Space Weather Guest Lecture

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Outline

- Overview
- Cause
- Effects
- Orbit Characteristics
- Mitigation Strategies
- Case Study

Natural Environments Branch

- Provides analysis of the space and terrestrial environments
- Operational support
- Anomaly investigations
- Model development
- Instrument build and test
- Data analysis

Bridge between science and engineering

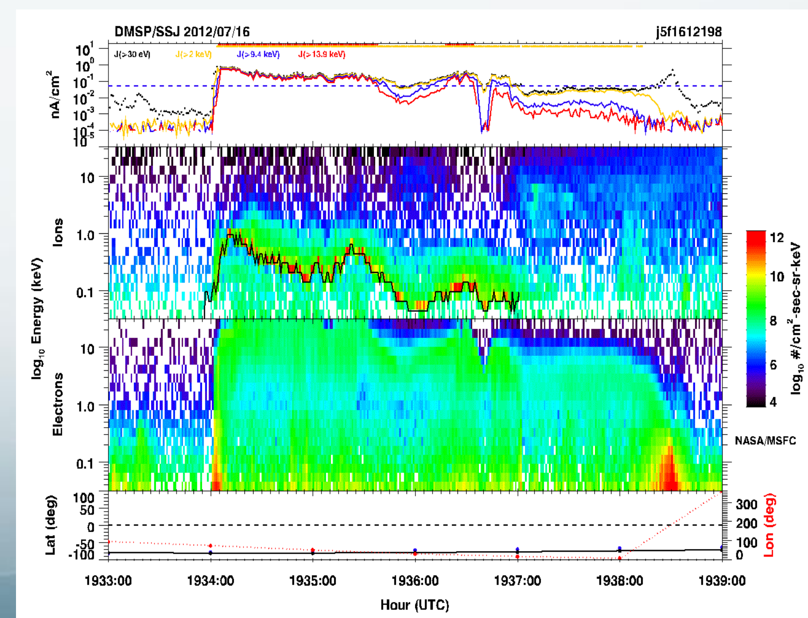
My role

- Plasma environment definition and analysis
- Spacecraft charging
  - Surface
  - Internal
- Radiation environment definition and analysis

Applied Space Weather Support to NASA Programs

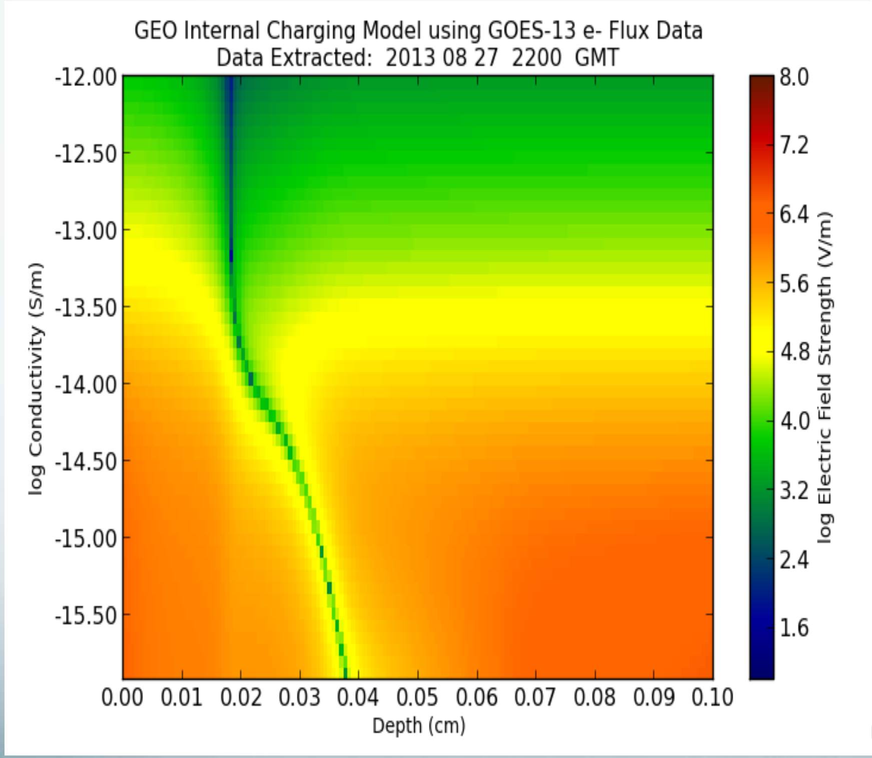
- **International Space Station (ISS) Floating Potential Measurement Unit (FPMU)**
  - Instrument suite for monitoring ISS charging, plasma environments
  - Monitor visiting vehicle and payload charging
  - Characterize US high voltage (160V) solar array interactions with LEO plasma environment
  - Anomaly investigation

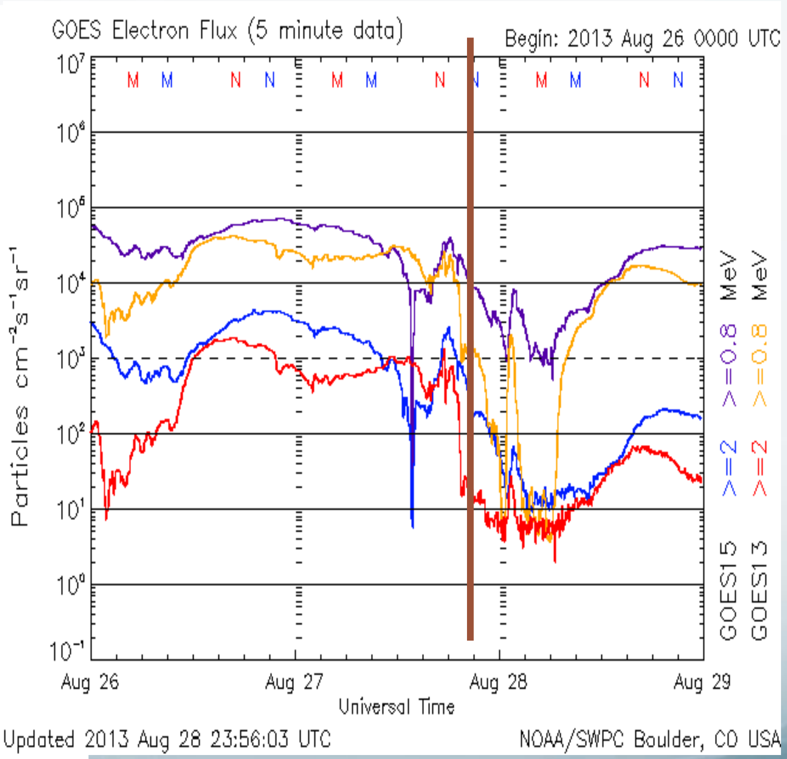
- **DMSP auroral charging, solar array plasma interaction studies**
  - MSFC developed software tools for working with DMSP SSJ and SSIES sensor data (F6 – F18)
  - Developing automated charging event identification algorithms, useful for "charging indices"
  - Characterize extreme charging to support spacecraft design, polar orbit operations



Real Time Space Environmental Effects Tools

- **Developing prototype engineering tools for evaluating effects of space environments on satellite systems**
  - Geostationary orbit single event upset tool (real time version of CREME96)
  - Geostationary orbit internal charging tool





Electric fields resulting from internal (deep dielectric) charging as function of depth in dielectric material and electrical conductivity. Fields are updated at 5 minute intervals using NOAA GOES >0.8 MeV, >2.0 MeV electron data.

