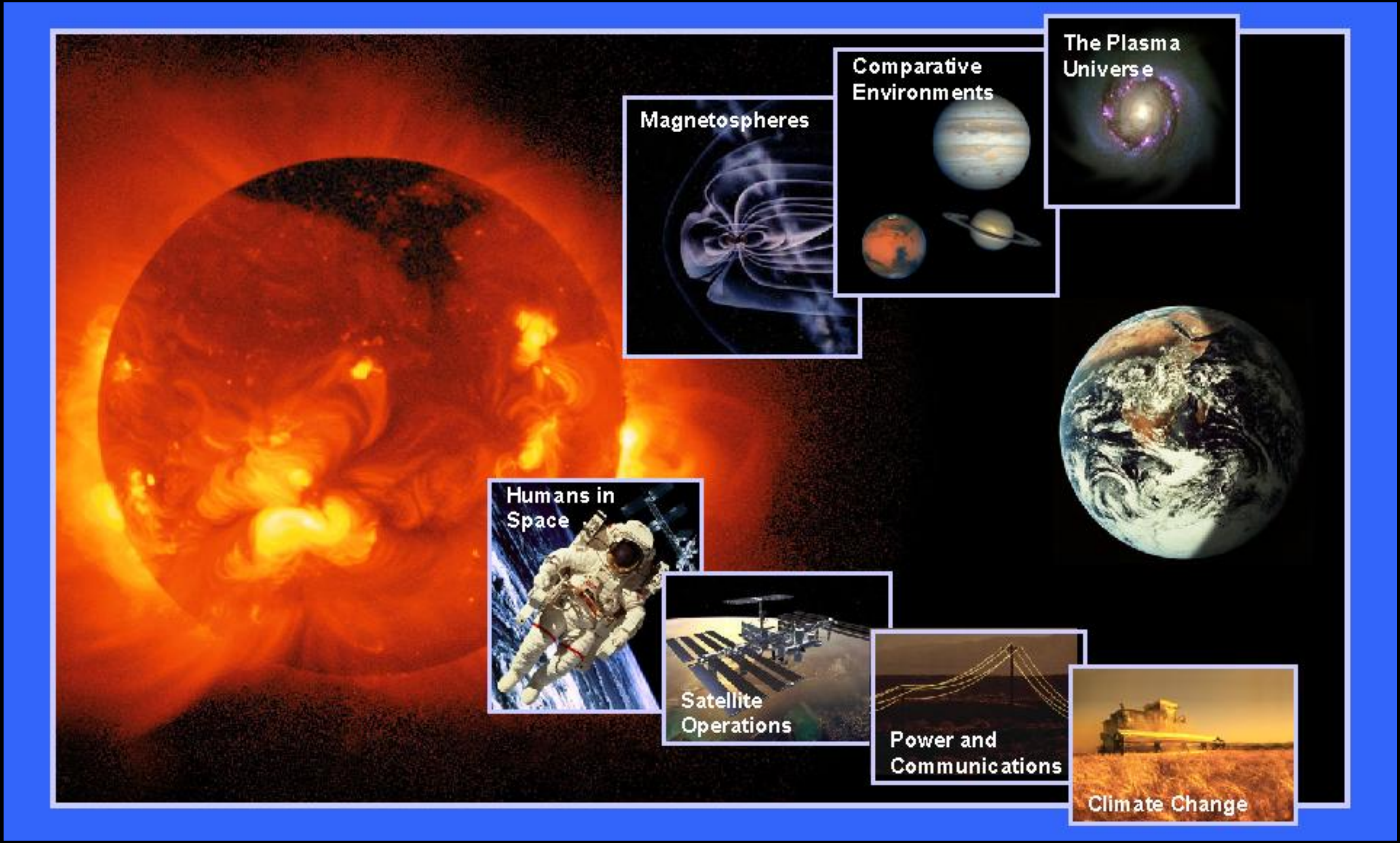


Energetic Particles and Their Impacts

Part 2

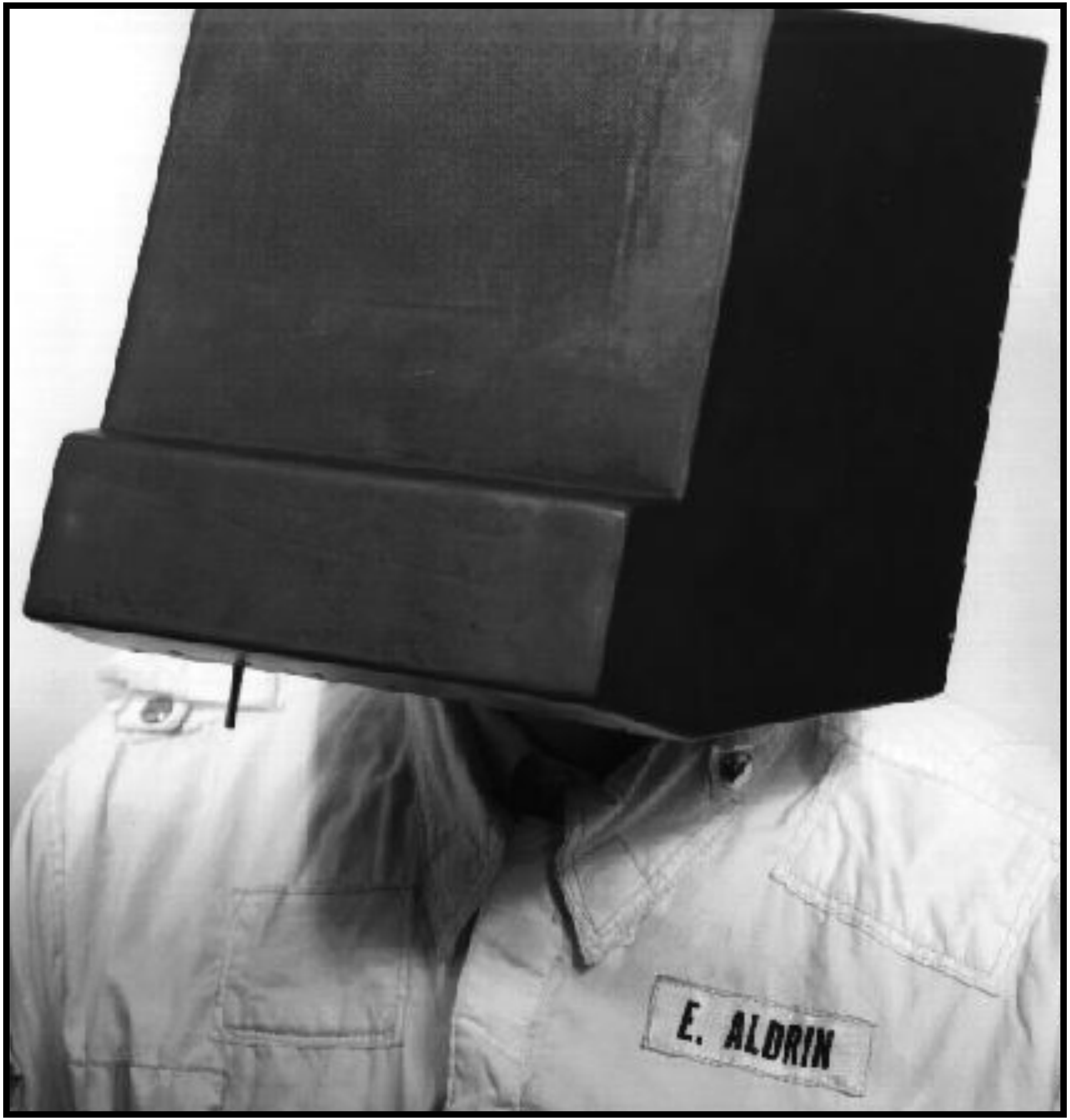
We Live in the Outer Atmosphere of a Highly Variable Magnetic Star…

Understanding Sun-Earth Connections



Radiation in Past and Current Spaceflight Operations: Apollo-Era

- Apollo-era cosmic ray detection and human effects experiment
- Buzz Aldrin’s head-gear was used for assessing cosmic ray effects in the human head
- This is what the astronaut did who rode around the Moon in the CM while the others cavorted on the surface



Radiation Measurements for Lunar Operations

Eddie Semones
Space Radiation Analysis Group
Johnson Space Center

Purpose of Radiation Monitoring

- Active radiation monitoring is the primary means for controlling/evaluating crew exposure during missions.
- Provides Flight Control Team insight to radiation environment that could cause acute medical effects that would impact success of mission.
- Provides data for post mission analysis of incurred risk due to crew during mission.
  - Forms database of exposure conditions for risk analysis supporting future missions and crew medical record.

Radiation Monitoring History

- All human spaceflight programs have had radiation monitoring hardware
  - Mercury, Gemini, Apollo, Shuttle, ISS

- Typical suite included passive monitoring of crew/area locations and active monitoring with charged particle spectrometers and dosimeters (ion chambers/tissue equivalent proportional counters).

- Improvements have been made in functionality and performance of the types of monitoring, but physics/sensor solutions are similar today.

Apollo Radiation Monitoring (active)

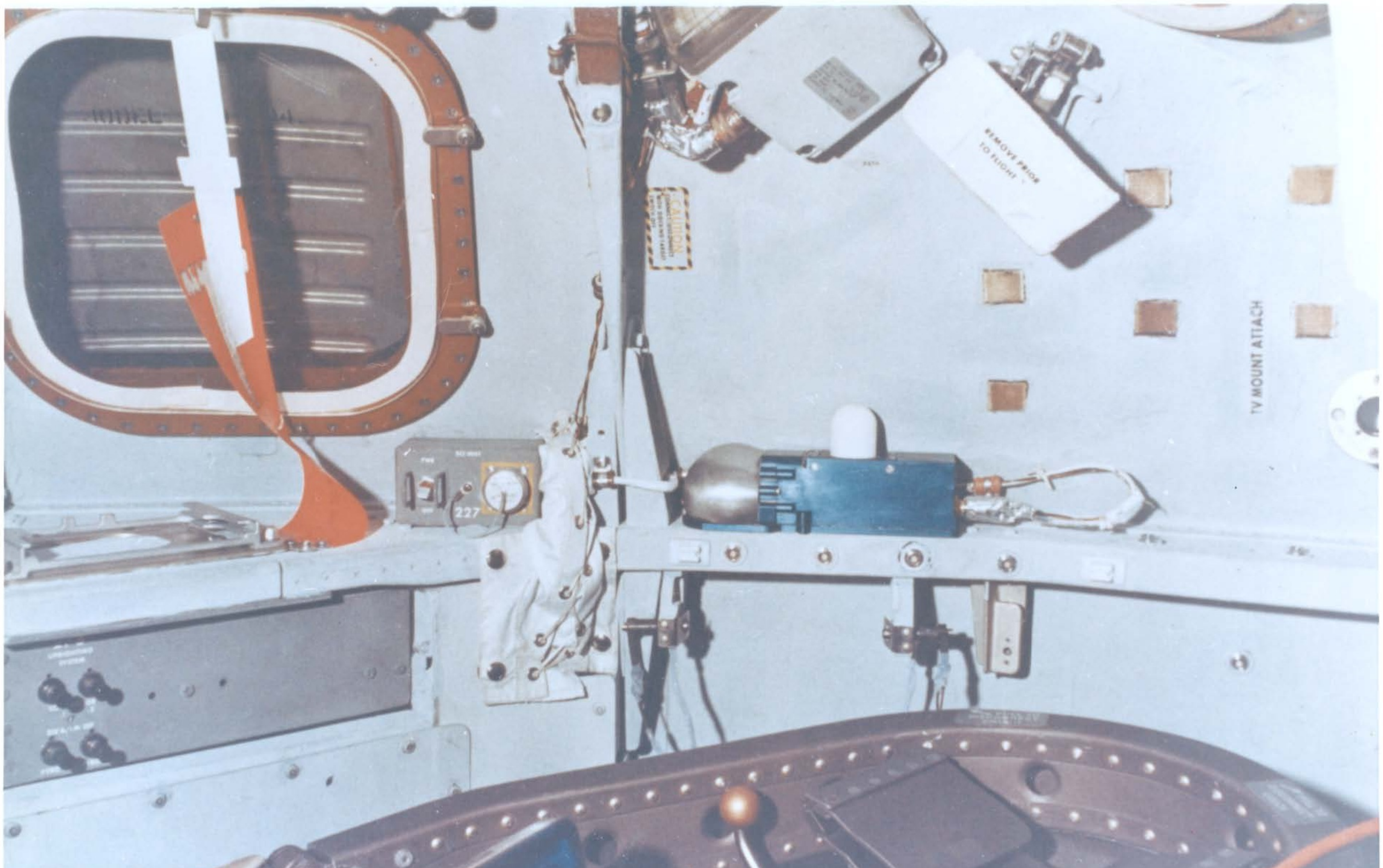
- Nuclear Particle Detection System (NPDS)
  - 5 lbs, 83 in^3
- Van Allen Belt Dosimeter (VABD)
  - 4 lbs, 60 in^3
- Radiation Survey Meter (RSM)
  - 1.5 lbs, 27 in^3
- Personal Radiation Dosimeter
  - 0.44 lbs, 5.4 in^3 (3X)
  - 2 units integrated into area monitor

Total = 11.8 lbs,185 in^3

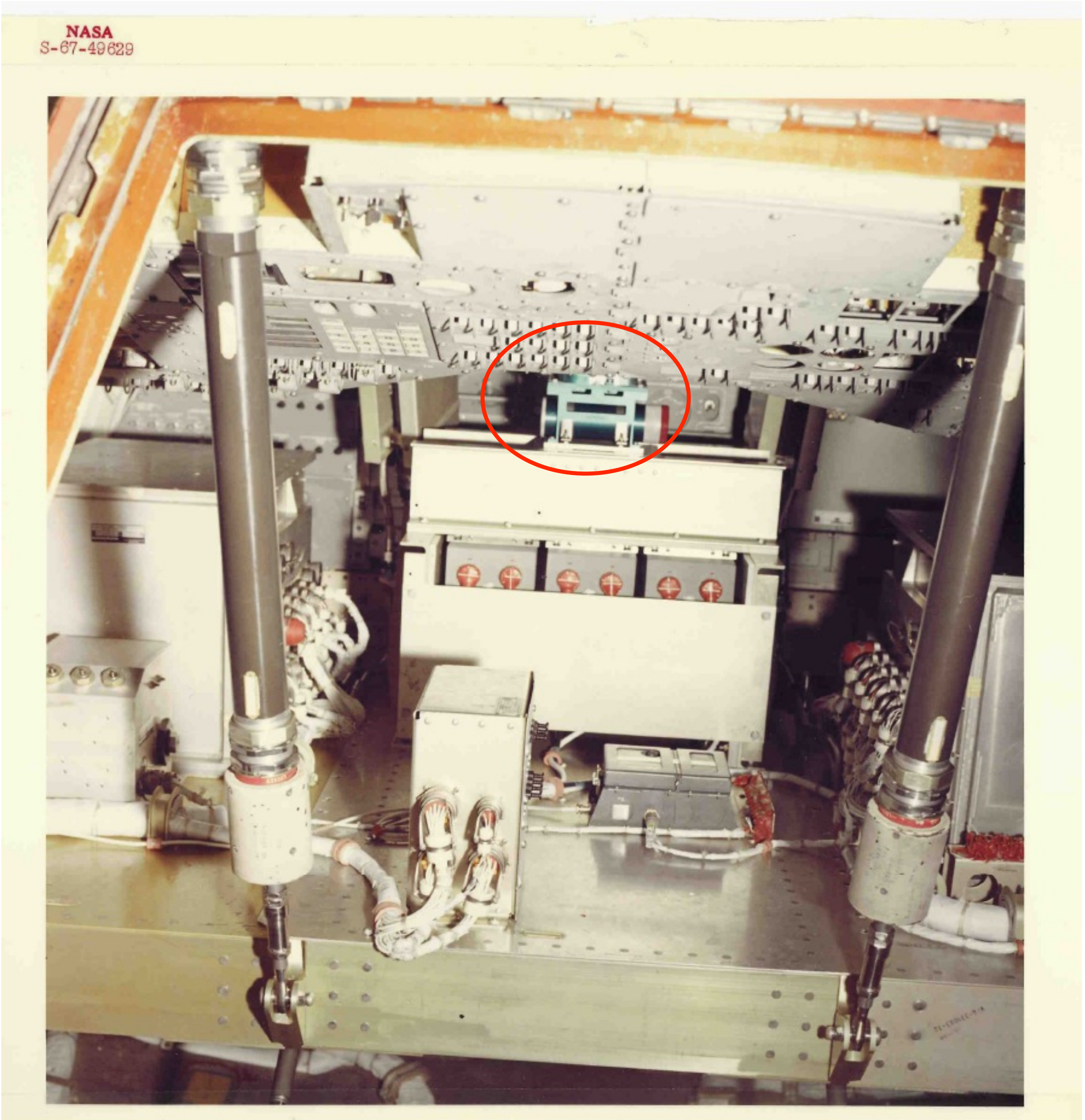
NOTE: Additional passive hardware and flight specific measurements were conducted.

NASA-S-69-455

VAN ALLEN BELT DOSIMETER



Personnel Radiation Dosimeter and Passive Dosimeter Stack



Personal Radiation Dosimeter (Class I)

Radiation in Past and Current Spaceflight Operations: Shuttle/ISS

Radiation Measurement Requirements for ISS

3.2.7.2.4 Absorbed Dose Monitoring

The vehicle shall provide an omnidirectional, portable system that can continuously measure and record the absorbed dose from charged particles with linear energy transfer 0.2 to 1000 keV/micrometer, as a function of time, at a tissue depth of >=2 mm. [HS3089]

3.2.7.2.3 Dose Equivalent Monitoring

The vehicle shall provide an omnidirectional, portable system that can continuously measure and record the dose equivalent from charged particles with linear energy transfer 0.2 to 1000 keV/micrometer, as a function of time, at a tissue depth of >=2 mm. [HS3088]

Both requirements can be met by a single instrument currently are on ISS

Measurement Requirements (continued)

3.2.7.2.1 Charged Particle Monitoring

The vehicle shall continuously measure and record the external fluence of particles of Z<3, in the energy range 30 to 300 MeV/nucleon and particles of 3 ≤ Z ≤ 26, in the energy range 100 to 400 MeV/nucleon and integral fluence measurement at higher energies, as a function of energy and time, from a monitoring location that ensures an unobstructed free space full-angle field of view 1.1345 Radians (65 degrees) (TBR-006-023) or greater. [HS3086]

Provides different capability than HS3088-3099.
Not redundant.

Radiation and Future Spaceflight Operations: Moon, Mars, and Beyond

ConOps Overview

- **Operational awareness during mission**
  - **Alarming**
  - **Tracking and trending of mission exposure**
  - **Flight rules**
- **Solar particle event alarming and characterization**
  - **High exposure rates in the CEV possible**
  - **Crews most vulnerable to acute effects during lunar phases**
- **Dynamic, unpredictable radiation environment**
  - **No rapid crew return**
  - **Uncertain modeling capability drives need for monitoring**
- **Crew exposure records (post mission)**
  - **Radiation Exposure Histories**
  - **Crew selection – re-flight**
  - **Measurement of primary fields allows for changes in radiation protection philosophy over time**

In-situ radiation monitoring is the main input to operations

CEV ConOps

- Omnidirectional system will be used to provide point measurements of the ambient exposure quantities (absorbed dose/dose equivalent). Flight Rules and Mission limits will be based on these quantities.
  - During quiet conditions the measurement will be made at a fixed location in habitable volume.
  - During solar particle events crew would be survey the habitable volume at various locations to determine lowest dose rate areas.

- Charged Particle Monitor will be used to characterize the primary charged particle radiation environment that can be used to calculate doses at any location within CEV-> human body. Omnidirectional system cannot be used for this purpose.
  - This includes galactic cosmic rays (GCR), trapped belt, and SPE radiation field measurements. This provides a complete record of crew exposure for the duration of the mission.

CEV ConOps

- SPE Monitoring
  - Events can last several days
  - The intensity of the radiation field can change orders of magnitude in periods of time less than 1 hour
  - Ground following/processing of the telemetered data is required to enable analyses utilized in the decision making process
  - Event could occur/continue during sleep periods
    - Decision to wake up crew would be aided by on ground analysis of cyclic data
  - Event could occur during critical phase of mission that would limit crew involvement and would require ground only evaluation
  - Local display/alarm will be available
    - For times when crew is LOS, alarm would allow for autonomous action by crew
- TLI (Trans Lunar Injection)
  - For incomplete TLI burn, CEV could be in orbit that is in an intense region of the trapped radiation belts. High dose rates would be possible
  - Crew would need to survey habitable volume to determine impacts

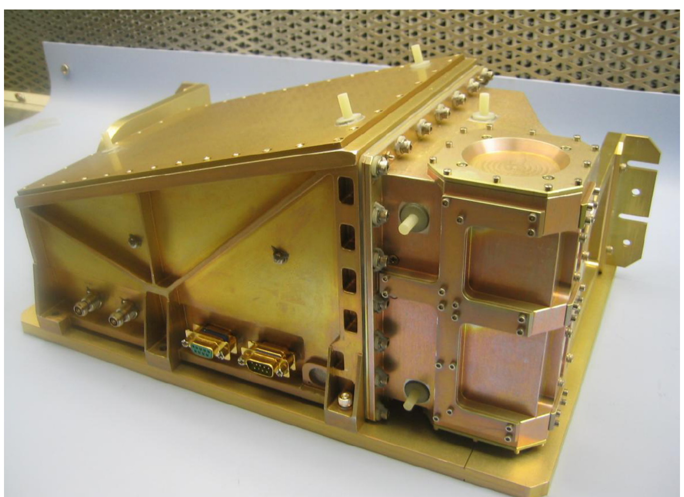
Characterizing the Deep Space Radiation Environment: Observations

CRaTER Instrument Summary

Cosmic Ray Telescope for the Effects of Radiation (CRaTER) Investigation

(Spence et al., SSR, 2010)

"Luna Ut Nos Animalia Tueri Experiri Possimus"
("In order that we might be able to protect and make trial of living things on the Moon")

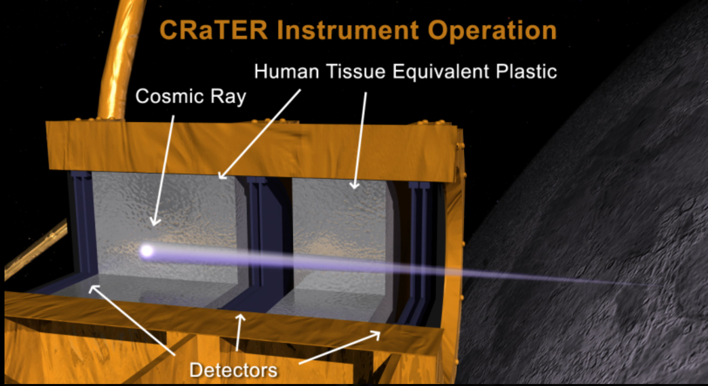


ESMD Measurement Goals

To characterize the global lunar radiation environment and its biological impacts

- Six-element, solid-state detector and tissue-equivalent plastic (TEP) telescope
- Sensitive to cosmic ray particles with energies greater than ~10 MeV, primarily protons, but also heavy ions, electrons, and neutrons
  - *Galactic cosmic rays – GCRs*
  - *Solar energetic particles– SEPs*
- Measure spectrum of Linear Energy Transfer (LET = energy per unit path length deposited by cosmic rays as they pass through or stop in matter) behind different amounts of TEP
- Accurate LET spectrum is missing link needed to constrain radiation transport models and radiation biology to aid safe exploration

CRaTER Concept of Operations



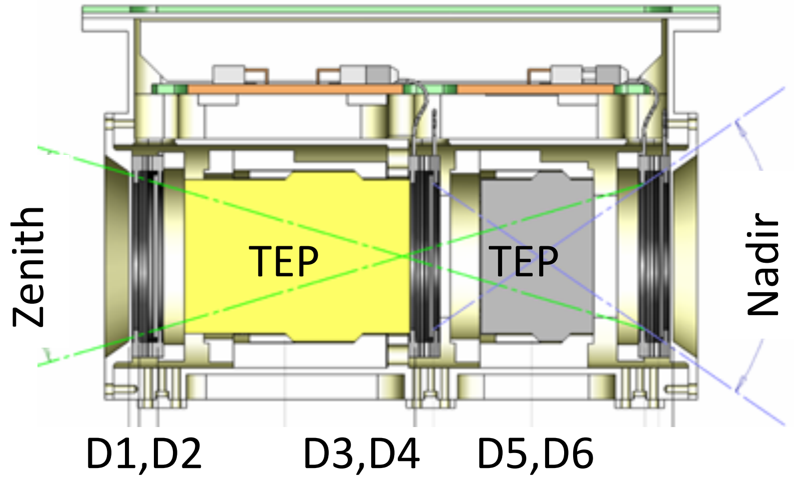
CRaTER Performance Specifications

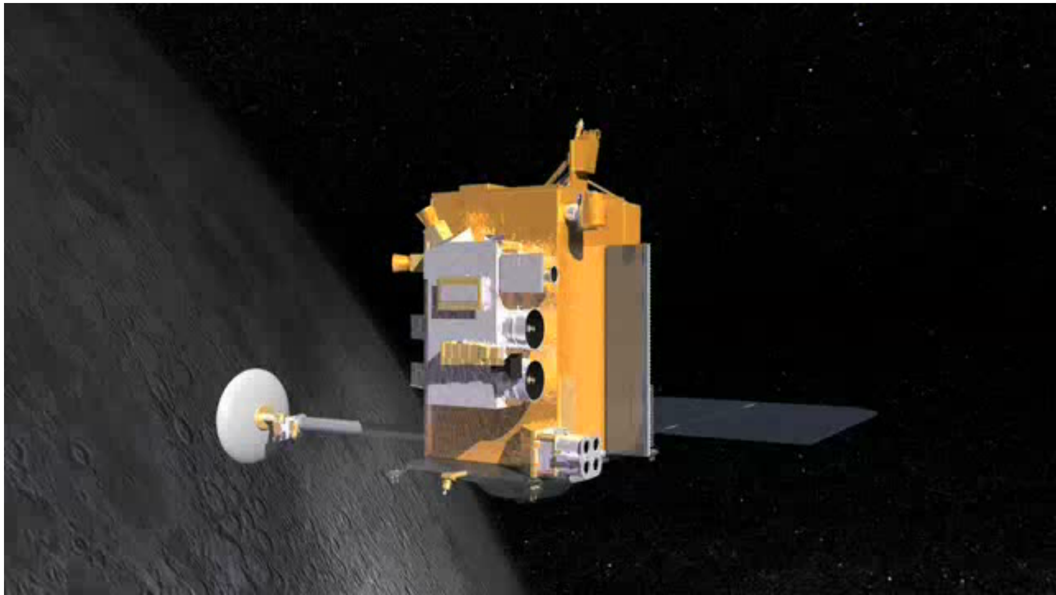
CRaTER's design has thick/thin detector pairs at 3 points through TEP:

- 3 "low LET" thick detectors (D2,D4,D6)- 200 keV to 100 MeV
- 3 "high LET" thin detectors (D1,D3,D5) - 2 MeV to >300 MeV
- **Energy resolution <0.5%** (at max energy); GF ~1 cm^2-sr (typical)

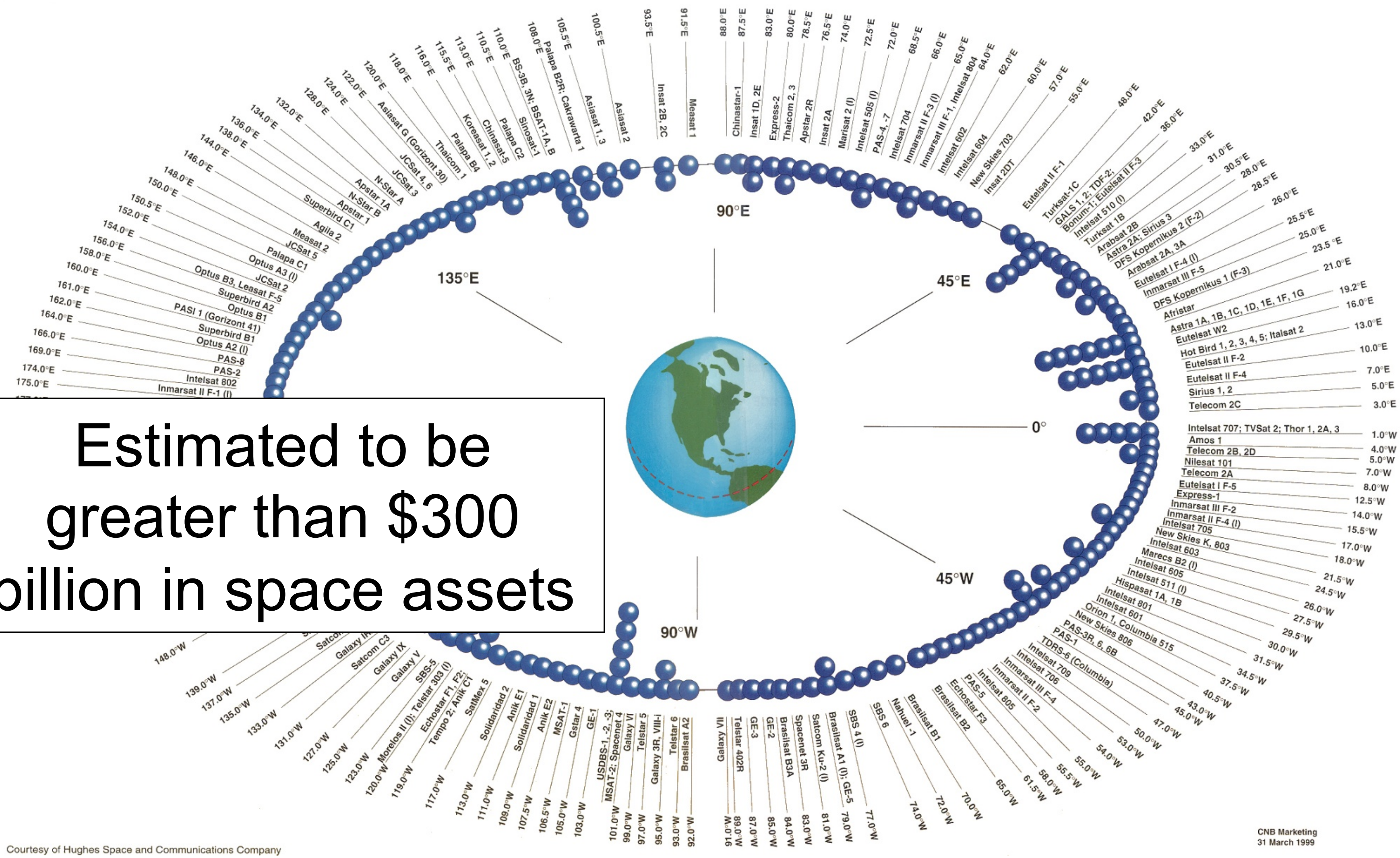
This corresponds to:

- LET from **0.2 keV/μ to 2 MeV/ μ**
- Excellent spectral overlap in the **100 kev/μ** range (key range for RBEs)
- 100 kbps data rate – telemeter every pulse height in all six detectors whenever any one detector passes its detection threshold (i.e., no inflight coincidence logic required as is typical with most experiments)





Civilian Spacecraft at Geostationary Orbit

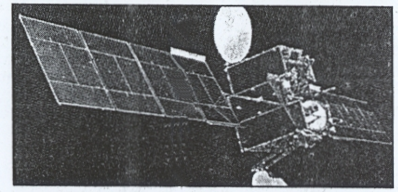


Estimated to be greater than $300 billion in space assets

The Hamilton Spectator

Established 1846 • Mon-Fri 47¢ + 3¢ GST

P-ANIK!



High-tech chaos as satellites spin out of control

Plug pulled on phones, TV, radio, papers

OTTAWA — Telesat Canada was facing some tough questions today as it tries to explain how its two main communication satellites tumbled out of control, interrupting TV, radio, newspaper and telephone signals across the country.

After struggling for more than eight hours to bring the wobbly Anik E-1 under control, Telesat technicians thought they had the problem licked late yesterday.

The were only half right.

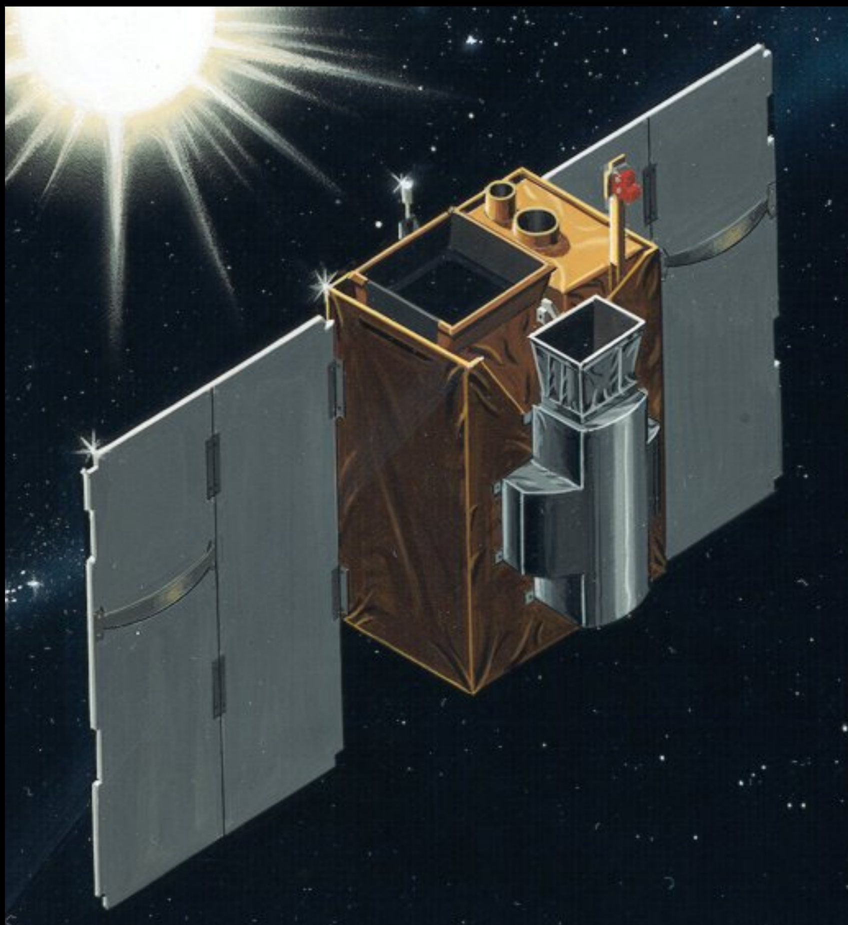
Shortly after 9 p.m. EST, as Anik E-1 settled back into position, Telesat's primary broadcasting satellite, Anik E-2, also got a bad case of the shakes.

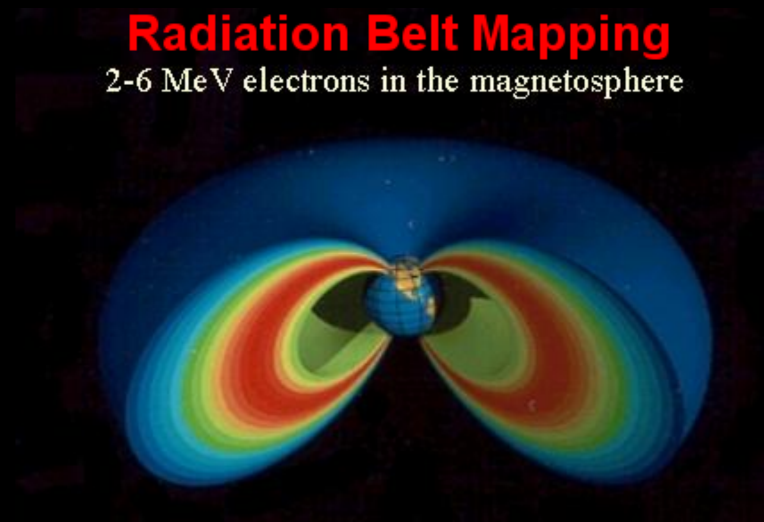
CBC Newsworld and other national specialty cable channels, including MuchMusic, TSN, Vision and the Weather Channel, were knocked off the air. Partial service, with signals carried by fibre-optic cable, was later restored in some major centres, including Toronto.

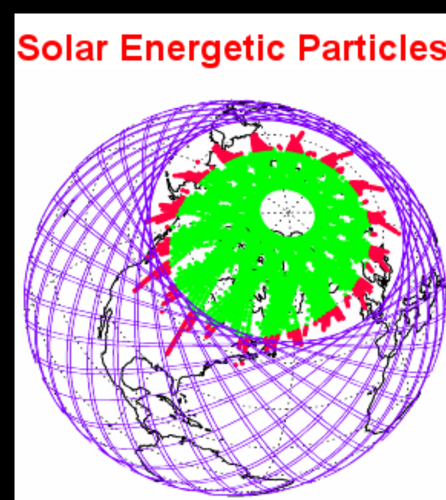
In Hamilton local cable companies and police communications were unaffected. The Mt. Hope weather office had minor disruptions.