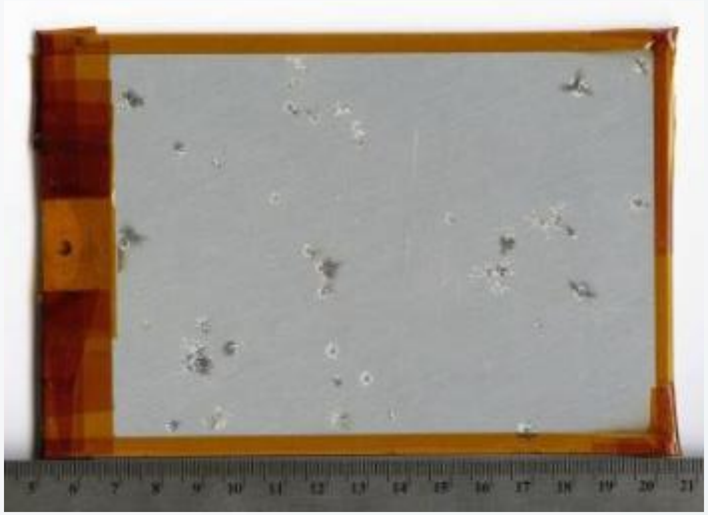
Space Environment Effects Testing and Calibration

Space environmental effects testing for broad spectrum of environments and effects:

- Energetic electron, ion radiation
- Ultraviolet (UV) radiation
- High intensity solar simulator
- Spacecraft charging (surface, internal)
- Atomic oxygen
- Thermo-optical properties
- Solar array interaction with space plasma, radiation environments
- Hypervelocity (meteor/orbital debris) impacts
- Thermo/vacuum/vibration
- Contamination/outgassing

Low Energy Electron and Ion facility (LEEIF)

- Charged particle instrument calibration for particle energy, mass, flux, and angular acceptance
- Supports iterative design, build, and testing of space plasma instruments for variety of environments
- Electron/ion/UV sources, ISO 7 tent, ISO 5 bench, vacuum chamber, and data acquisition and analysis

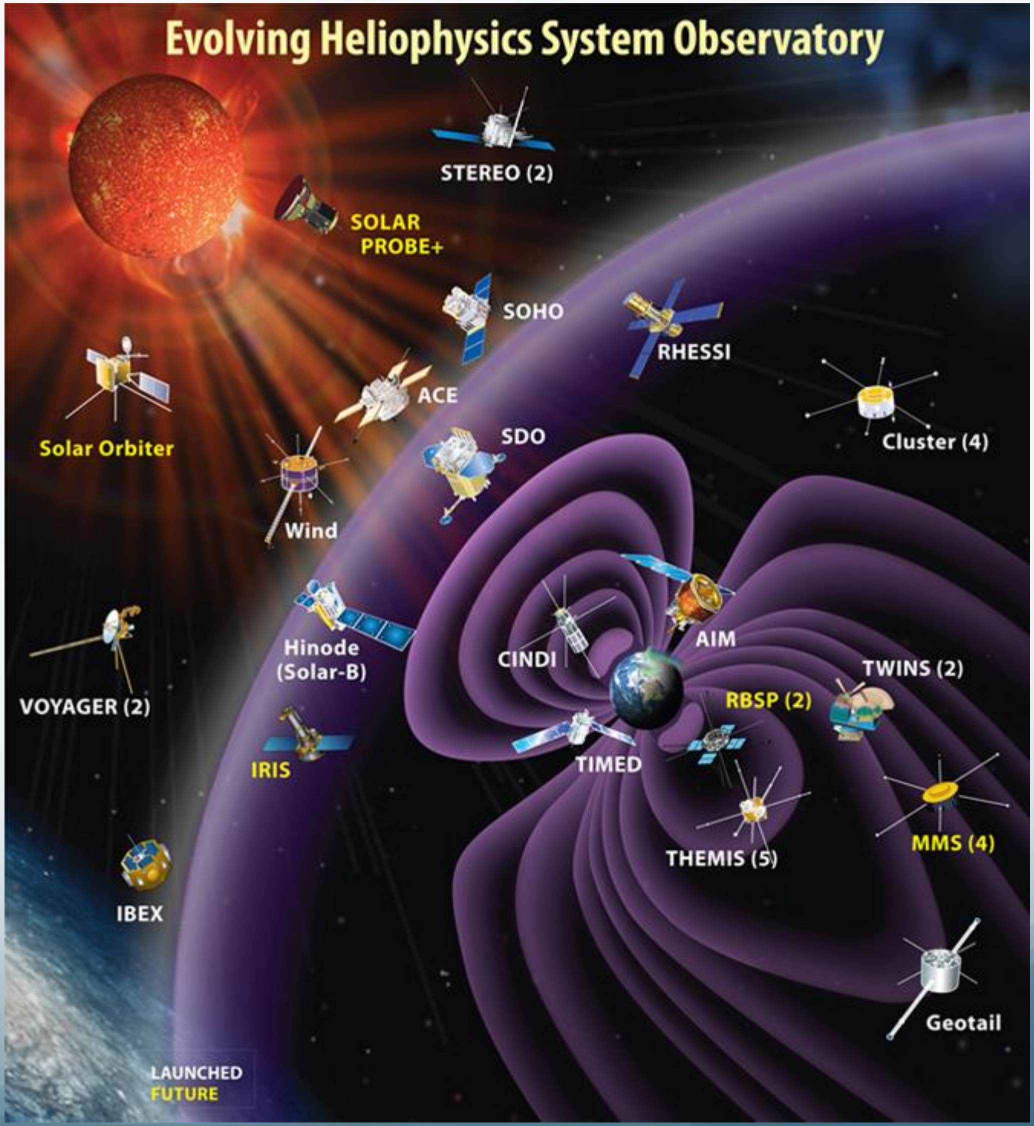


Electrostatic discharge arc damage of ISS thermal control coatings

LEEIF chamber with test device in mount

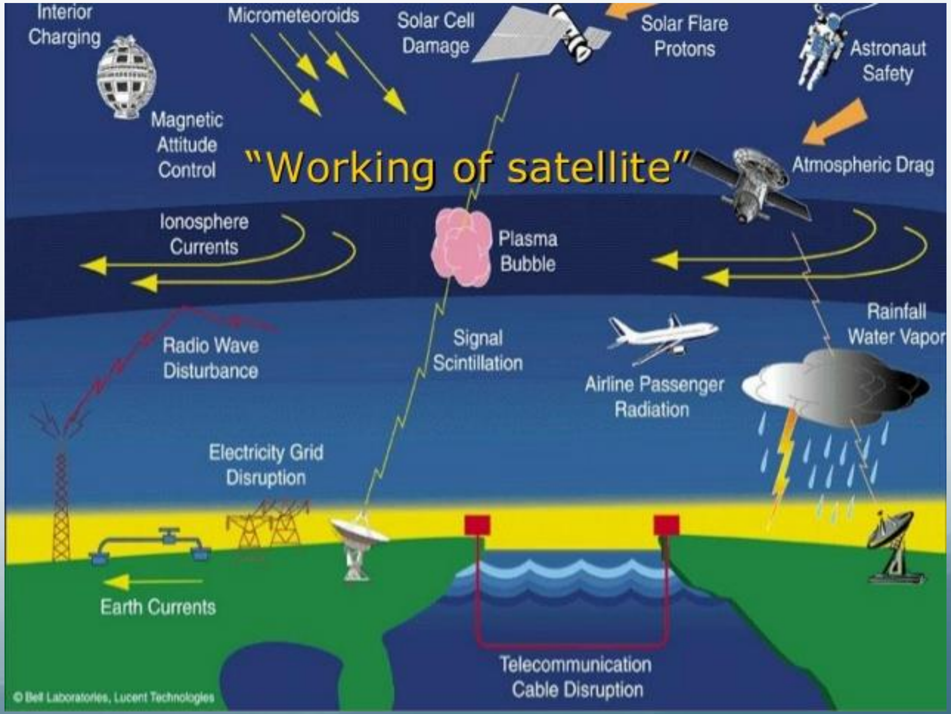
Who cares about Space Weather?

- National Space Weather Program
- Space Weather Prediction Center, NOAA
- NASA
- Military
  - Air Force Space Weather Command
  - Army Space and Missile Defense Command

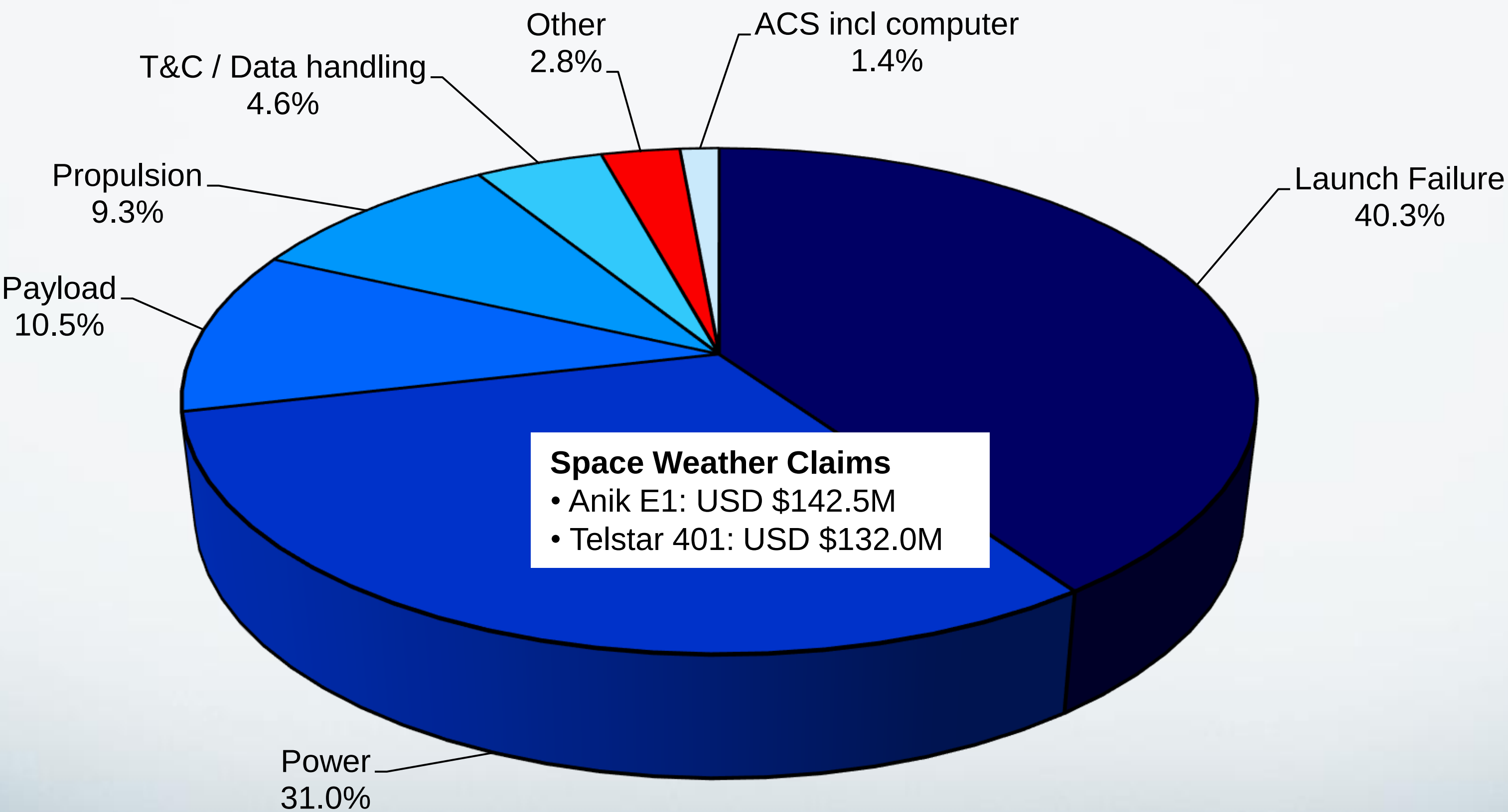


Why do we care about Space Weather?

- Warning for satellite
- Geomagnetic Induced Currents
- Charging
- Radiation
- Scintillation