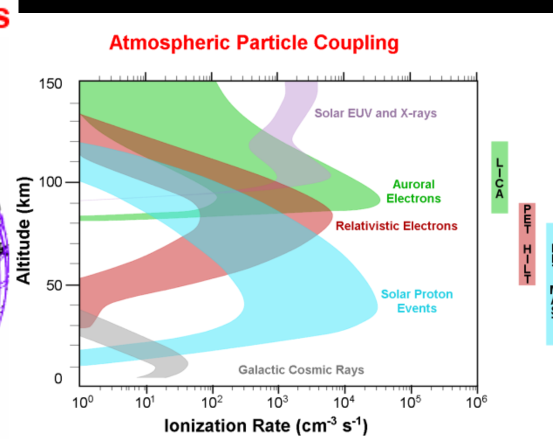
"We don't know how it was brought about," said Chris Frank, Telesat's director of public affairs.

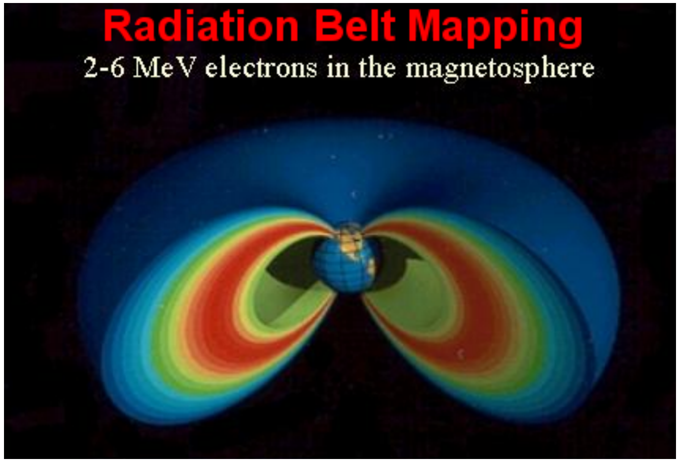
The Solar, Anomalous, and Magnetospheric Particle Explorer: SAMPEX

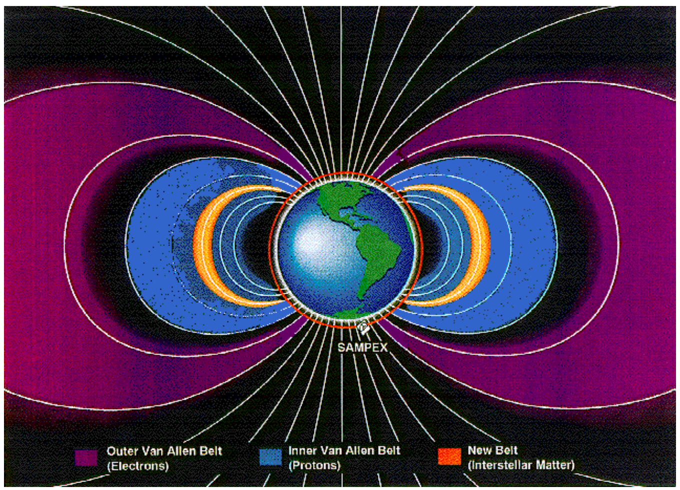




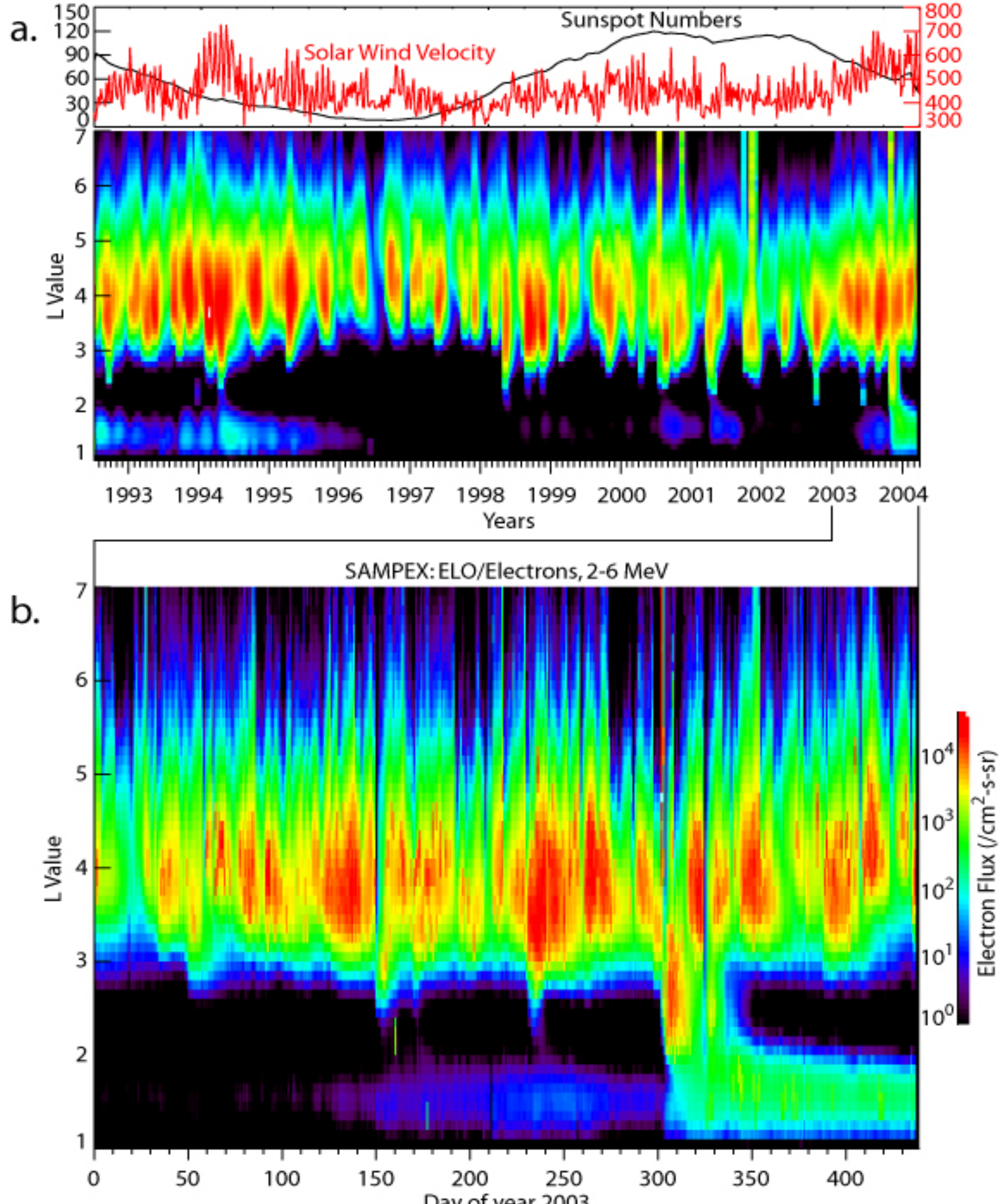








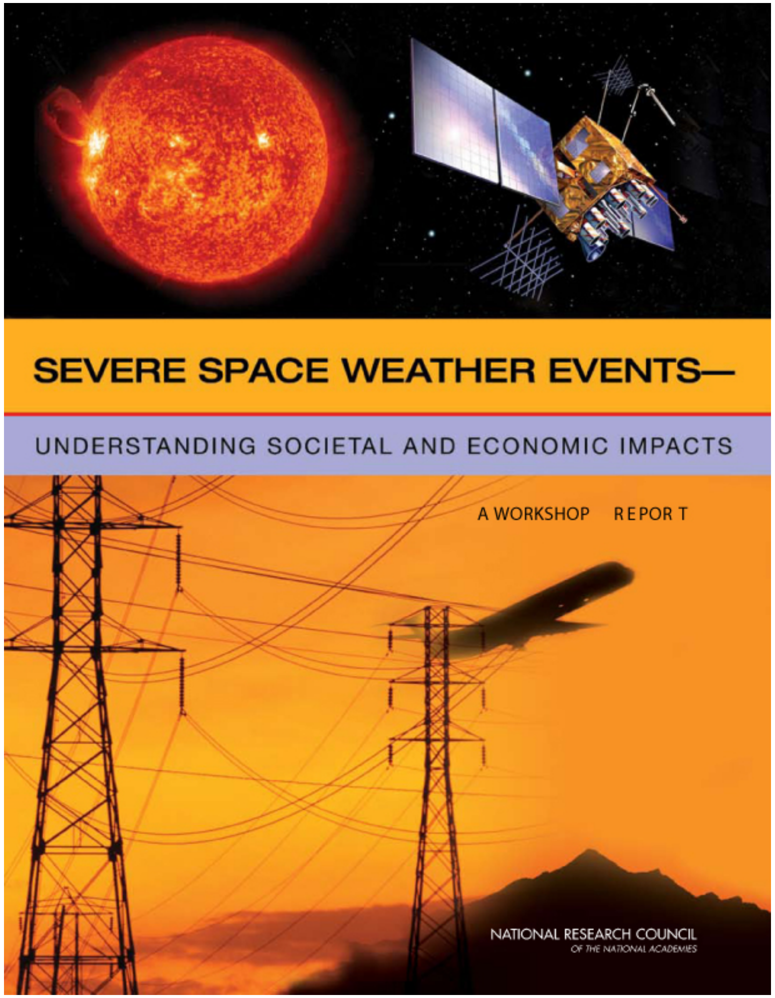
The SAMPEX mission played a key role in radiation belt studies



[Baker et al.,*Nature*, 2004]

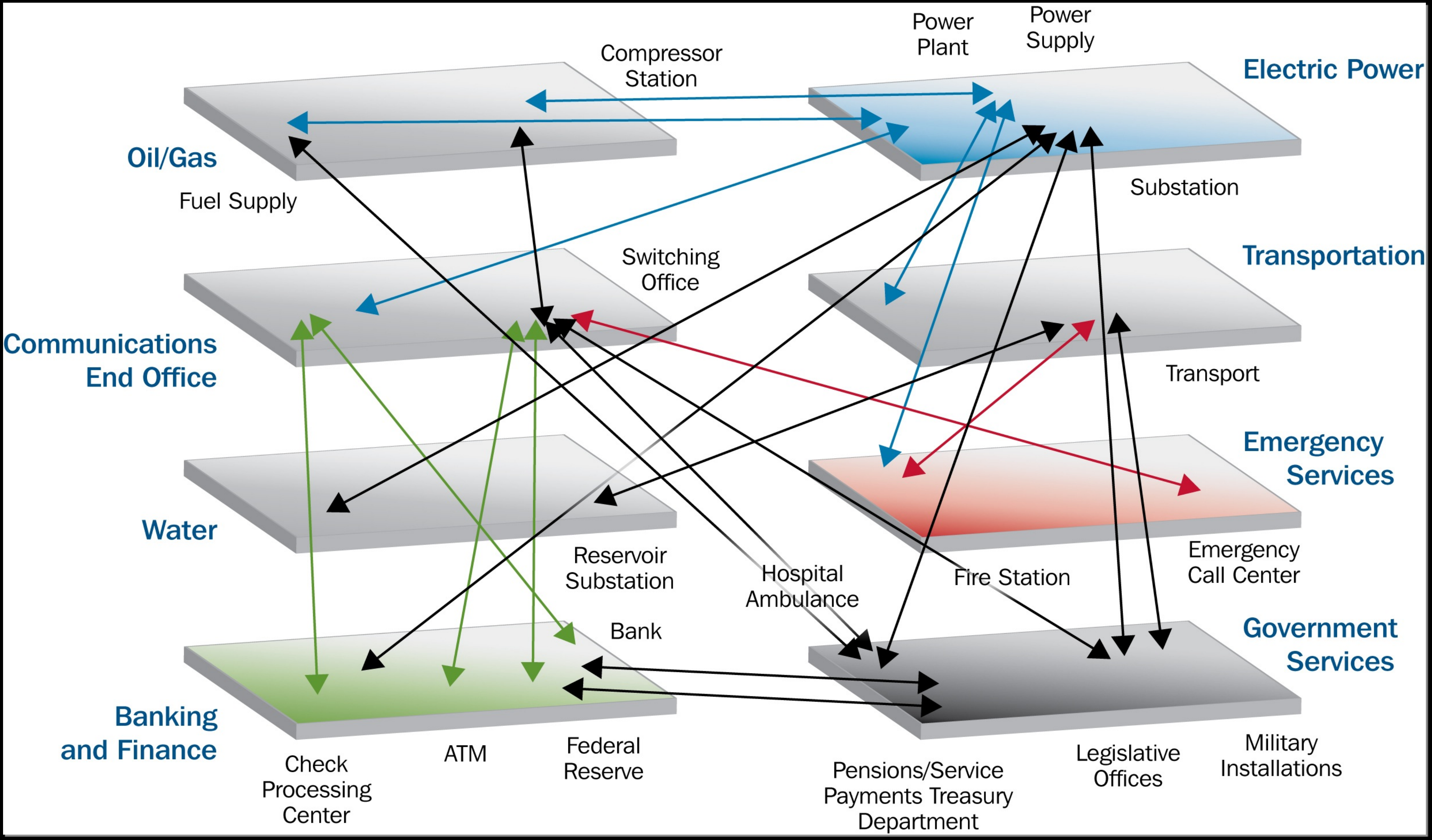
The Societal and Economic Impacts of Severe Space Weather Events

- *May 22-23, 2008 in DC*
- *Approximately 80 attendees from academia, industry, government, and industry associations*
  - **Association reps aggregated data and helped avoid concerns about proprietary or competition-sensitive data**
- *Analyses in specific areas; e.g., GPS, power industry, aviation, military systems, human and robotic exploration beyond low-Earth orbit*
- *Econometric analysis of value of improved SpaceWx forecasts*



[http://www.nap.edu/catalog.php?record_id=12507]

The Interdependencies of Society



Electrical Power Grid…

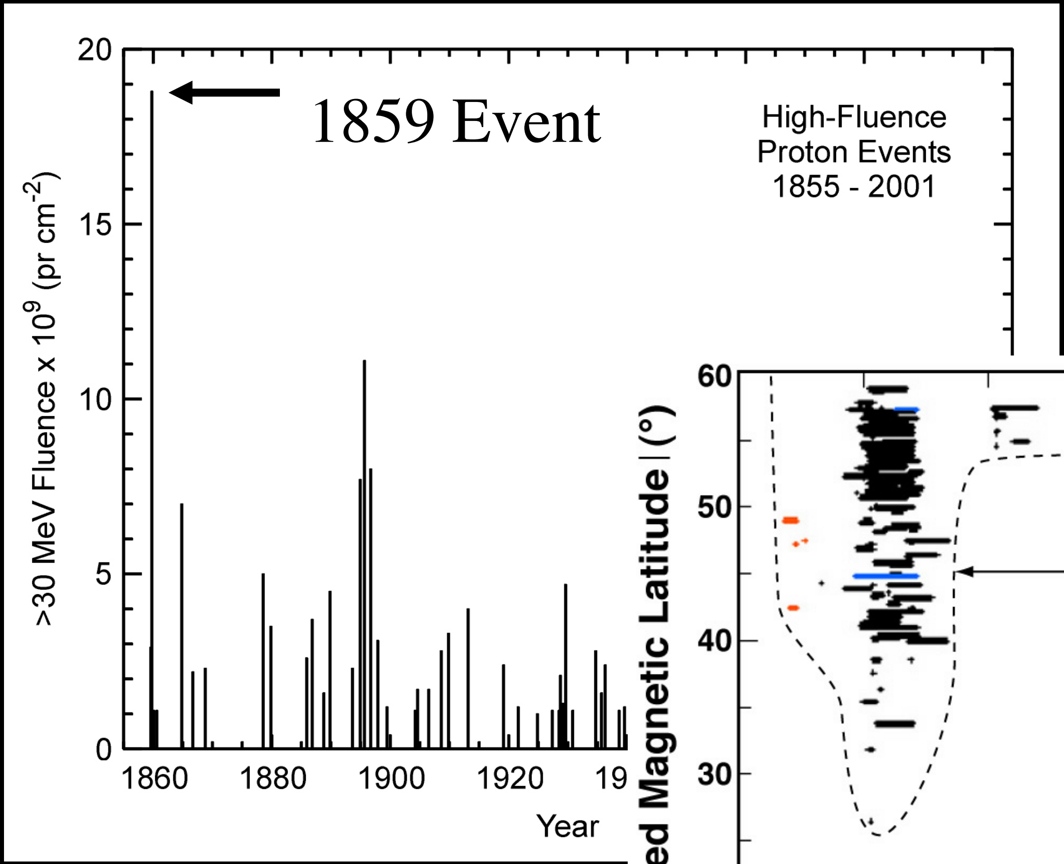
The grid is becoming increasingly vulnerable to space weather events *Future Directions in Satellite-derived Weather and Climate Information for the Electric Energy Industry – Workshop Report Jun 2004*

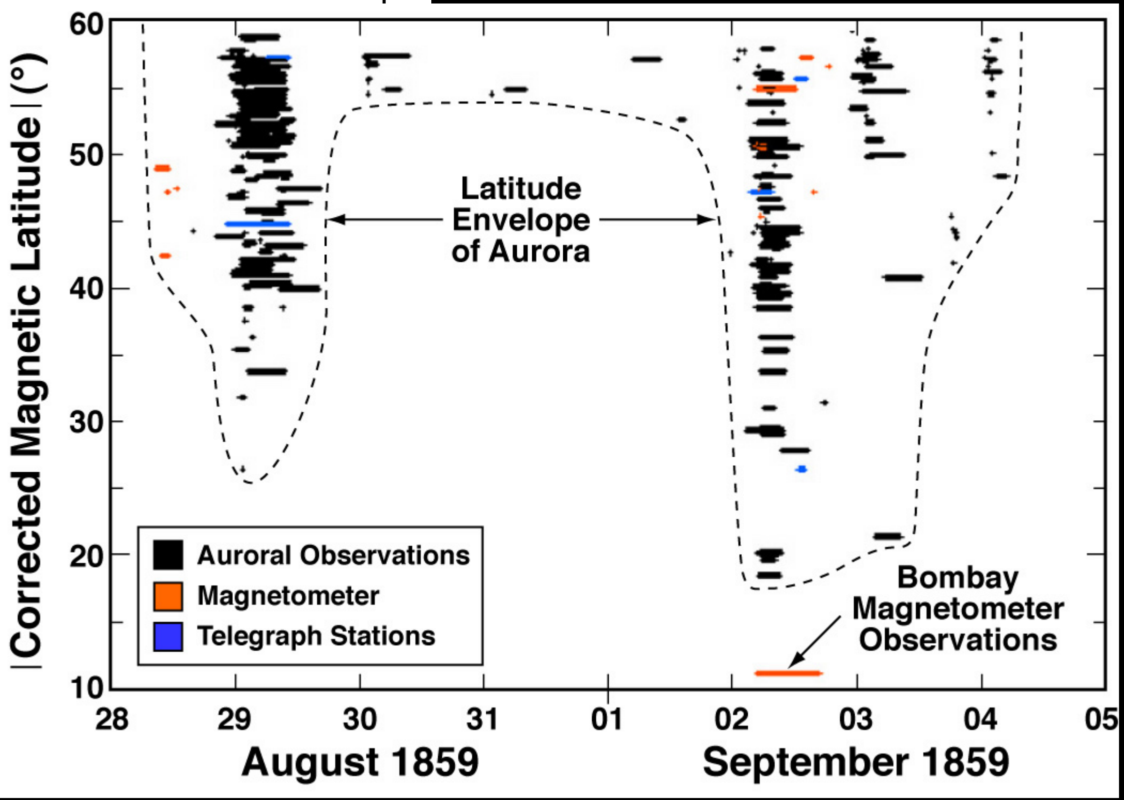
"…blackouts could exceed even that of the very large blackout that occurred in August 14, 2003. And there is no part of the U.S. power grid that is immune to this… we could impact over 100 million population in the worst case scenario." John Kappenman - before U.S. House Subcommittee on Environment, Technology & Standards Subcommittee Hearing on *"What is Space Weather and Who Should Forecast It?"*