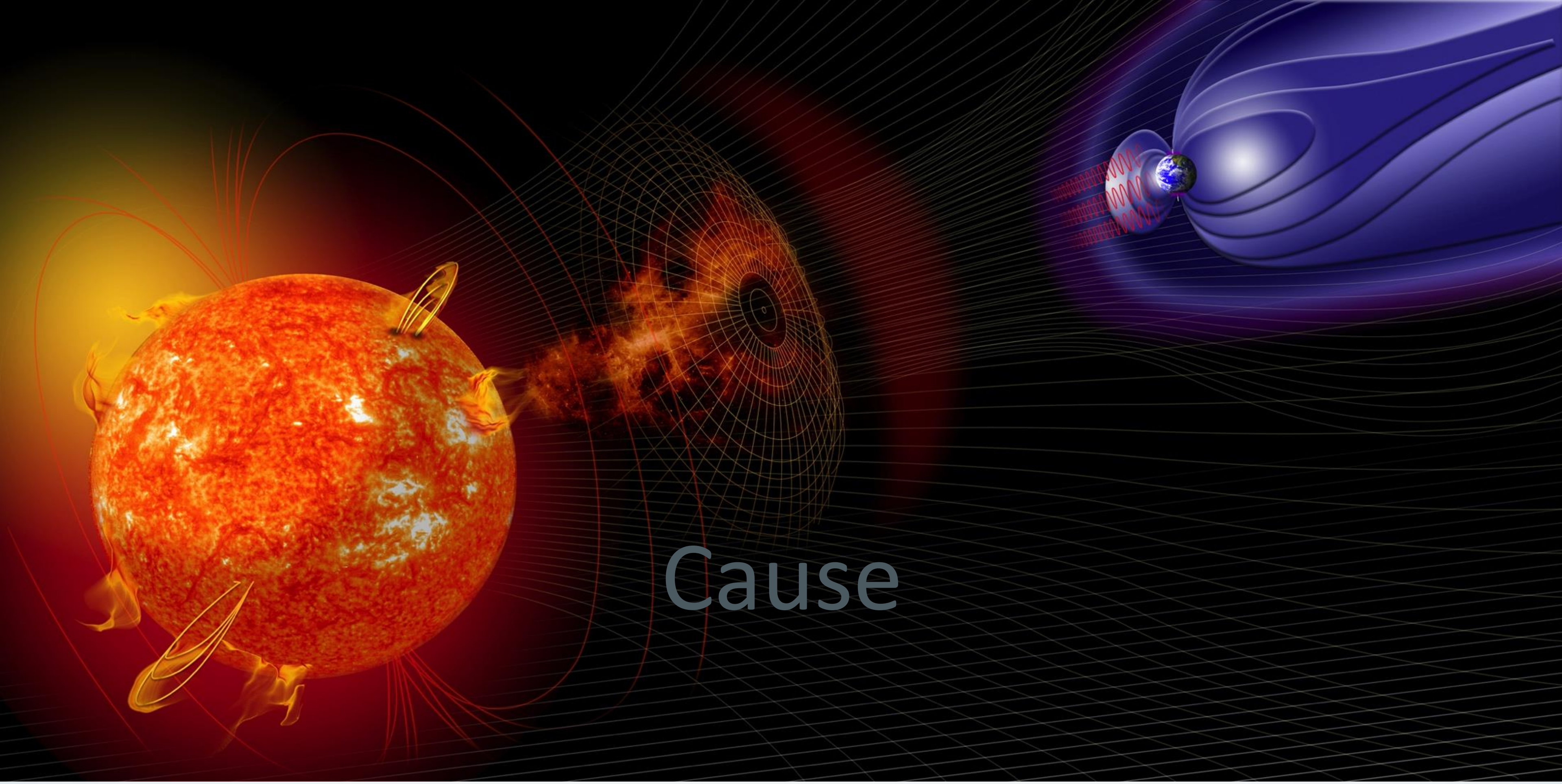
Charging Failures are Expensive



Space Weather Claims

- Anik E1: USD $142.5M
- Telstar 401: USD $132.0M

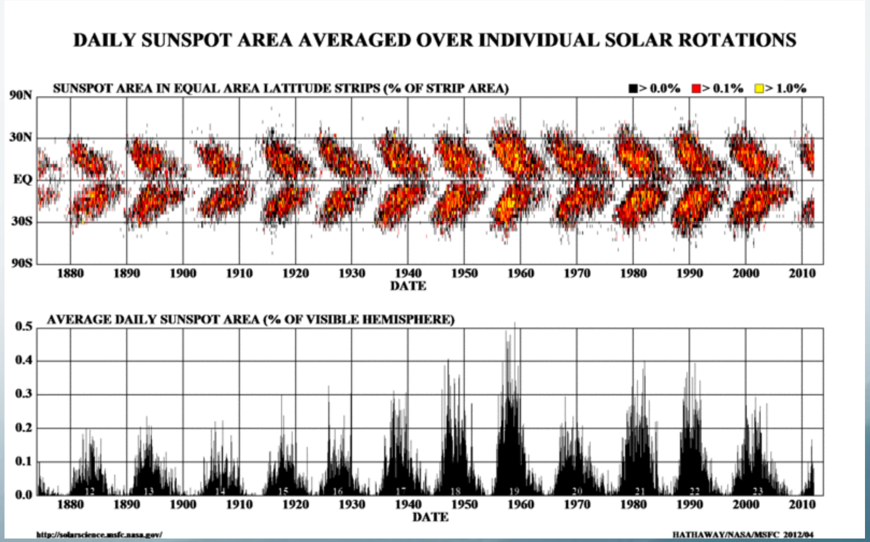
Total claims (1994 – 2013) = USD $12.64 billion [Wade, 2014]



Cause

Solar cycle

- Why do we care about solar cycle
  - Maximum – more geomagnetic storms, CMEs, solar flares, electron radiation environment
  - Minimum – GCR, auroral charging, proton radiation environment
- Approximately 11 years in length, sun's polarity changes with each cycle.
- F10.7 - Represents a measure of diffuse, nonradiative heating of the coronal plasma trapped by magnetic fields over active regions.
- Solar Sunspot number - Measure of the area of solar surface covered by sunspots. Possible geomagnetic storms because CMEs and SEPs can come from those regions.

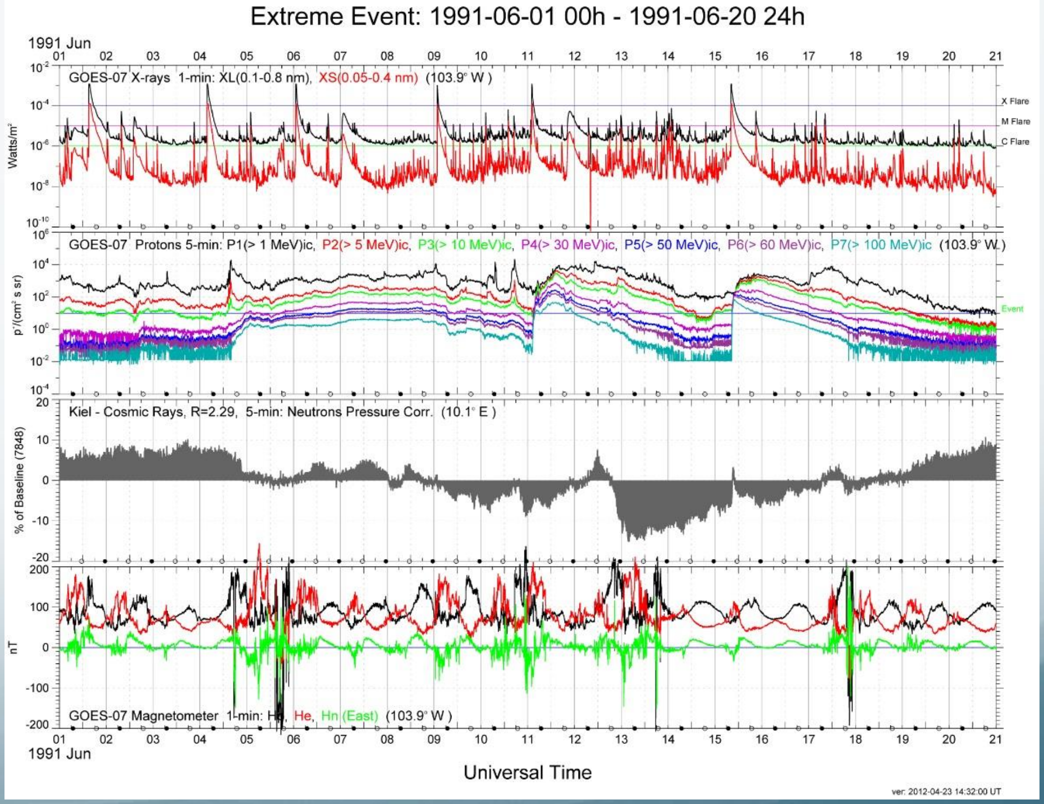


Solar Flare

- Two types:
  - Compact flares – smaller, develop lower in the corona
  - Two-ribbon flare – larger, more energetic, more likely be to be associated with an eruption.
- Sudden brightening interpreted as a large energy release
- Occurs in active regions around sunspots.
- Flare ejects clouds of electrons, ions, heavy ions, and atoms through the corona to space.

Types of Flares

Classification	Peak Flux Range at 100-800 picometer (Watts/square meter)
A	$< 10^{-7}$
B	10^{-7} - 10^{-6}
C	10^{-6} - 10^{-5}
M	10^{-5} - 10^{-4}
X	$> 10^{-4}$



Flares are used as an alert for possible SEP event.

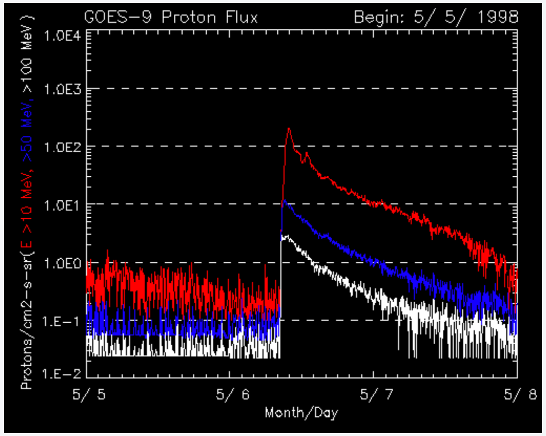
Coronal Mass Ejection (CME)

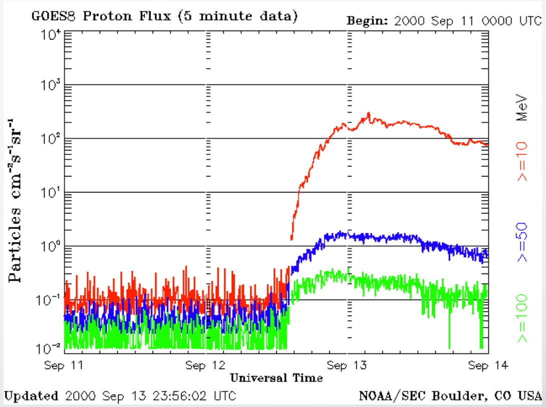
- Massive burst of solar wind
- Associated with solar flares, but causal relationship has not been established
- Solar maximum – 3 a day
- Solar minimum – 1 every five days
- Ejected material is mostly electrons and protons, but may contain heavier ions.

Solar Energetic Particle (SEP) Events

SEPs can originate from two processes:

- Impulsive
  - Originate from energetization at a solar flare site
  - Lasts a few hours and has smaller fluences
  - Electron-rich, associated with Type III radio bursts
- Gradual
  - Originate at shock waves associated with CMEs.
  - Lasts several days and has larger fluences
  - Proton-rich, associated with Type II radio bursts
  - Diffusive shock acceleration

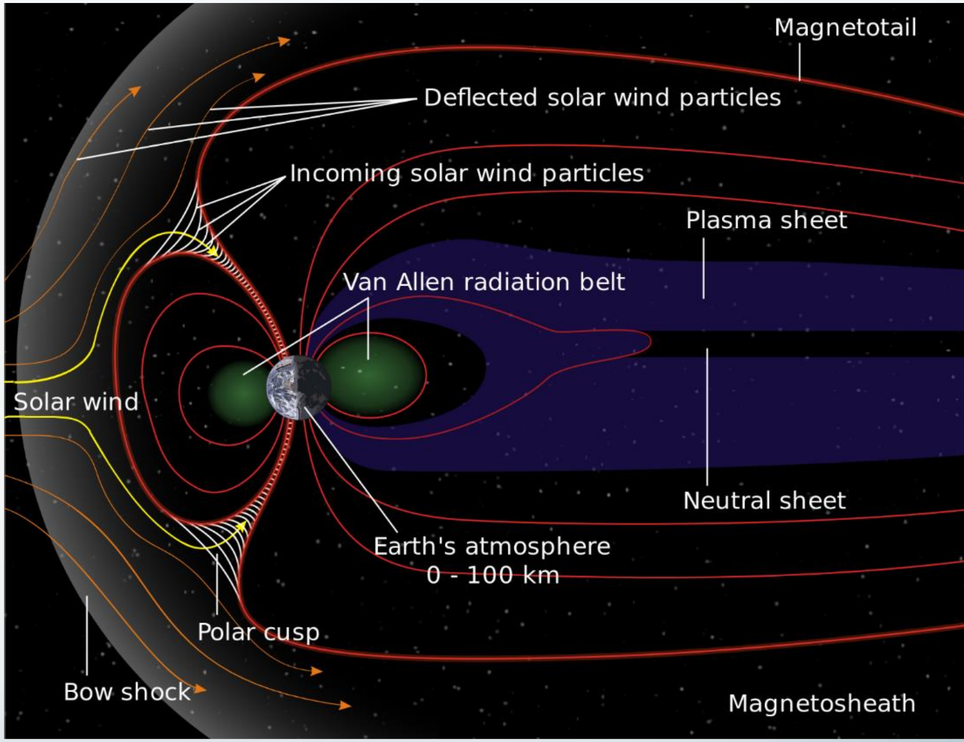




- SEPs can be accelerated to energies of several tens of MeV within 5-10 solar radii
- Can reach Earth in a matter of tens of minutes to a few hours after a flare or an ejection.