Transformer winding failure

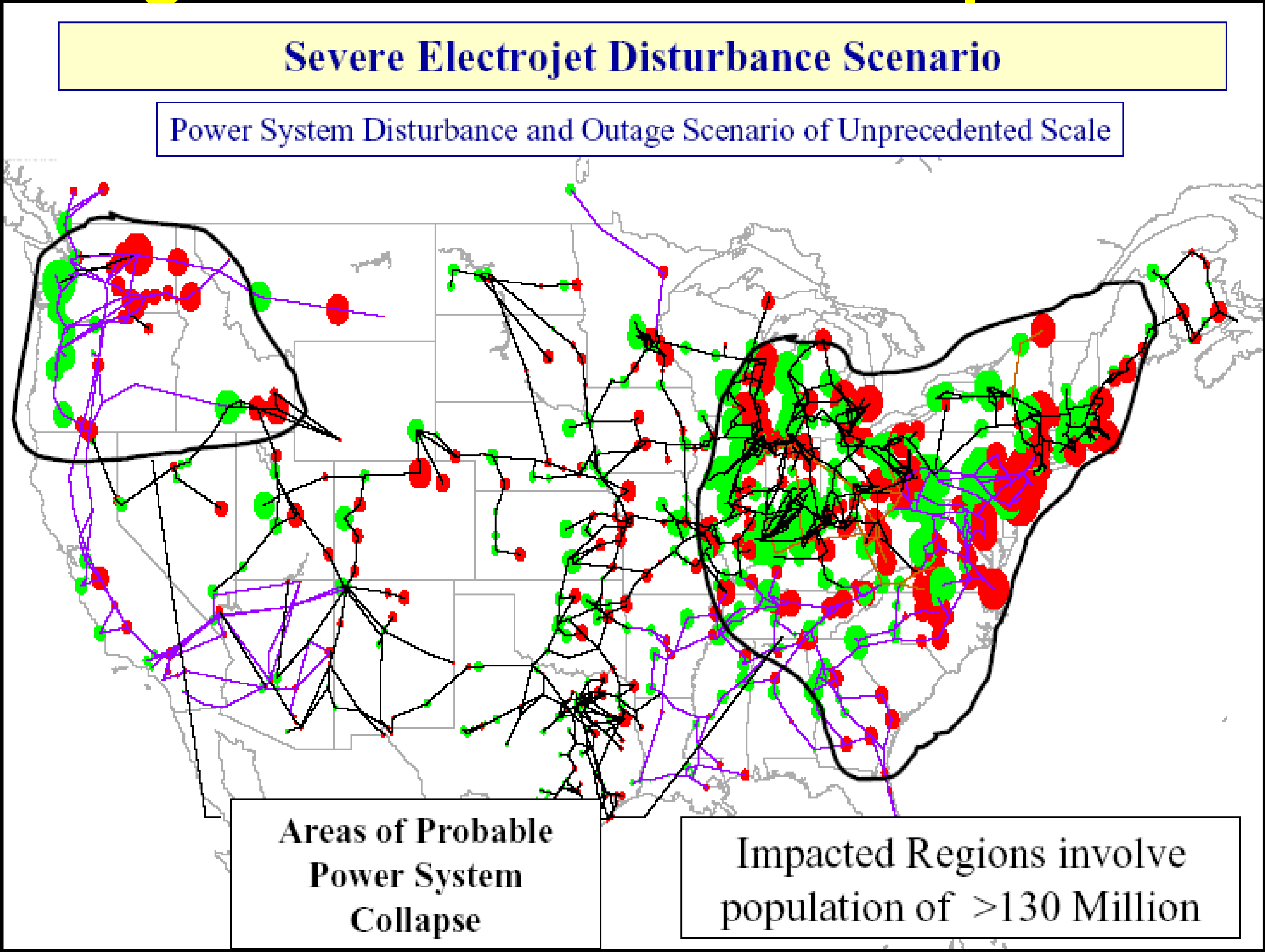
Transformer exit lead overheating

Extreme Event: Carrington 1859





Regional Power Grid Disruptions

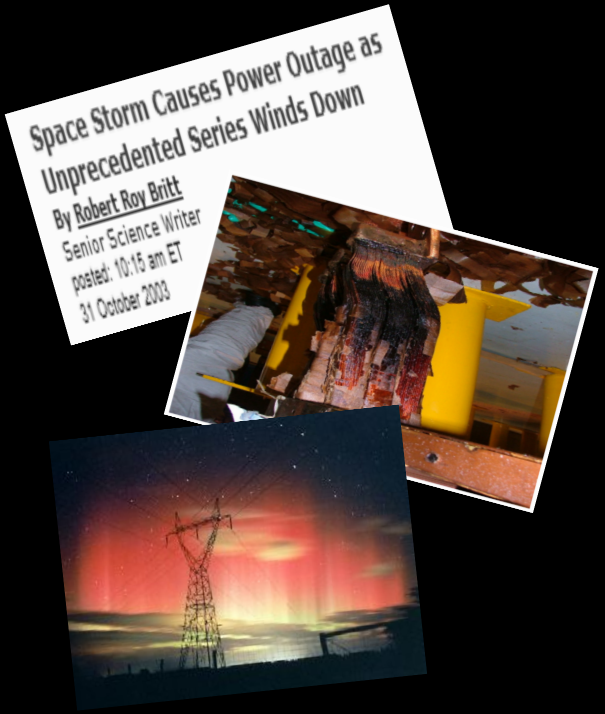


Low Frequency/High Consequence:

Increasing Power Grid Vulnerability

"The grid is becoming increasingly vulnerable to space weather events"

Future Directions in Satellite-derived Weather and Climate Information for the Electric Energy Industry – Workshop Report Jun 2004

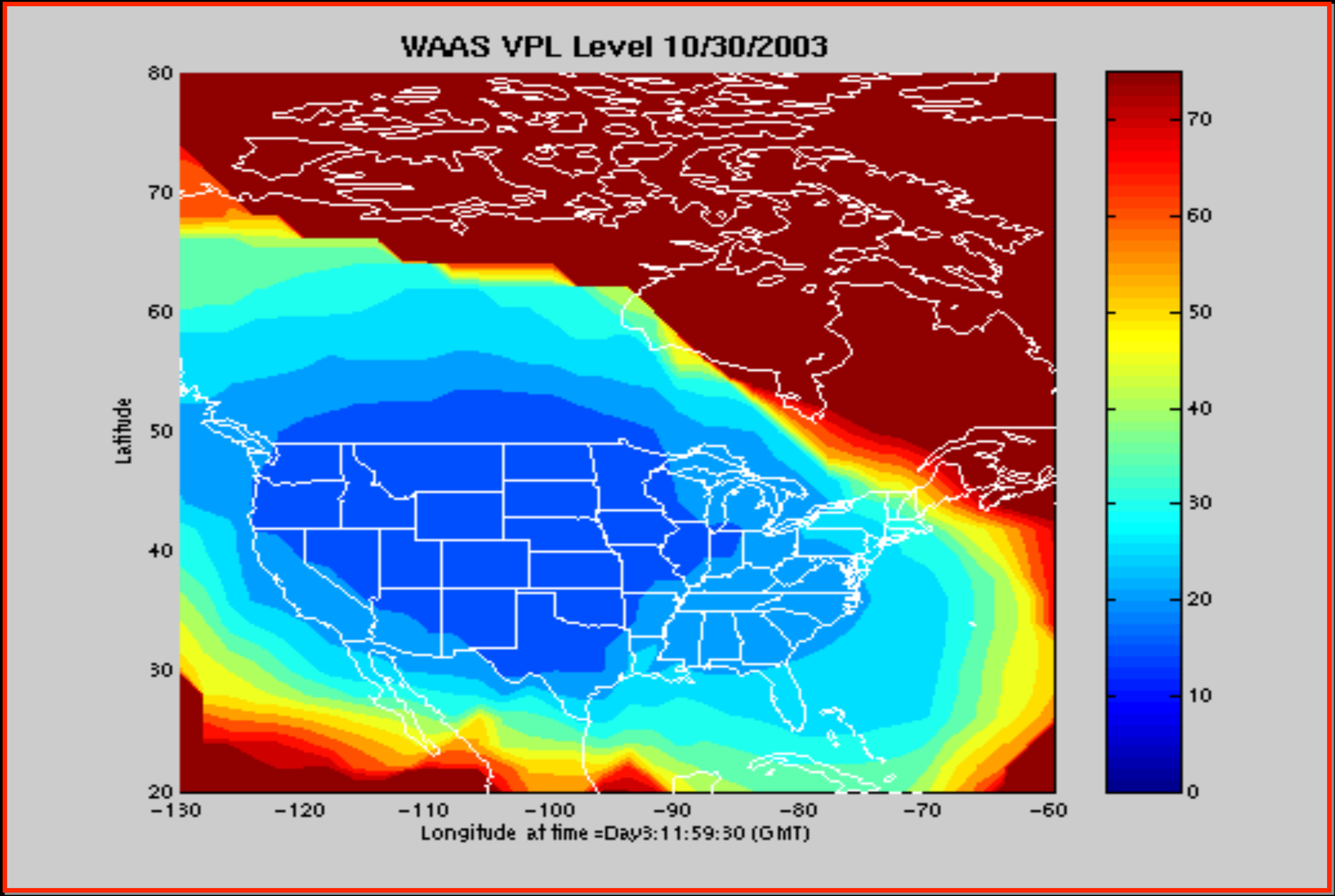


$1-2 trillion | **Potential loss due to widespread power grid Blackout following severe geomagnetic storm**

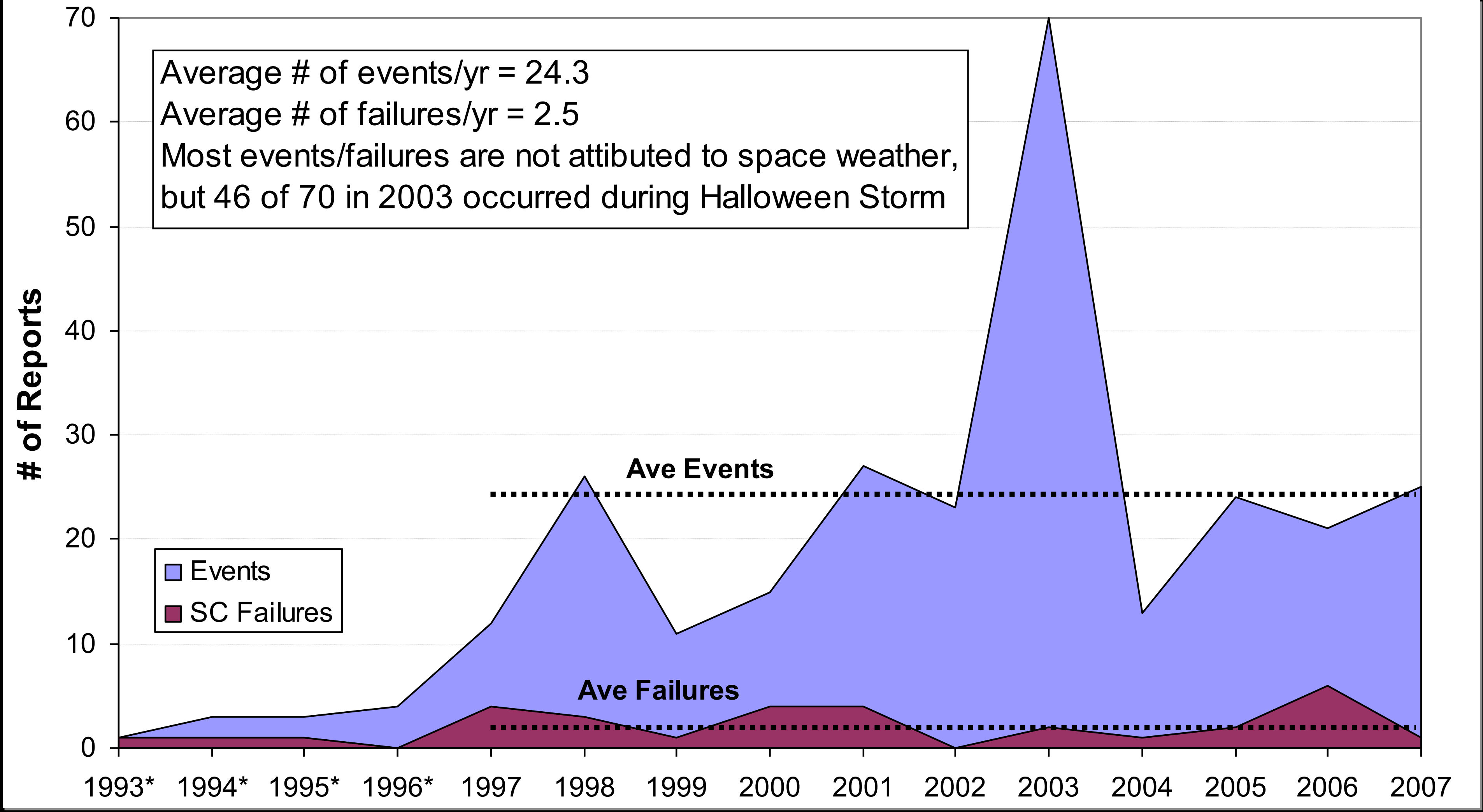
4-10 years | **Recovery time from a widespread power grid Blackout following severe geomagnetic storm**

Source: National Academy Workshop on the Societal and Economic Impacts of Severe Space Weather Events held in Washington, D.C., May 2008.

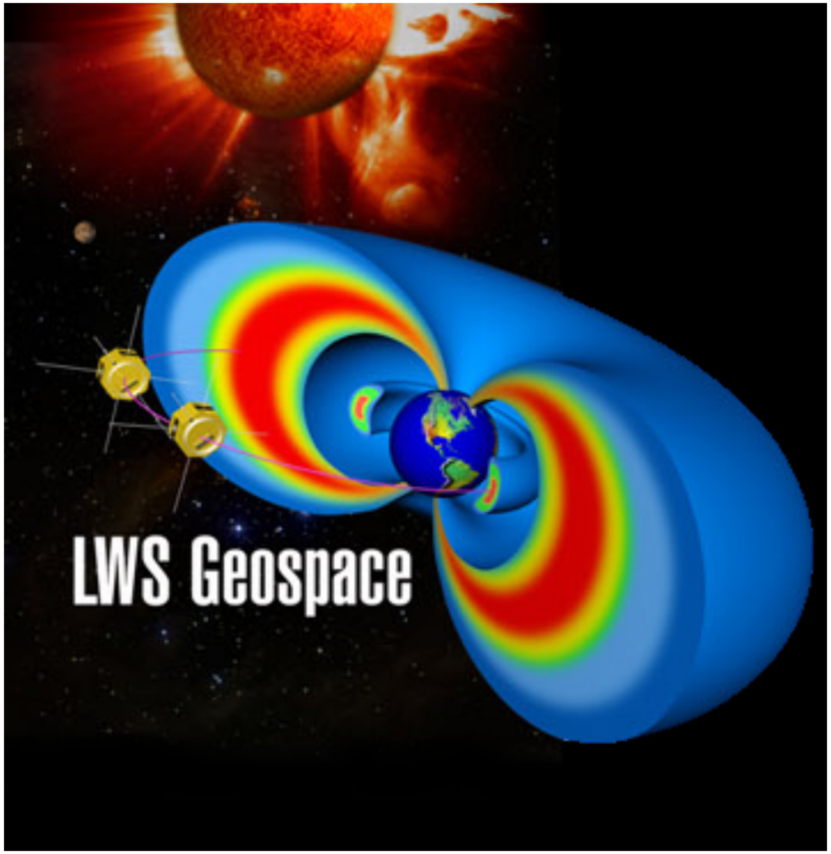
Wide Area Augmentation System (October 2003)



Spacecraft Anomalies and Failures



RBSP Science Definition Report



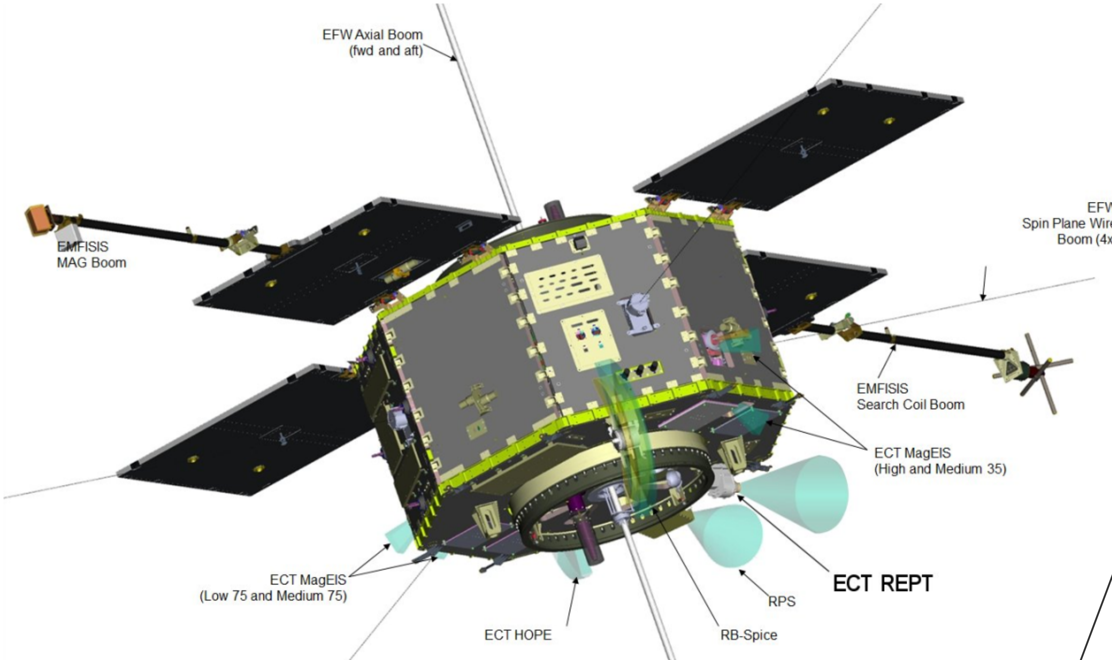
Radiation Belt Storm Probes (RBSP) constellation

Mission Objectives:

1. Differentiate among competing processes affecting the acceleration and loss of radiation belt electrons;
2. Understand the creation and decay of new radiation belts;
3. Quantify the relative contribution of adiabatic and nonadiabatic processes;
4. Understand the role of “seed” or source populations; and
5. Develop and validate specification models of the radiation belts.