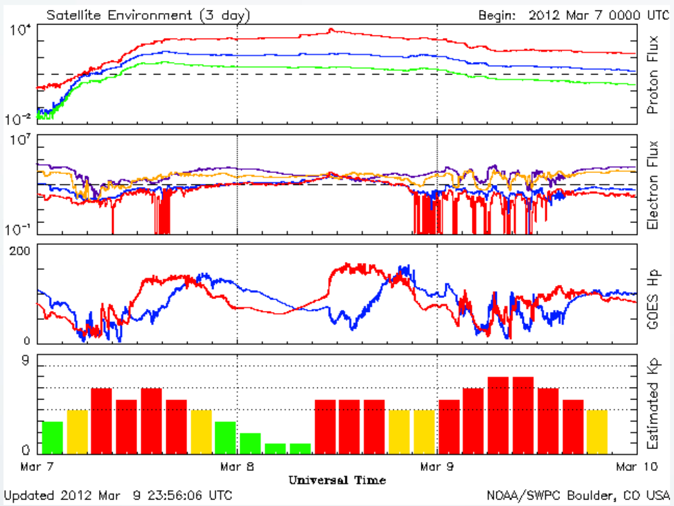
Geomagnetic Storm

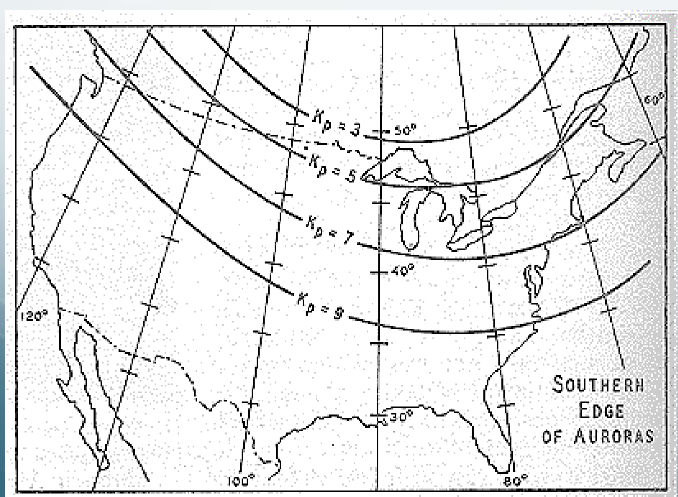
- Temporary disturbance in the Earth's magnetosphere caused by a disturbance in the interplanetary medium.
  - Solar wind shock wave
  - Cloud of magnetic field.
- Increase in the solar wind pressure compresses the magnetosphere.
- Interplanetary B interacts with Earth's B and transfers an increased amount of energy into the magnetosphere. Most coupling occurs when Bz < 0.
- Weather phenomenon that are associated with or caused by geomagnetic storms:
  - Solar Energetic Particle events
  - Geomagnetically induced currents
  - Ionospheric disturbances which cause radio and radar scintillation
  - Disruption of navigation by magnetic compass and auroral displays at much lower latitudes than normal
  - Aurora



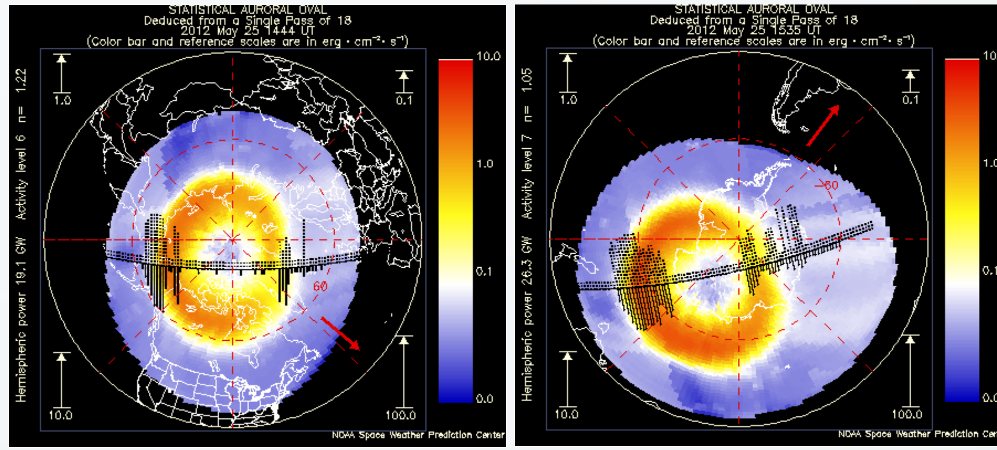
How do we know there’s a storm

Kp – Mid latitudes

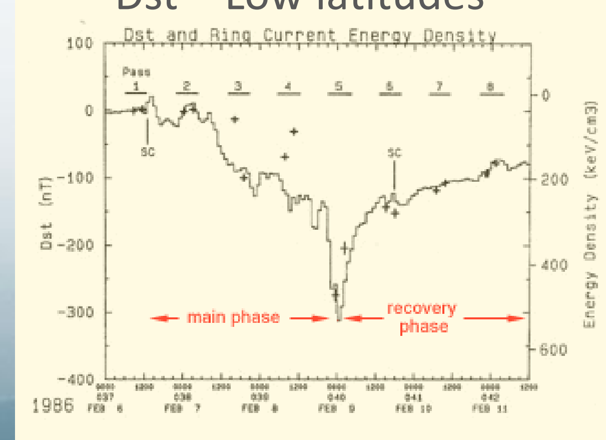




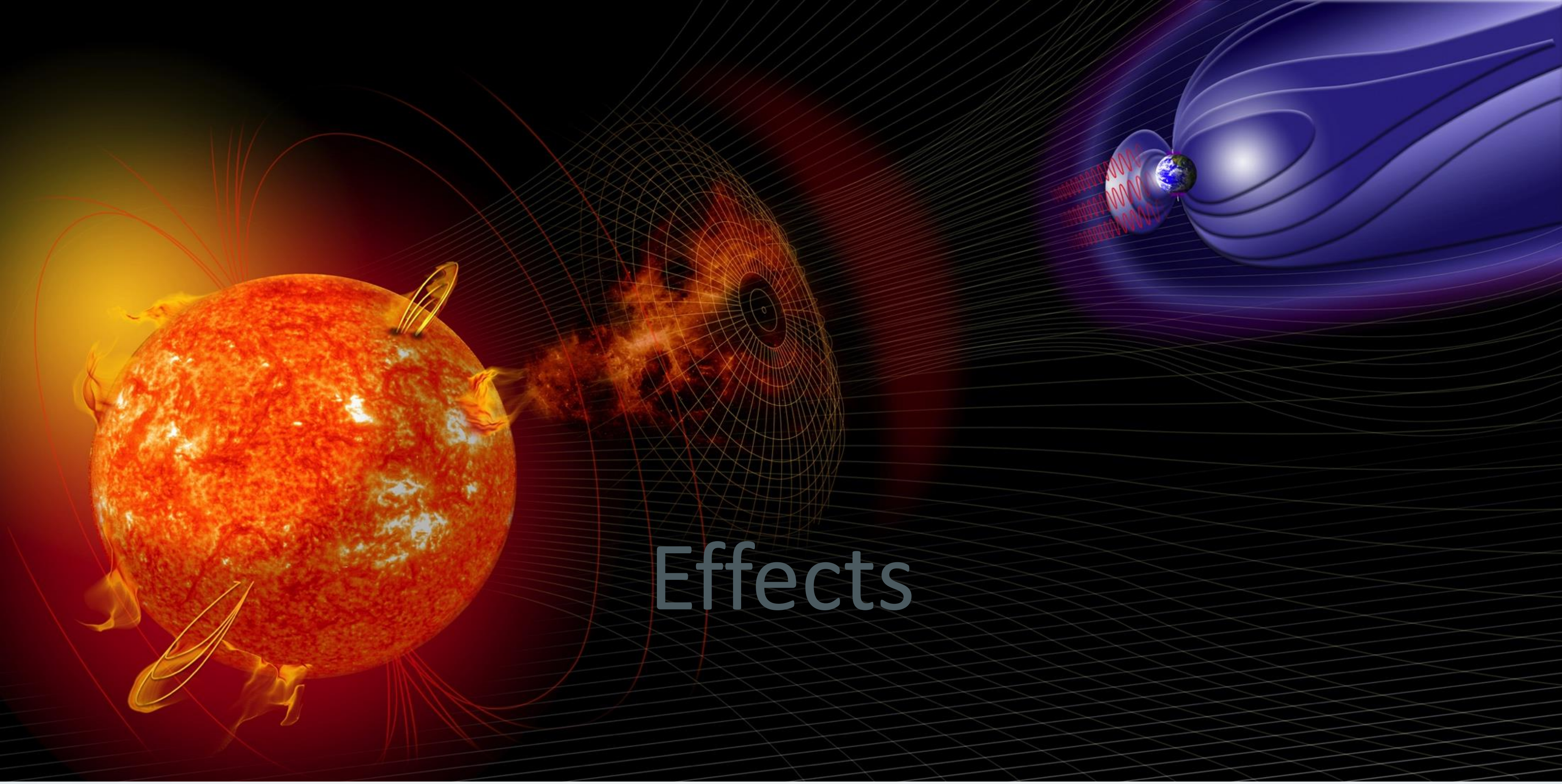
Hemispheric Power Data – High latitudes



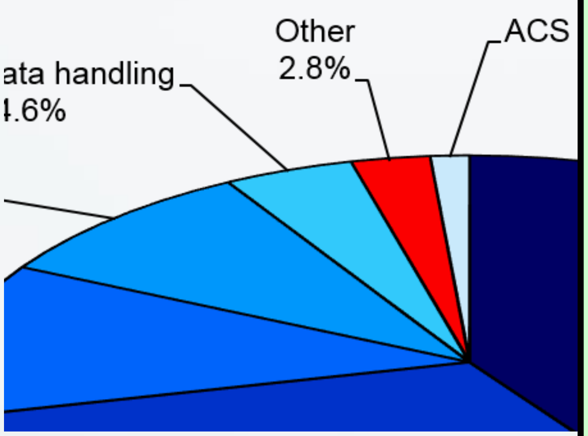
Dst – Low latitudes



Effects



Space Weather Risk to Satellites



Space Environment Impacts on Space Systems		
Anomaly Diagnosis	Number	%
ESD-Internal, surface and uncategorized	162	54.1
SEU (GCR, SPE, SAA, etc.)	85	28.4
Radiation dose	16	5.4
Meteoroids, orbital debris	10	3.3
Atomic oxygen	1	0.3
Atmospheric drag	1	0.3
Other	24	8.0
Total	299	100.0%

[Koons et al., 2000]

Anomalies and Failures Attributed to Charging

Spacecraft	Year(s)	Orbit	Impact*	Spacecraft	Year(s)	Orbit	Impact*
DSCS II	1973	GEO	LOM	Intelsat K	1994		Anom
Voyager 1	1979	Jupiter	Anom	DMSP F13	1995	LEO	Anom
SCATHA	1982	GEO	Anom	Telstar 401	1994, 1997	GEO	Anom/LOM
GOES 4	1982	GEO	LOM	TSS-1R	1996	LEO	Failure
AUSSAT-A1, -A2, -A3	1986-1990	GEO	Anom	TDRS F-1	1986-1988	GEO	Anom
FLTSATCOM 6071	1987	GEO	Anom	TDRS F-3,F-4	1998-1989	GEO	Anom
GOES 7	1987-1989	GEO	Anom/SF	INSAT 2	1997	GEO	Anom/LOM
Feng Yun 1A	1988	LEO	Anom/LOM	Tempo-2	1997	GEO	LOM
MOP-1, -2	1989-1994	GEO	Anom	PAS-6	1997	GEO	LOM
GMS-4	1991	GEO	Anom	Feng Yun 1C	1999	LEO	Anom
BS-3A	1990	GEO	Anom	Landsat 7	1999-2003	LEO	Anom
MARECS A	1991	GEO	LOM	ADEOS-II	2003	LEO	LOM
Anik E1	1991	GEO	Anom/LOM	TC-1,2	2004	~2GTO, GTO	Anom
Anik E2	1991	GEO	Anom	Galaxy 15	2010	GEO	Anom
Intelsat 511	1995	GEO	Anom	Echostar 129	2011	GEO	Anom
SAMPEX	1992-2001	LEO	Anom	Suomi NPP	2011-2014	LEO	Anom

*Anom=anomaly, LOM=Loss of mission, SF=system failure

Satellite Charging

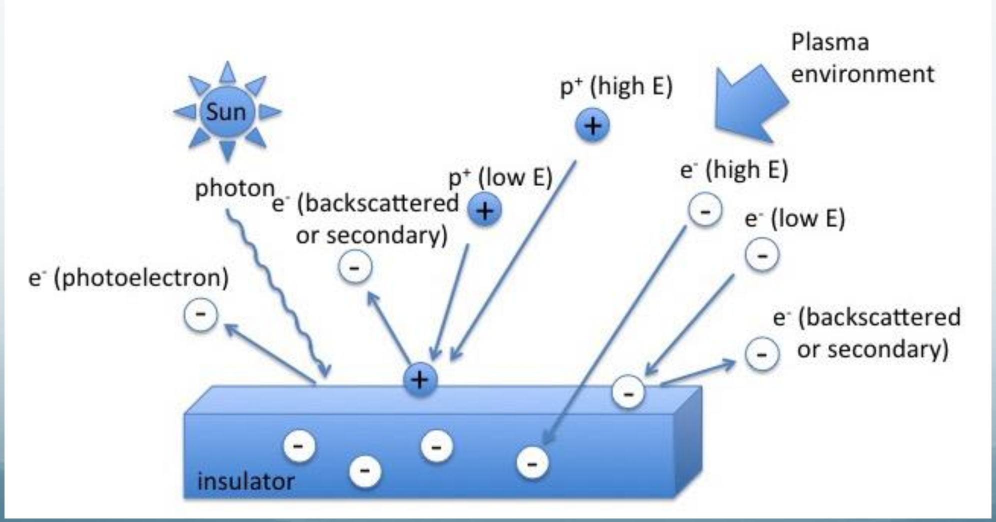
- Accumulation of charge (current) on or within the outer material of a spacecraft
  - Surface
  - Internal
- Charging can cause significant damage to spacecraft resulting in loss of mission, loss of functionality, loss of revenue
- Complicated physical process that is dependent on spacecraft configuration, material selection, and orbit (environment)
- Characterize charging environment and build spacecraft to withstand or avoid charging events
- Types of Discharges
  - Flashover – discharge from one outer surface to an adjacent surface
  - Punch through – discharge from outer surface to underlying ground
  - Discharge to space – discharge from outer surface of spacecraft to ambient plasma

Charging Process

- The net charge is due to the sum of the incident currents.

$$\frac{dQ}{dt} = \frac{d\sigma}{dt} A = C\frac{dV}{dt} = \sum_k I_k \approx \ 0 \text{ (at equilibrium)}$$

- Incident ions, incident electrons, backscattered electrons, conduction currents, secondary electrons, photoelectrons, and active current sources (beams, thrusters).