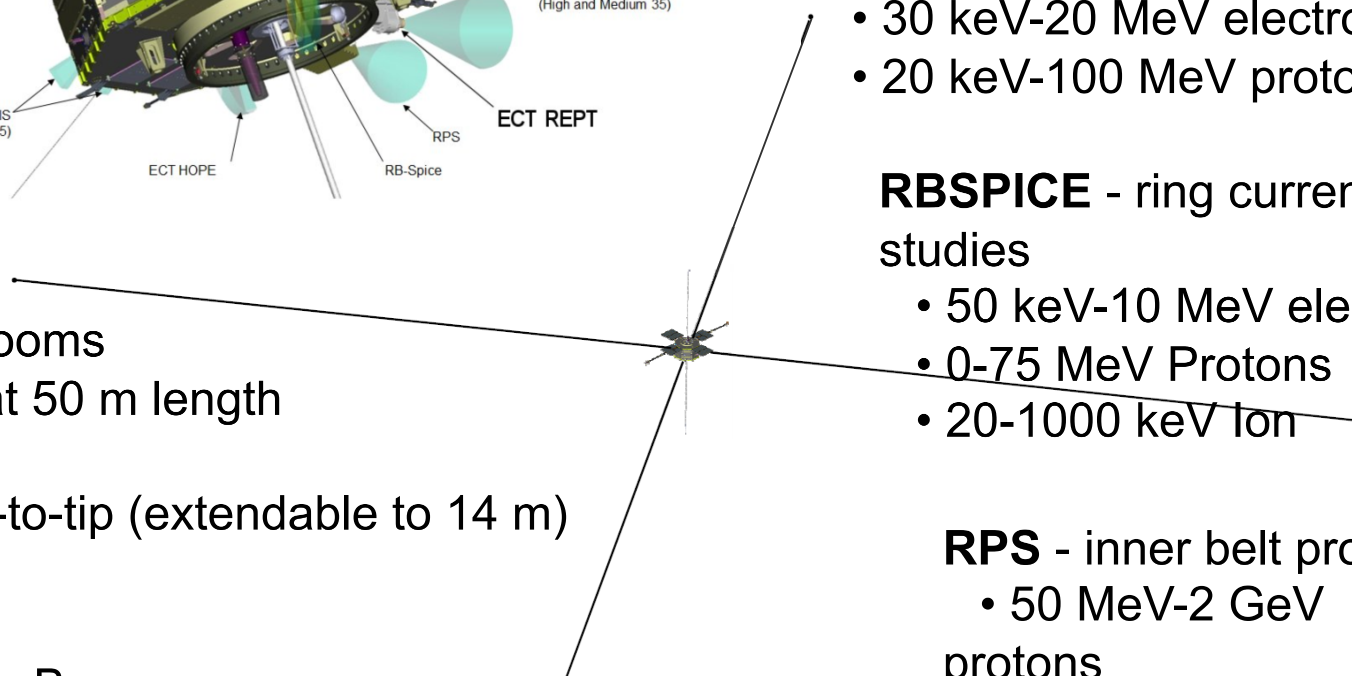
RBSP addresses the scientific and programmatic goals of the NASA Living With a Star program.

Van Allen Probes Spacecraft & Payload



ECT Suite - HOPE , MagEIS, REPT
(Energetic Particle, Composition, and Thermal Plasma)

- 20 eV-45 keV He+, O+, p+, e-
- 30 keV-20 MeV electrons
- 20 keV-100 MeV protons



RBSPICE - ring current studies

- 50 keV-10 MeV electrons
- 0-75 MeV Protons
- 20-1000 keV Ion

RPS - inner belt protons

- 50 MeV-2 GeV protons

EFW
Spin Plane Booms

- all four at 50 m length

Axial Booms

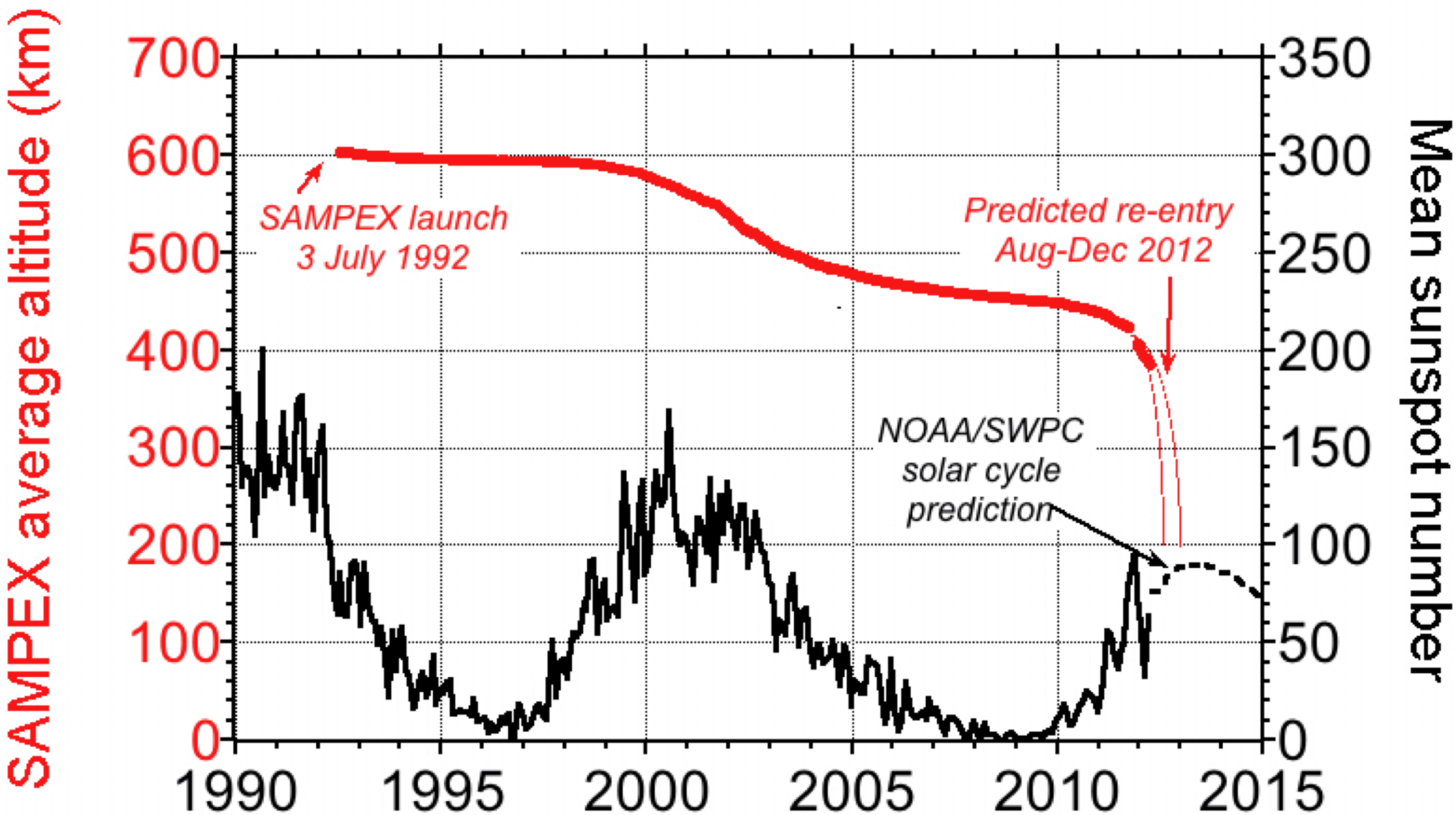
- 12 m tip-to-tip (extendable to 14 m)

EMFISIS
Magnetometer Booms

- Extend 3 m from edge of spacecraft

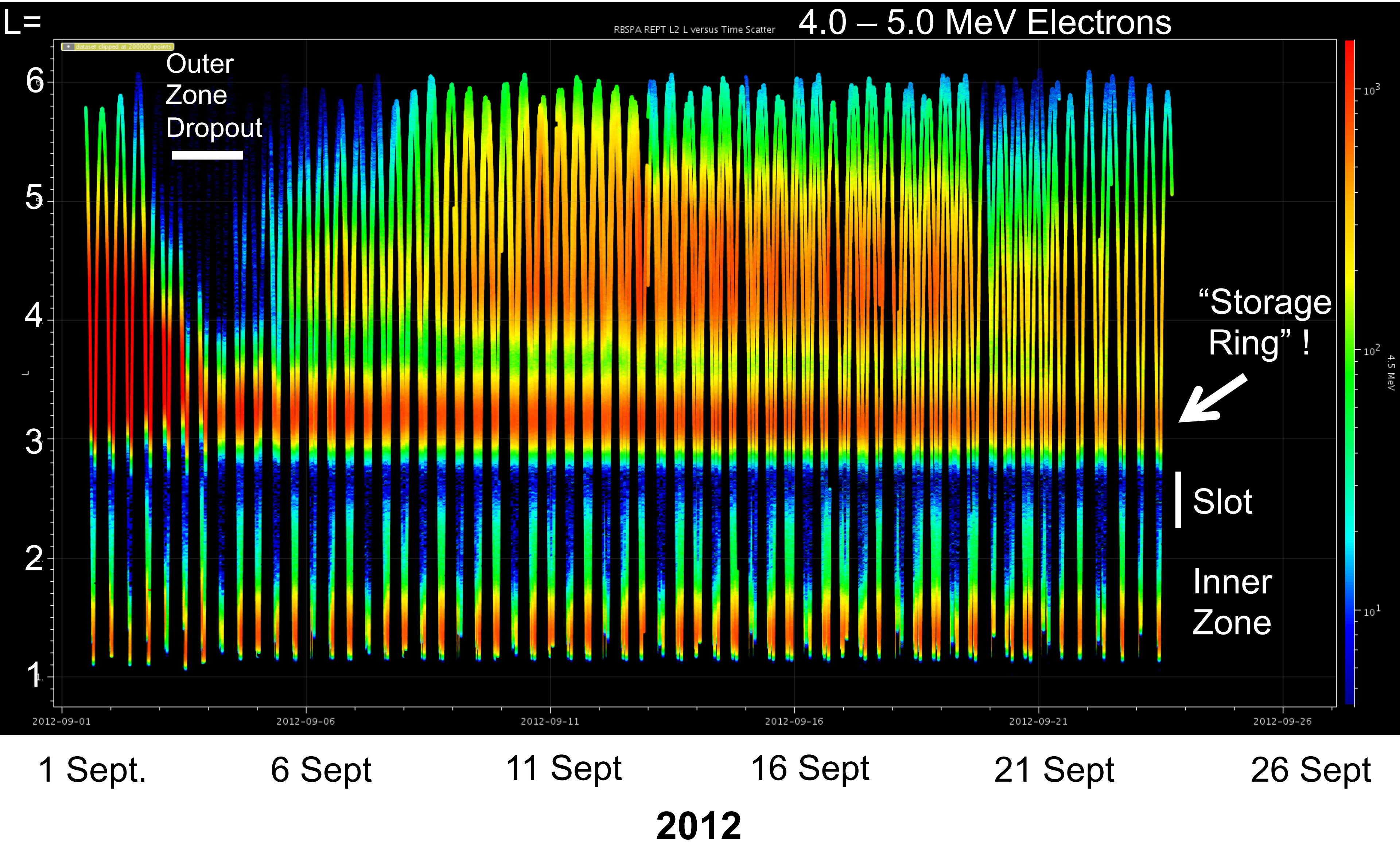
RBSP Launch—30 August 2012

Demise of SAMPEX

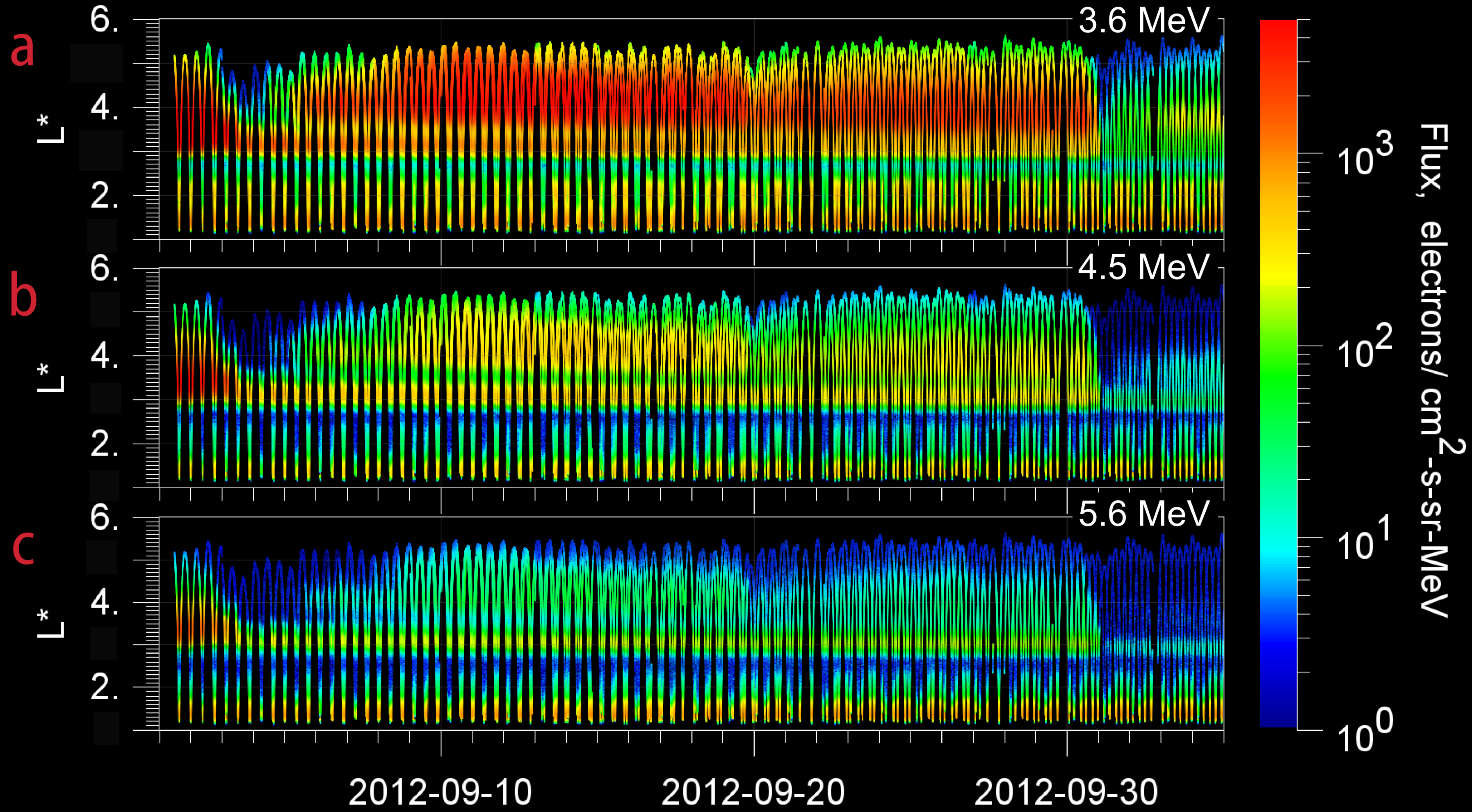


Re-entry on 13 November 2012

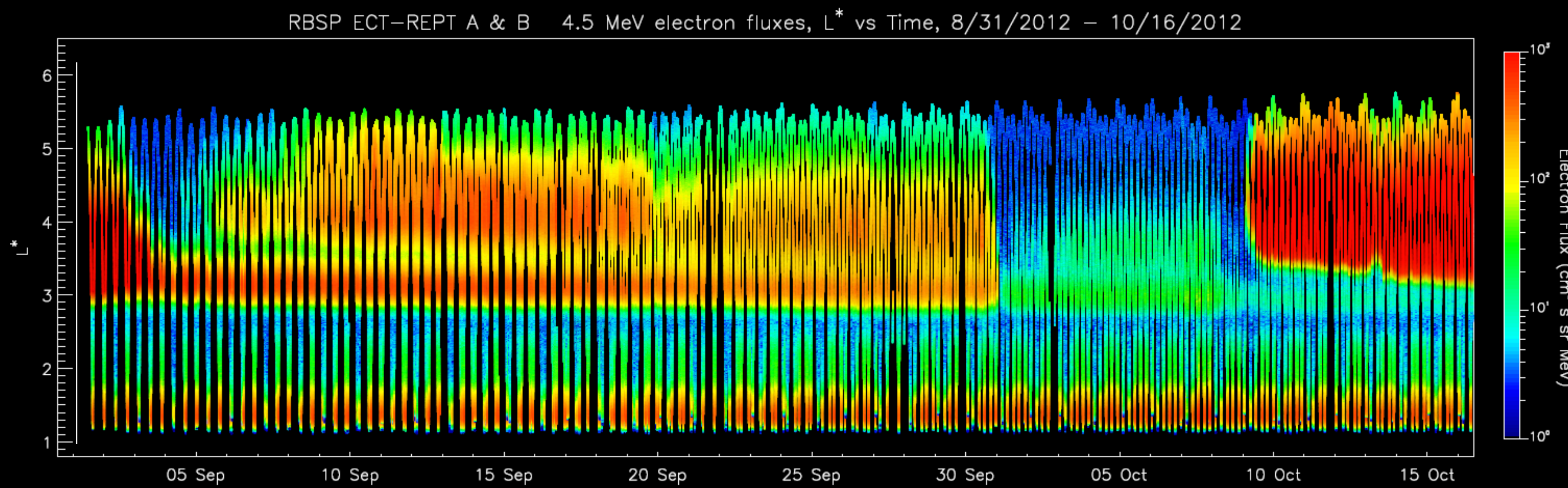
Radiation Belt Storm Probes—REPT A & REPT B

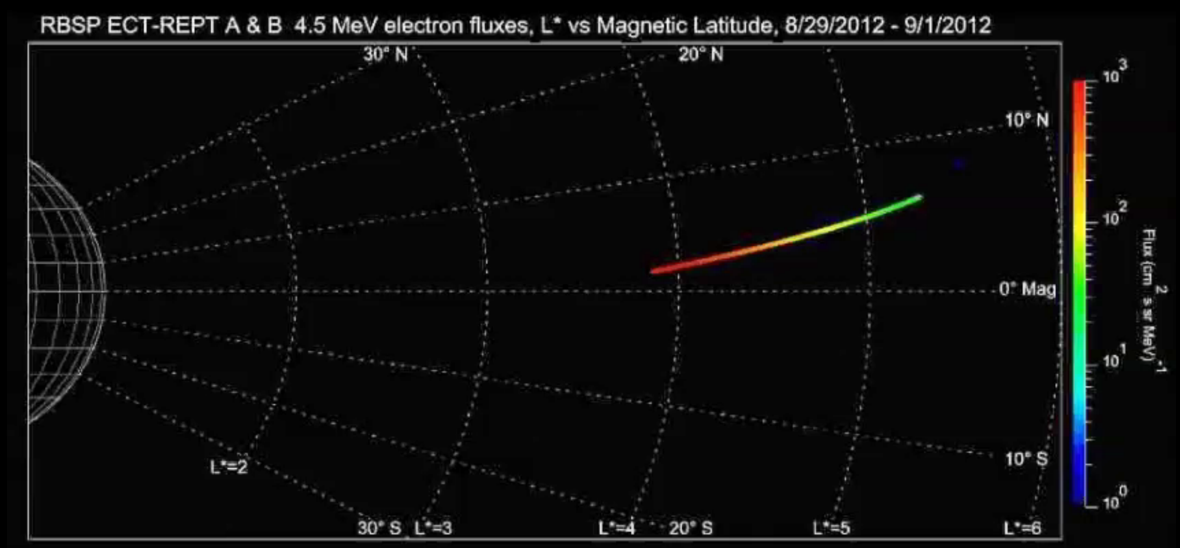


REPT Data: High-Energy Storage Ring



Radiation Belt Evolution



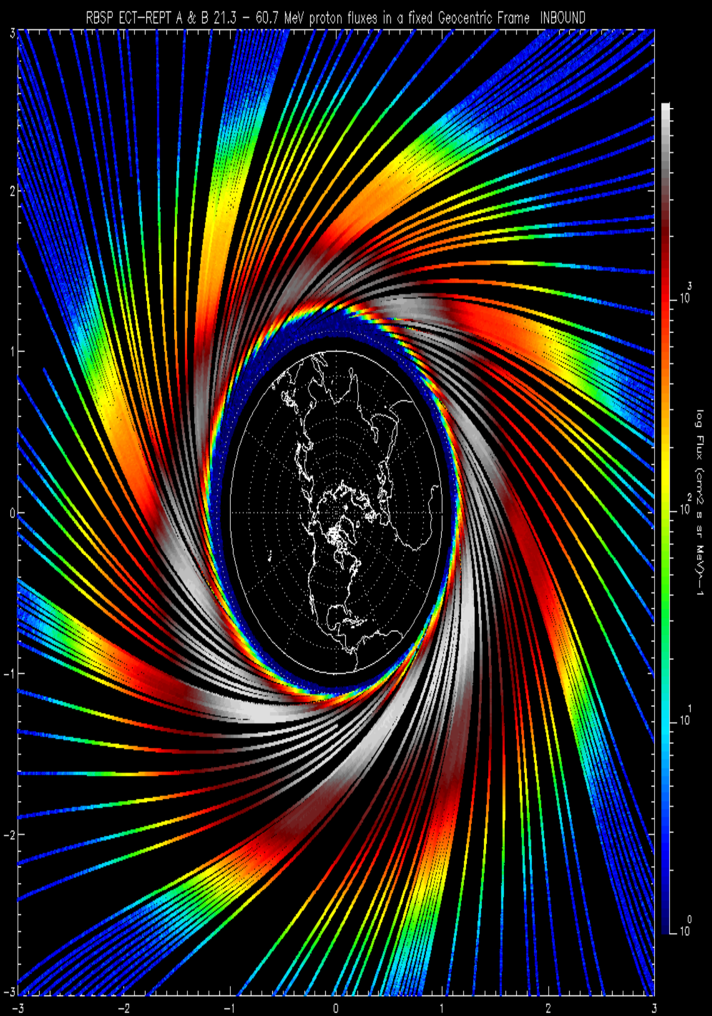


REPT L-shell sorted electron flux:

-Linear time plot (above)

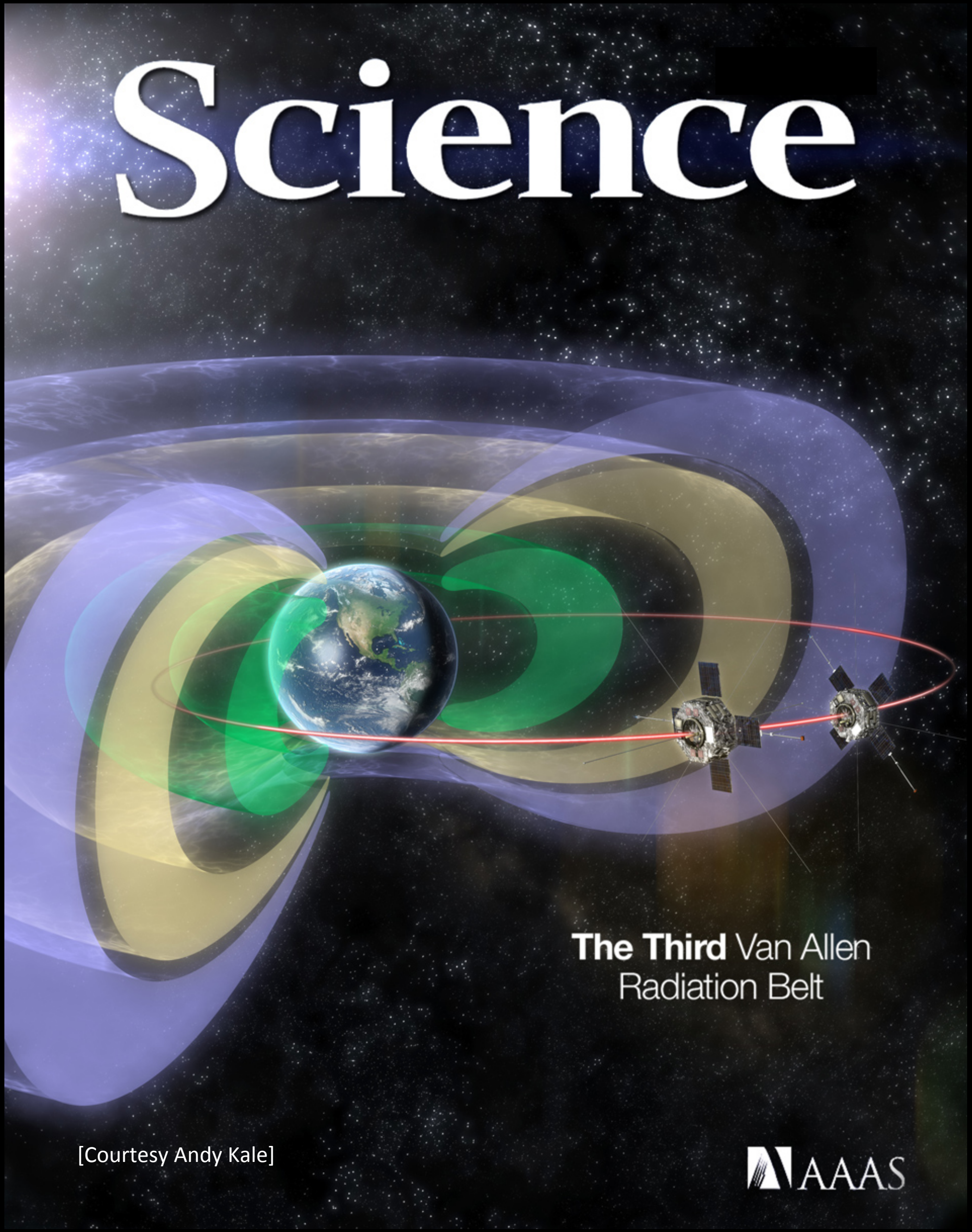
-Meridional magnetic latitude plot (left), 3 days at a time.

Baker et al., Science, 2013



RBSP ECT-REPT A & B 21.3 - 60.7 MeV proton fluxes in a fixed Geocentric Frame INBOUND
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3
10^3
10^2
10^1
10^0
log Flux (cm^2 s sr MeV)^-1

Remarkable Radiation Belt Discoveries

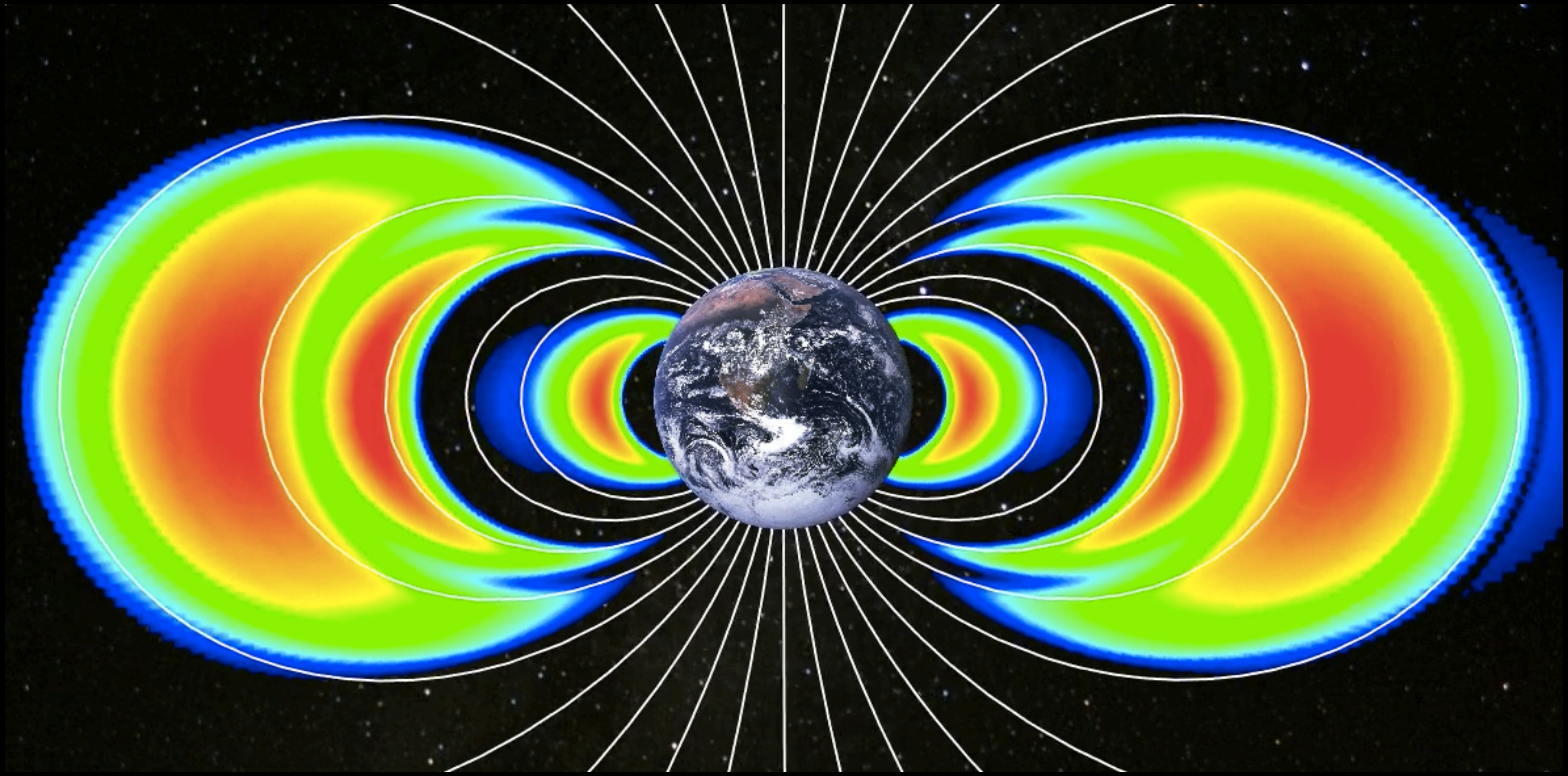


Science Express Online
28 February 2013

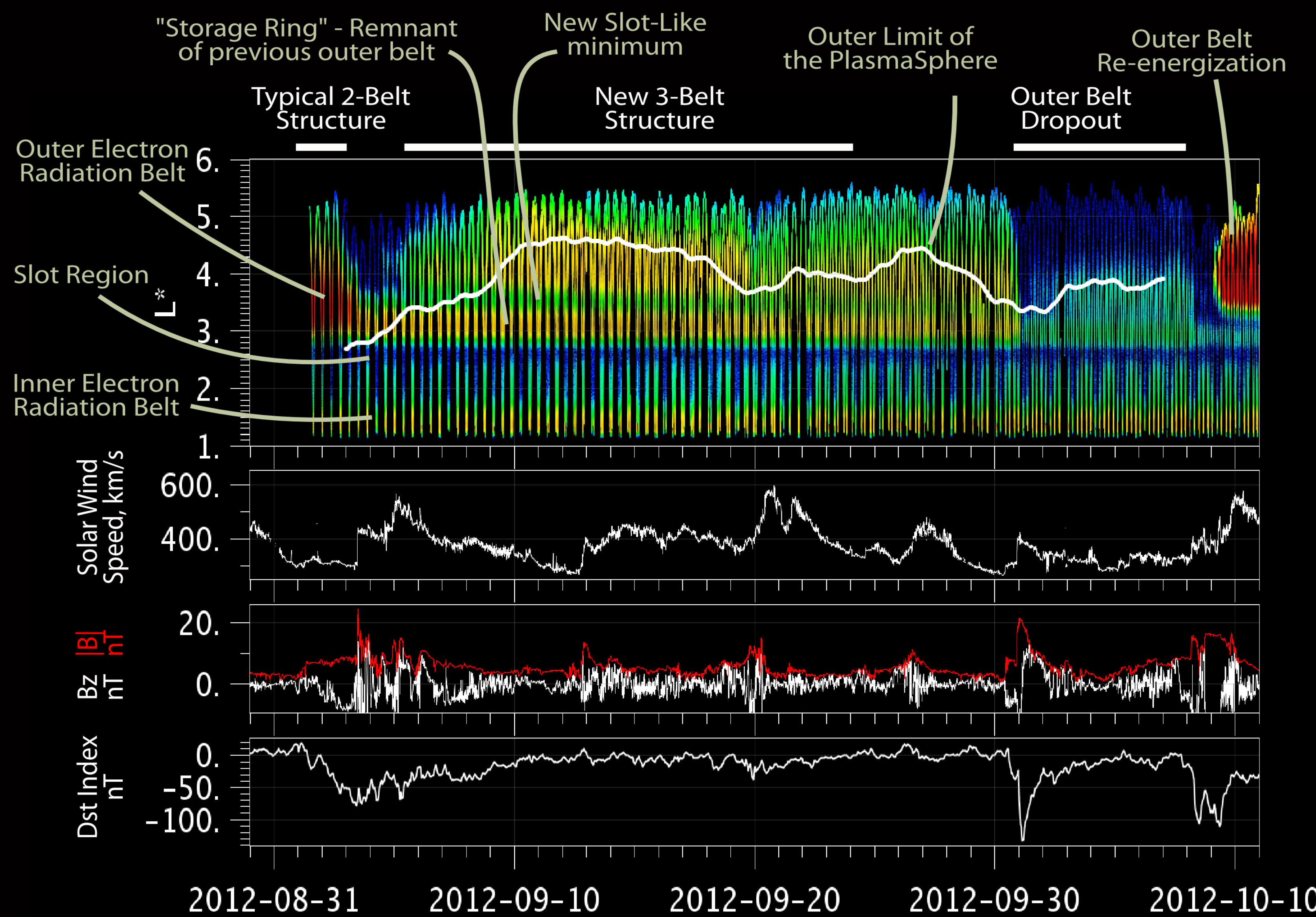
Science *Issue*
12 April 2013

Baker et al., 2013

REPT Data Assimilation: Three Radiation Belts



Courtesy of: Grant Stephens and Sasha Ukhorskiy

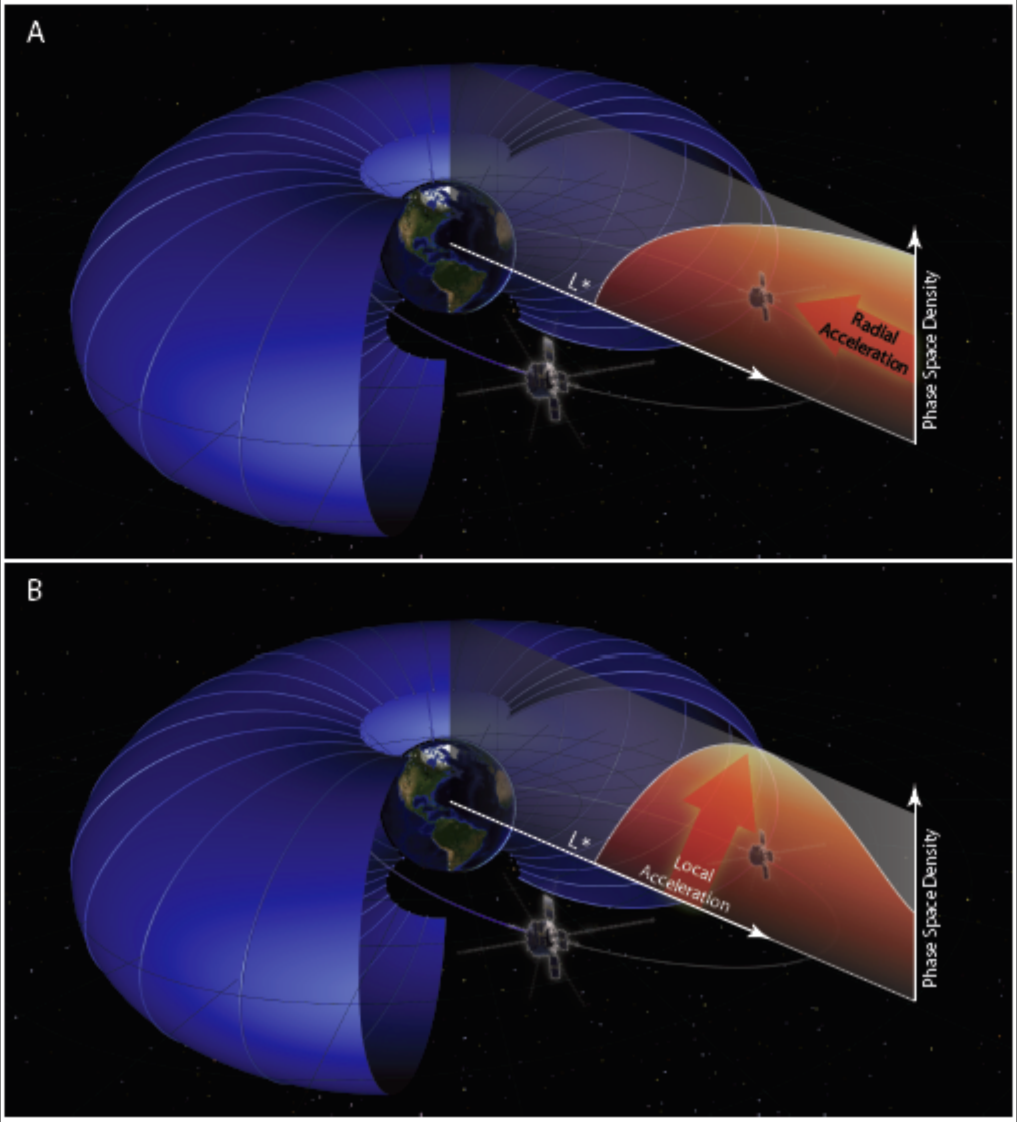


"Storage Ring" - Remnant of previous outer belt
New Slot-Like minimum
Outer Limit of the PlasmaSphere
Outer Belt Re-energization
Typical 2-Belt Structure
New 3-Belt Structure
Outer Belt Dropout
Outer Electron Radiation Belt
Slot Region
Inner Electron Radiation Belt
L*
6.
5.
4.
3.
2.
1.
Solar Wind Speed, km/s
600.
400.
Bz nT
|B| nT
20.
0.
Dst Index nT
0.
-50.
-100.
2012-08-31
2012-09-10
2012-09-20
2012-09-30
2012-10-10

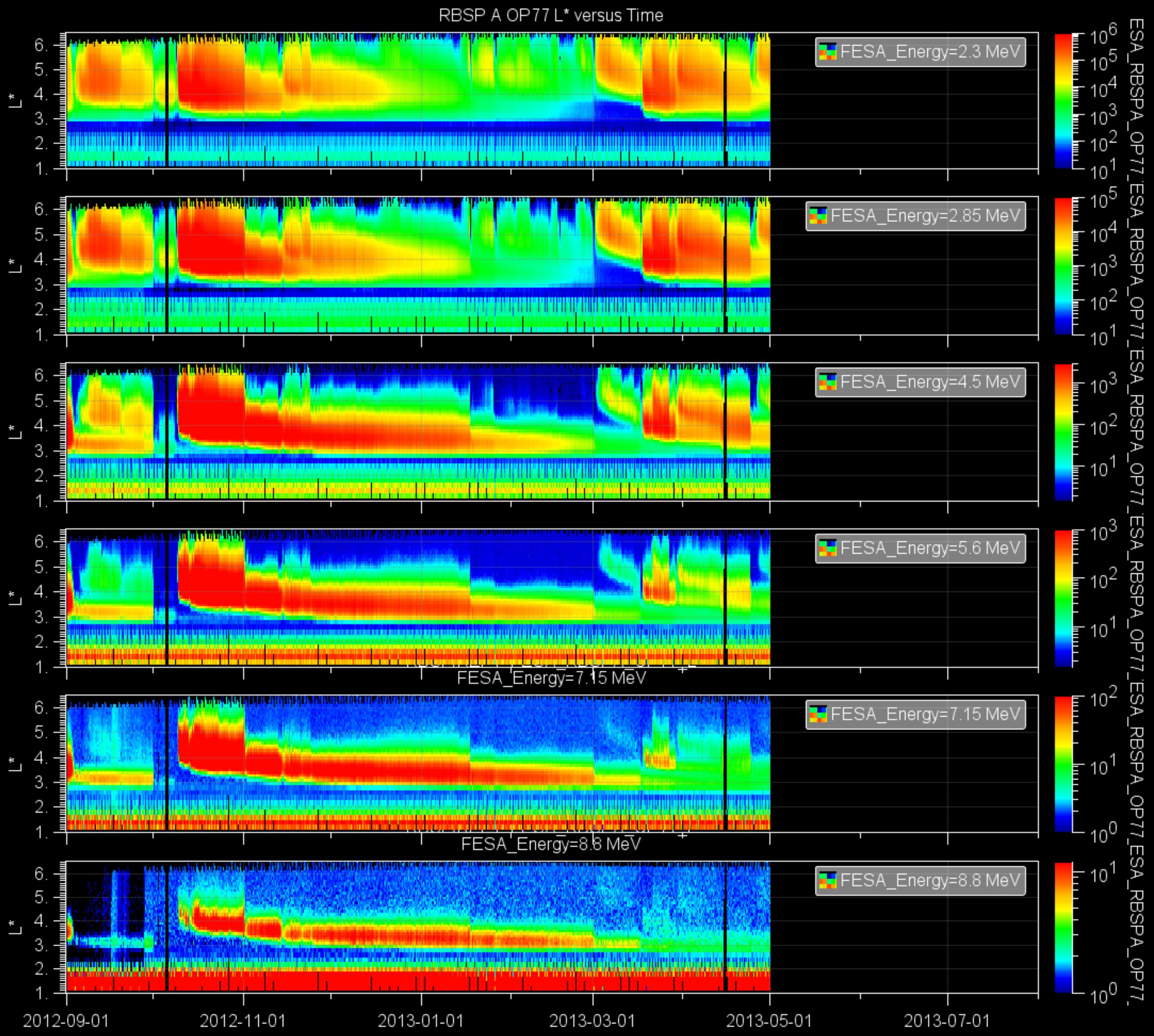
“Radial” versus “Local” Acceleration

- (A) Radial acceleration by diffusion inward from a source population at high L* creates monotonic gradients of phase space density.
- (B) In contrast, local acceleration of electrons by resonant interaction with VLF waves creates peaks in phase space density with a negative radial gradient at high L*.
- The twin RBSP satellites are designed to distinguish between radial and local acceleration processes.

From Reeves et al. (2013)

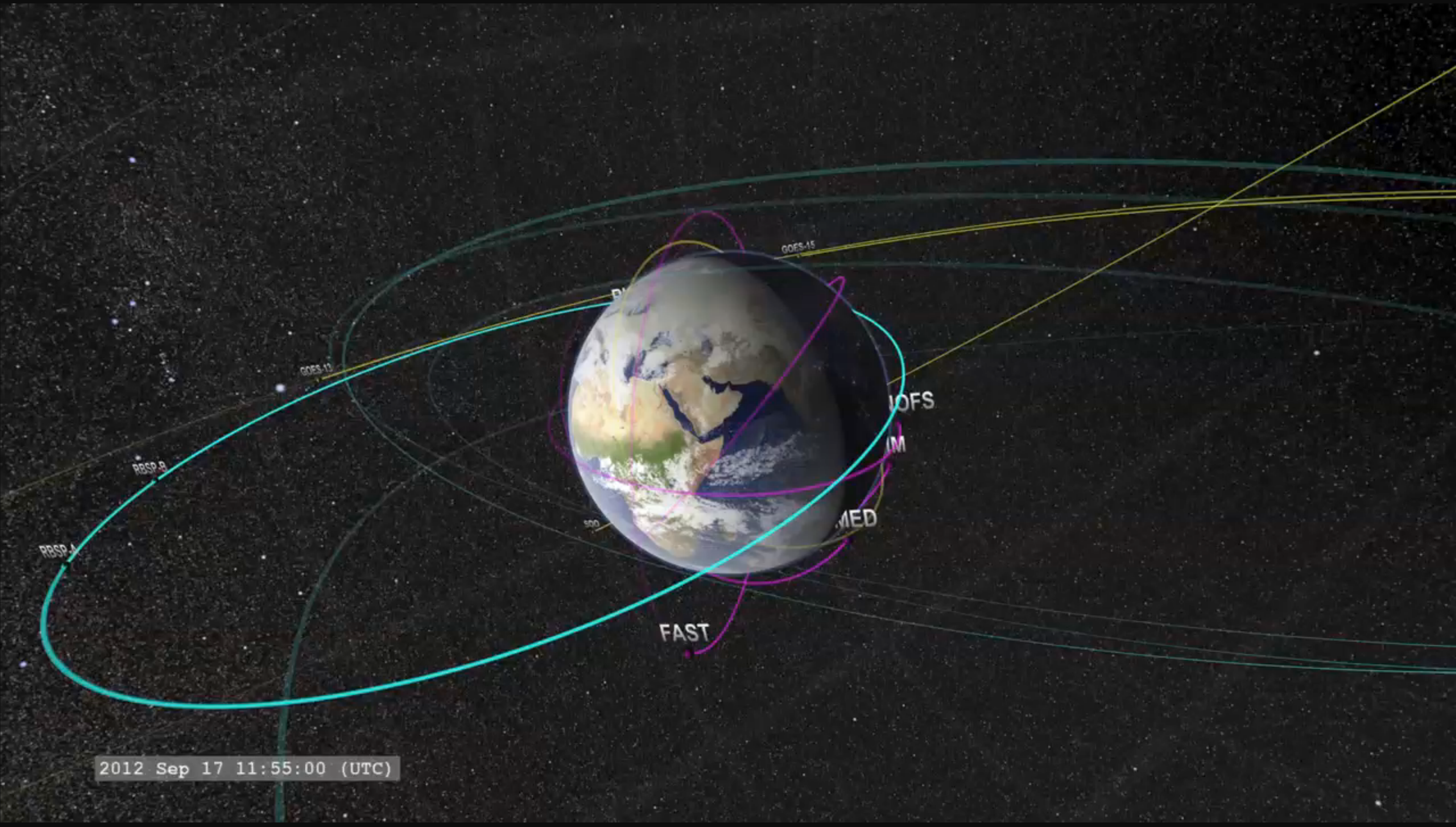


Long-Term Electron Data: REPT

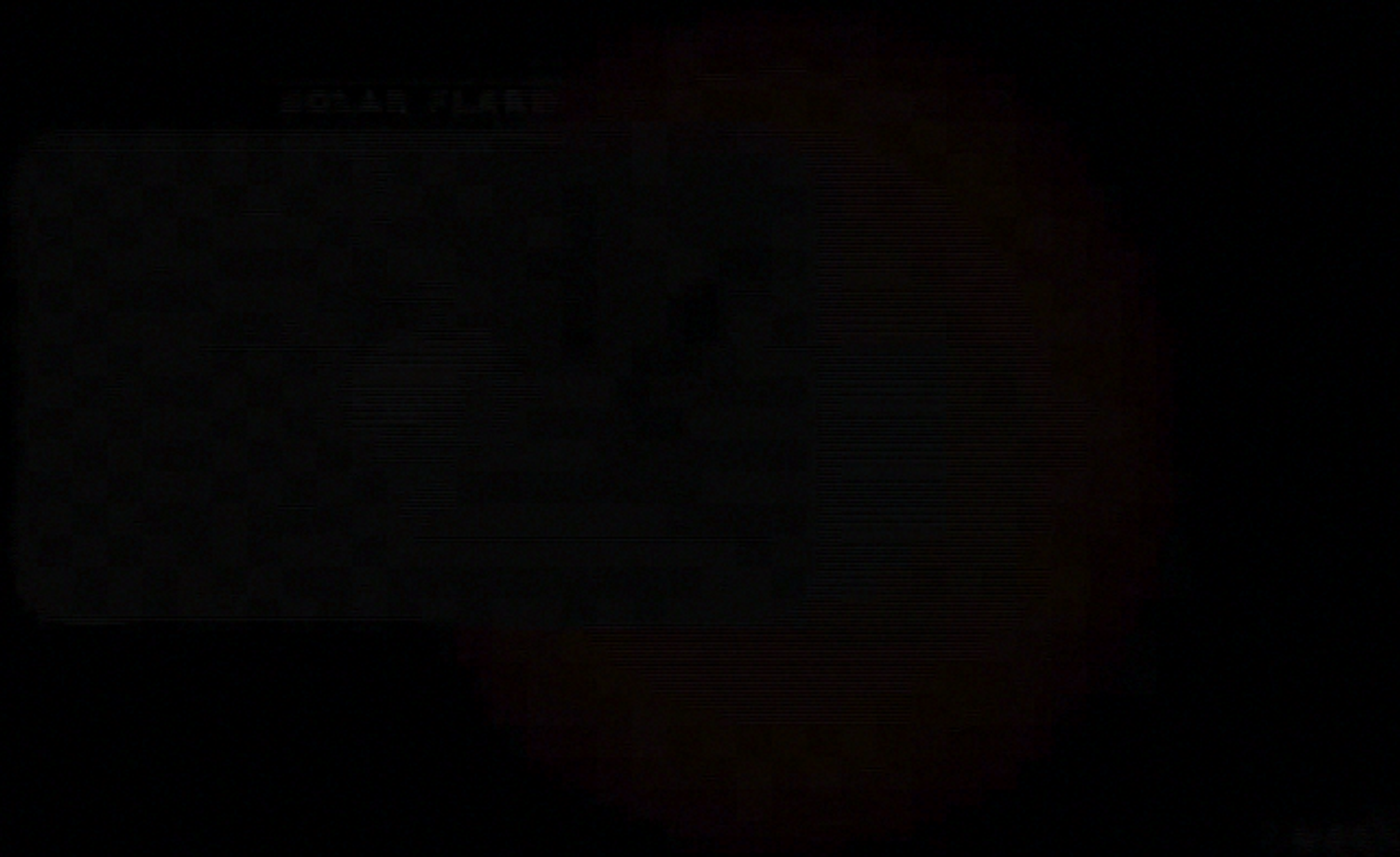


The Heliophysics Observatory Fleet

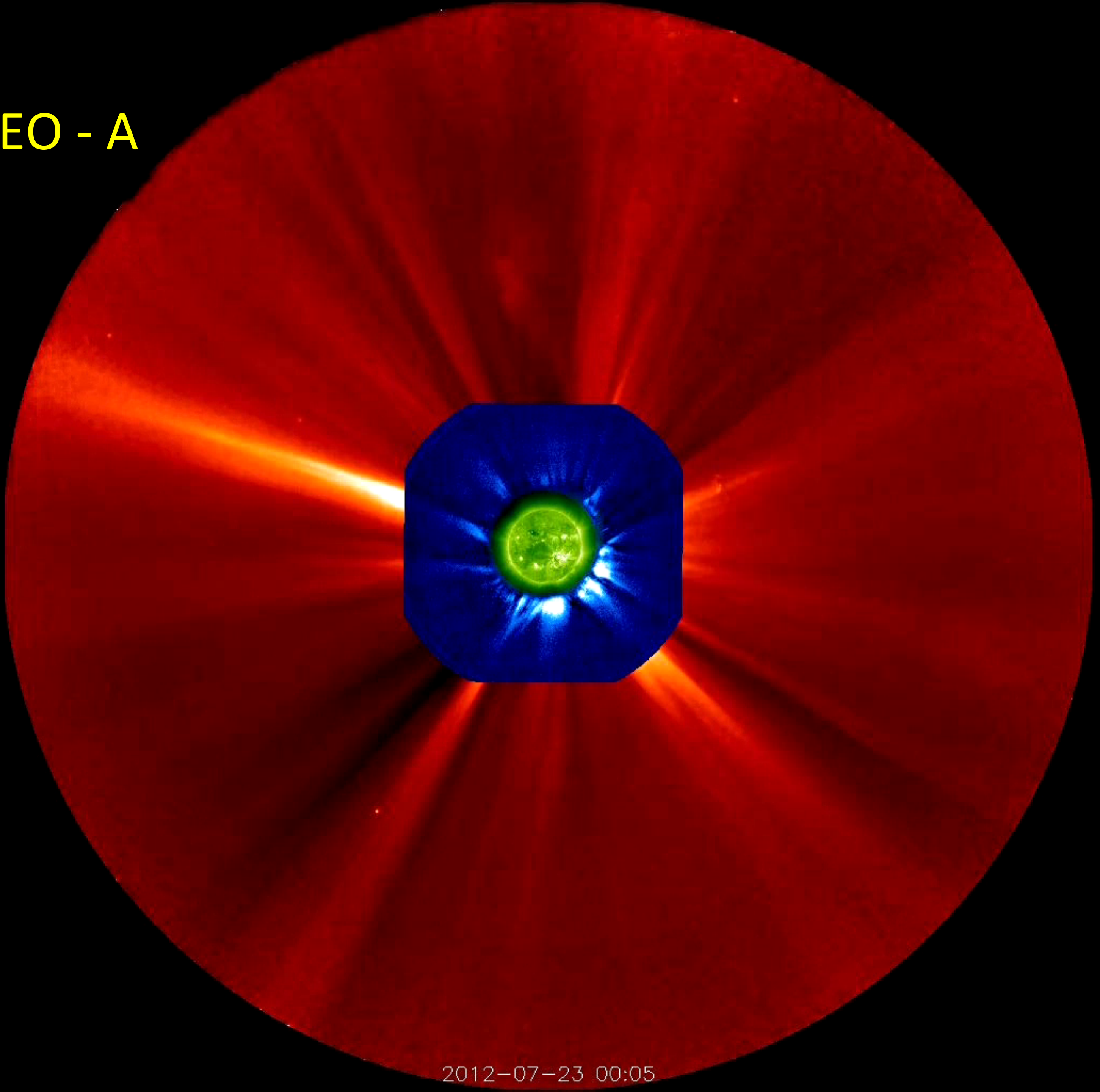
NASA/Goddard Space Flight Center Scientific Visualization Studio



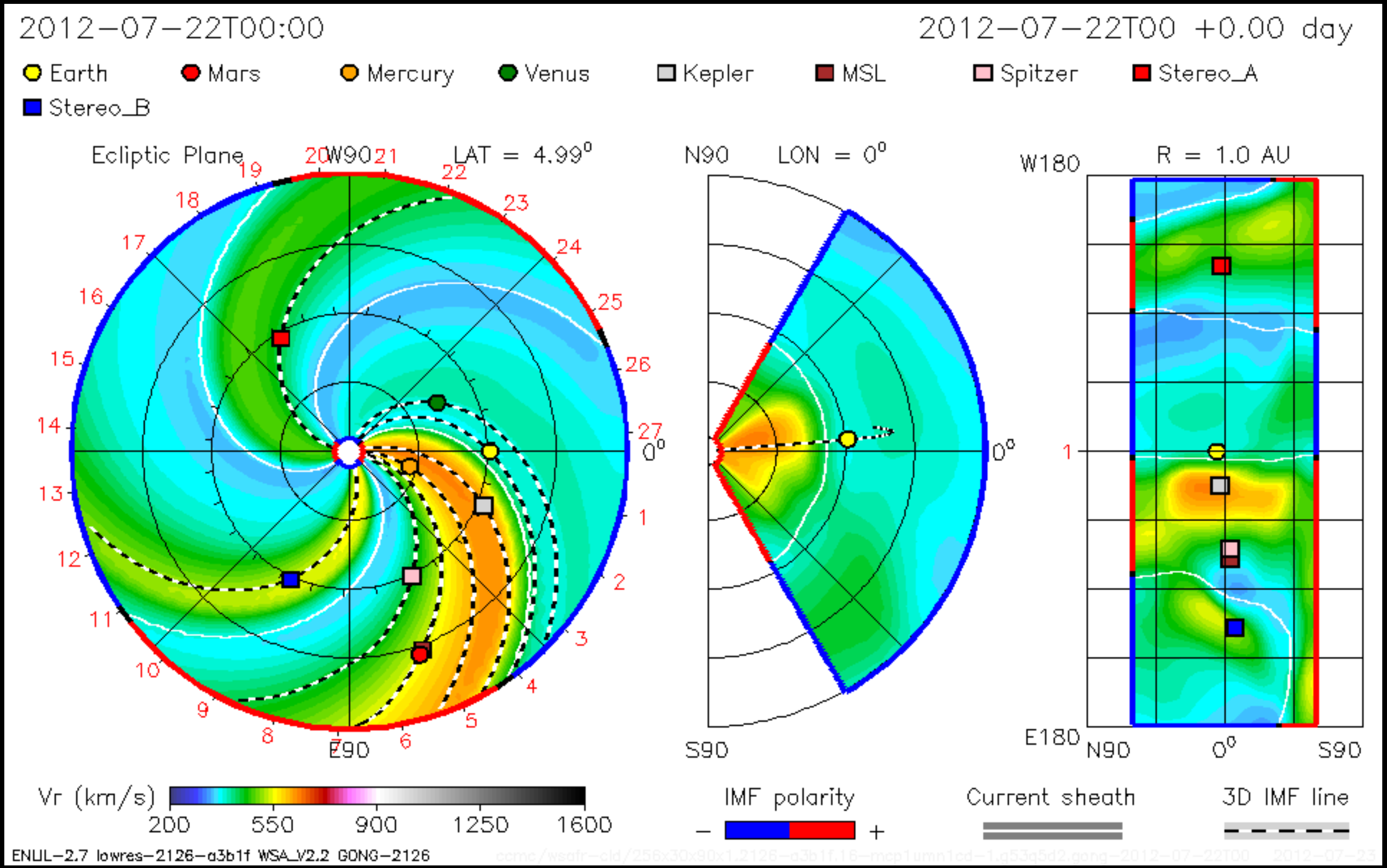
Addressing Space Weather

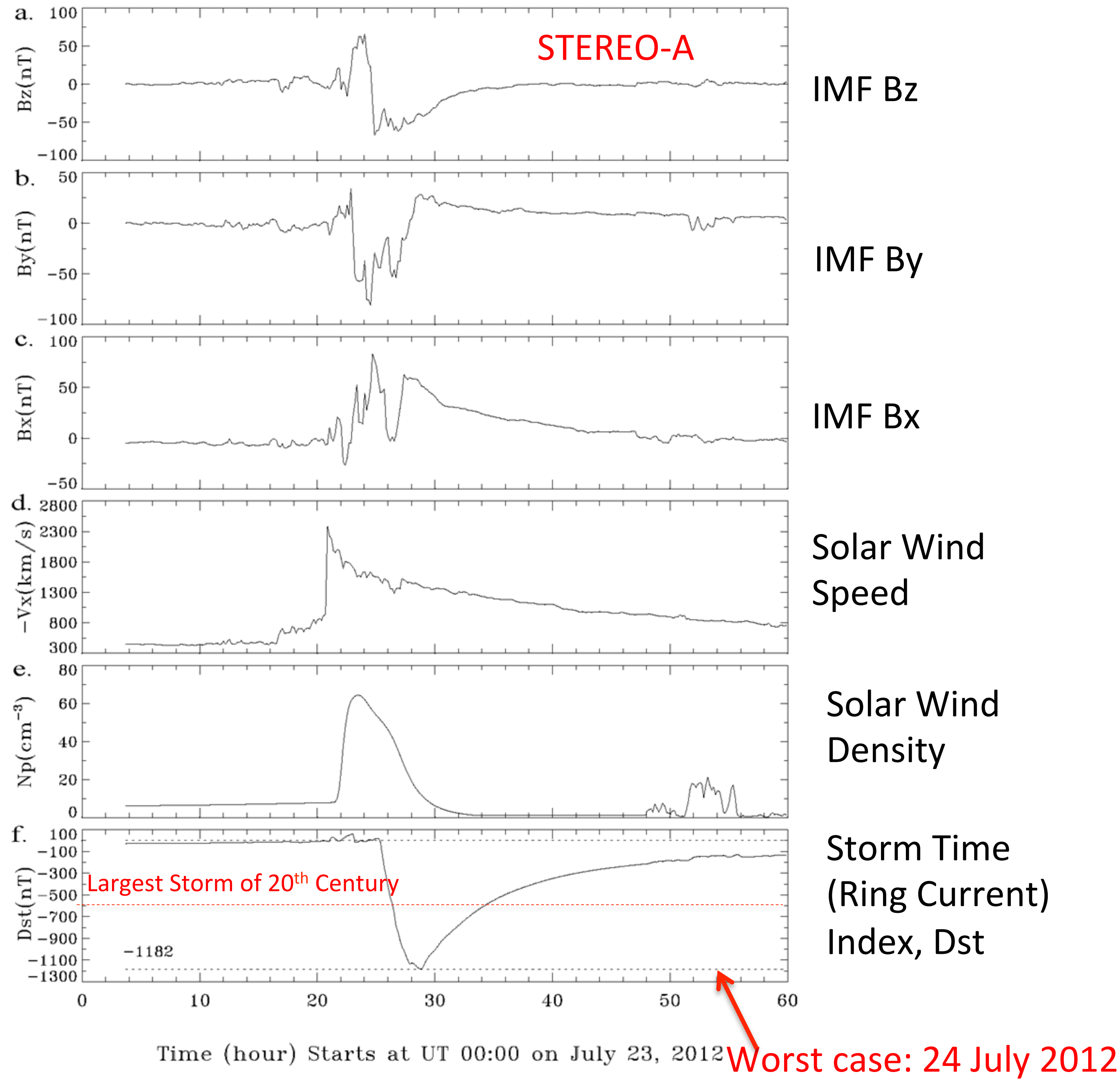


STEREO - A



WSA-ENLIL Model: Solar Wind Speed

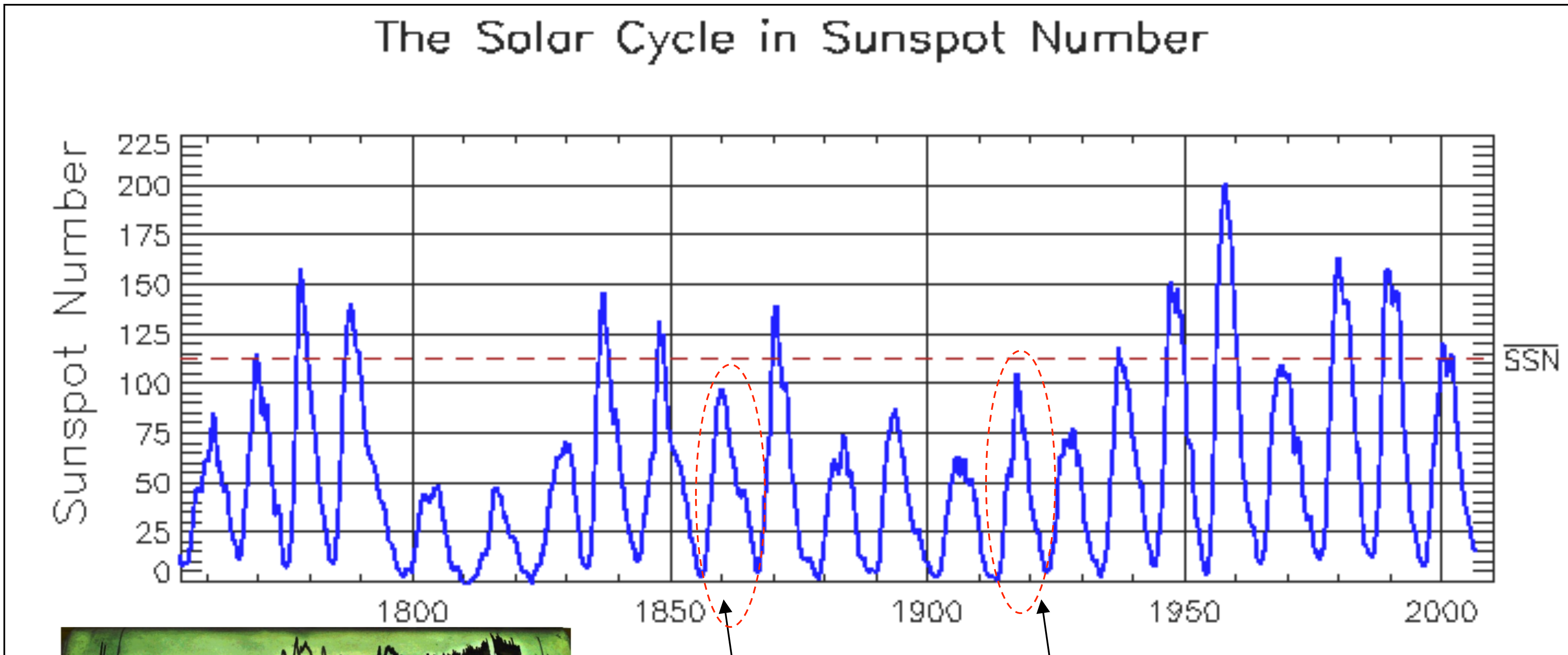


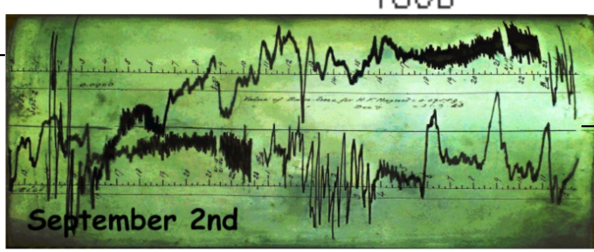


STEREO-A
IMF Bz
IMF By
IMF Bx
Solar Wind Speed
Solar Wind Density
Storm Time (Ring Current) Index, Dst
Bz(nT)
By(nT)
Bx(nT)
−Vx(km/s)
Np(cm⁻³)
Dst(nT)
Largest Storm of 20th Century
−1182
Time (hour) Starts at UT 00:00 on July 23, 2012
Worst case: 24 July 2012

• Large geomagnetic storms can occur with smaller cycles

• The largest geomagnetic storms on record occurred during lower than average cycles





1859 Storm

1921 Storm

Review: The Space Radiation Environment

Solar particle events (SPE) (generally associated with Coronal Mass Ejections from the Sun):

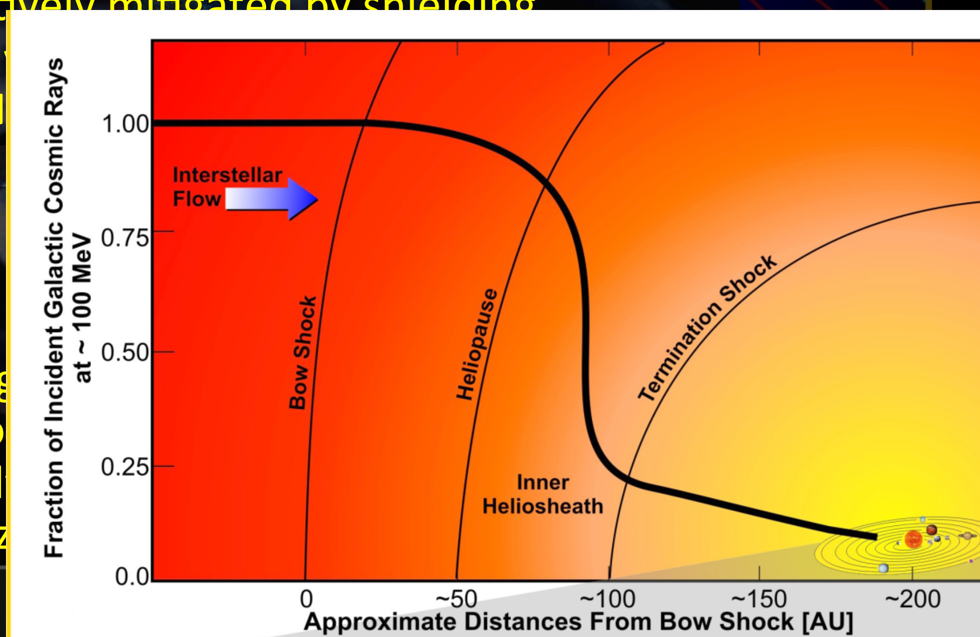
- medium to high energy protons
- largest doses occur during maximum solar activity
- not currently predictable
- MAIN PROBLEM: develop realistic forecasting and warning strategies

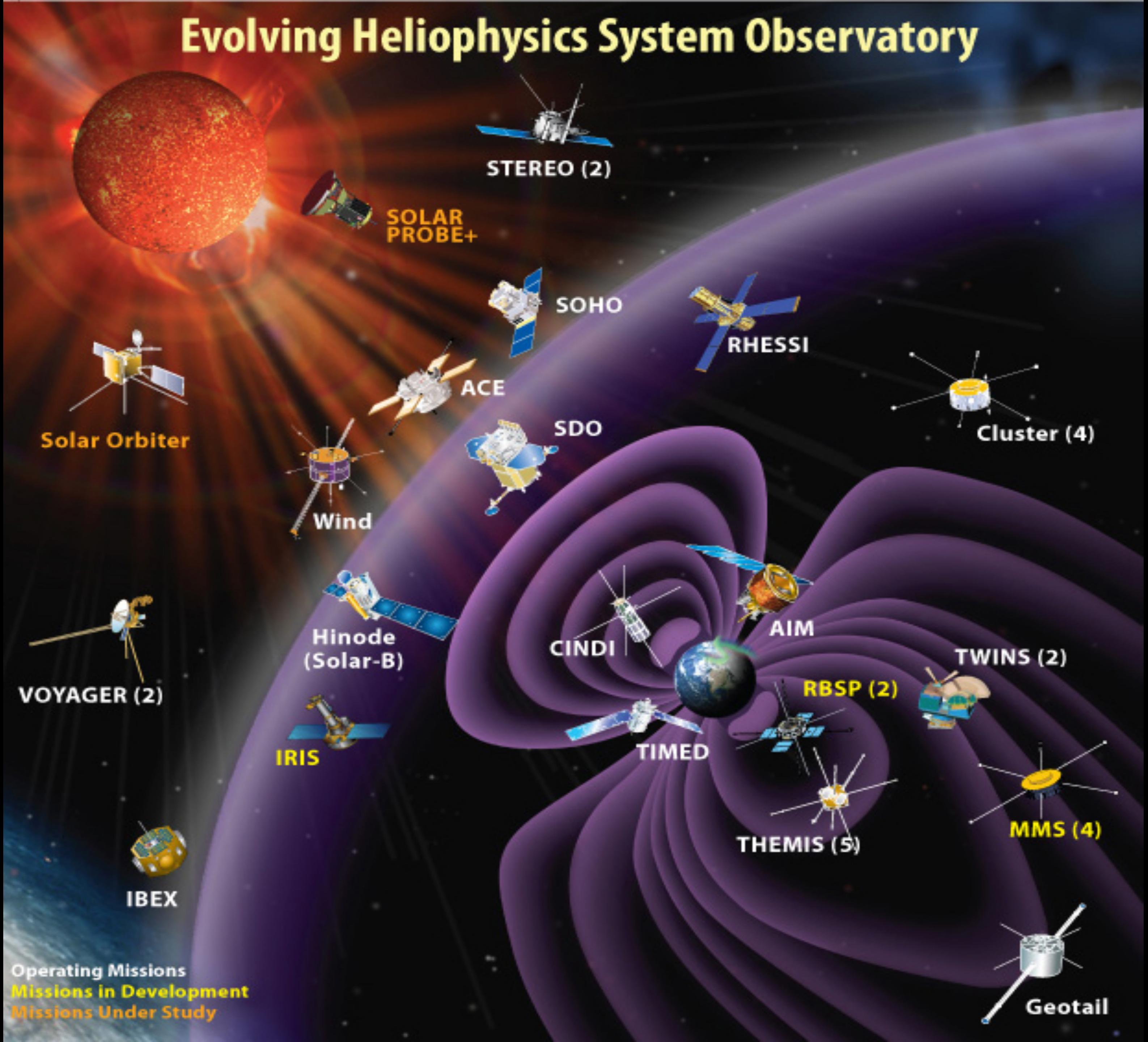
Trapped Radiation:

- medium energy protons and electrons
- effectively mitigated by shielding
- mainl
- MAIN

Galactic Cosmic Rays (GCR)

- high energy protons
- **highly charged, energetic atomic nuclei**
- not effectively shielded (break up into lig
- abundances and energies quite well kno
- MAIN PROBLEM: biological effects poorl
- significant long-term space radiation haz




Evolving Heliophysics System Observatory
STEREO (2)
SOLAR PROBE+
SOHO
RHESSI
Solar Orbiter
ACE
SDO
Cluster (4)
Wind
AIM
Hinode (Solar-B)
CINDI
TWINS (2)
VOYAGER (2)
RBSP (2)
IRIS
TIMED
MMS (4)
THEMIS (5)
IBEX
Operating Missions
Missions in Development
Missions Under Study
Geotail