Adapted from Garrett and Minow, 2004

Internal Charging: Physics

$$\nabla \bullet \varepsilon E = \rho$$

$$\varepsilon = \kappa \varepsilon_0$$

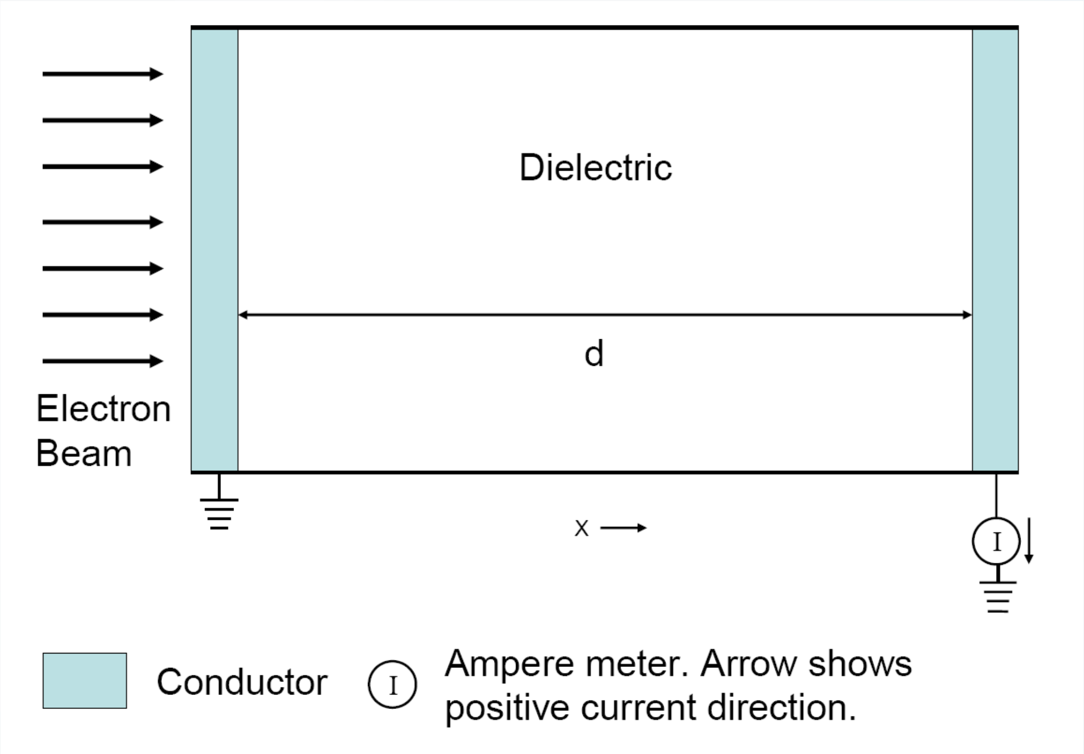
$$\nabla^2 \phi = -\rho/\varepsilon$$

$$\frac{\partial \rho}{\partial t} = -\nabla \bullet J$$

$$J = J_R + J_C$$

$$J = \sigma E$$
$$= \left(\sigma_{dark} + \sigma_{RIC}\right) E$$

$$\sigma_{RIC} = k\left(\frac{d\gamma}{dt}\right)^{\alpha} \qquad 0.5 < \alpha < 1.0$$



[*Jun et al.* 2007]

Solution to Poisson, continuity equation involves two problems:

- Radiation penetration with charge and energy deposition in material
- Electrostatic solution of fields from motion in insulator

Potential Distributions on Spacecraft Surfaces

- **Electrostatic potentials**
  - Due to net charge density on spacecraft surfaces or within insulating materials due to current collection to/from the space environment
- **Electrodynamic (inductive) potentials**
  - Modification of frame potentials without change in net charge on spacecraft
  - Plasma environment not required
  - Examples include
    - EMF generated by motion of conductor through magnetic field
    - Externally applied electric fields

Surface charging

$$\frac{dQ}{dt} = C\frac{d\phi}{dt} = \sum_k I_k$$ **~ 0 at equilibrium**

[c.f., *Whipple*, 1981; p. 272 *Wangness*, 1986; p. 210 *Jackson*, 1975; *Maynard*, 1998]

Internal (deep dielectric) charging

$$\vec{\nabla}\cdot\vec{D} = \vec{\nabla}\cdot\varepsilon\vec{E} = \vec{\nabla}\cdot\varepsilon(-\vec{\nabla}\phi) = \rho$$

$$\nabla^2\phi = -\rho/\varepsilon$$

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot J \quad \text{where } J = J_R + J_C$$

Electrodynamic (inductive) potentials

$\vec{F} = q(\vec{E} + \vec{v}\times\vec{B})$ Laboratory frame

$\vec{F}' = q\vec{E}'$ Spacecraft rest frame

$\vec{E}' = \vec{E} + \vec{v}\times\vec{B}$ Forces equal in both frames!

$$\varepsilon_m' = \oint_C \vec{E}'\cdot d\vec{S} = \oint_C (\vec{E} + \vec{v}\times\vec{B})\cdot d\vec{S}$$

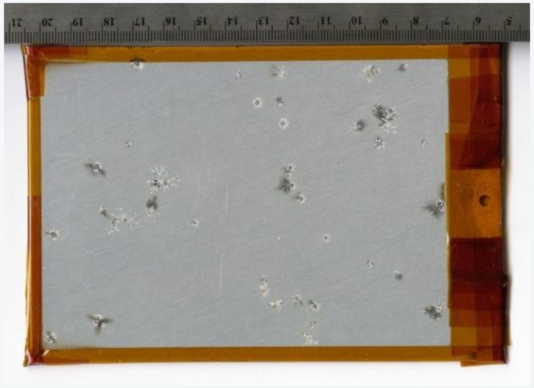
$$\Delta\varphi' = \oint_C (\vec{E} + \vec{v}\times\vec{B})\cdot d\vec{S}$$

Charging Anomaly and Failure Mechanisms

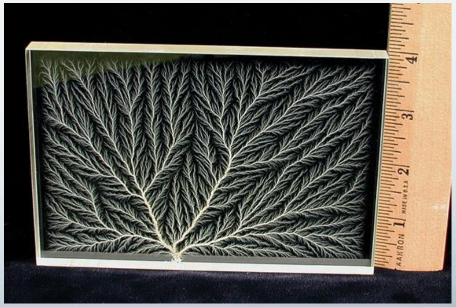
- Accumulation of excess negative charge or inductive re-distribution of charge generates potential differences between spacecraft and space (frame potential) or between two points on the spacecraft (differential potential)
- An electrostatic discharge (ESD) results when electric fields associated with potential differences ($\mathbf{E} = -\nabla\Phi$) exceed the dielectric breakdown strength of materials allowing charge to flow in an arc
- Damage depends on energy available to arc

$$E = \tfrac{1}{2}CV^2$$

- Charging anomalies and failures depend on
  - Magnitudes of the induced potentials and strength of the electric fields
  - Material configuration (and capacitance)
  - Electrical properties of the materials
    - Surface and volume resistivity, dielectric constant
    - Secondary and backscattered electron yields, photoemission yields
    - Dielectric breakdown strength

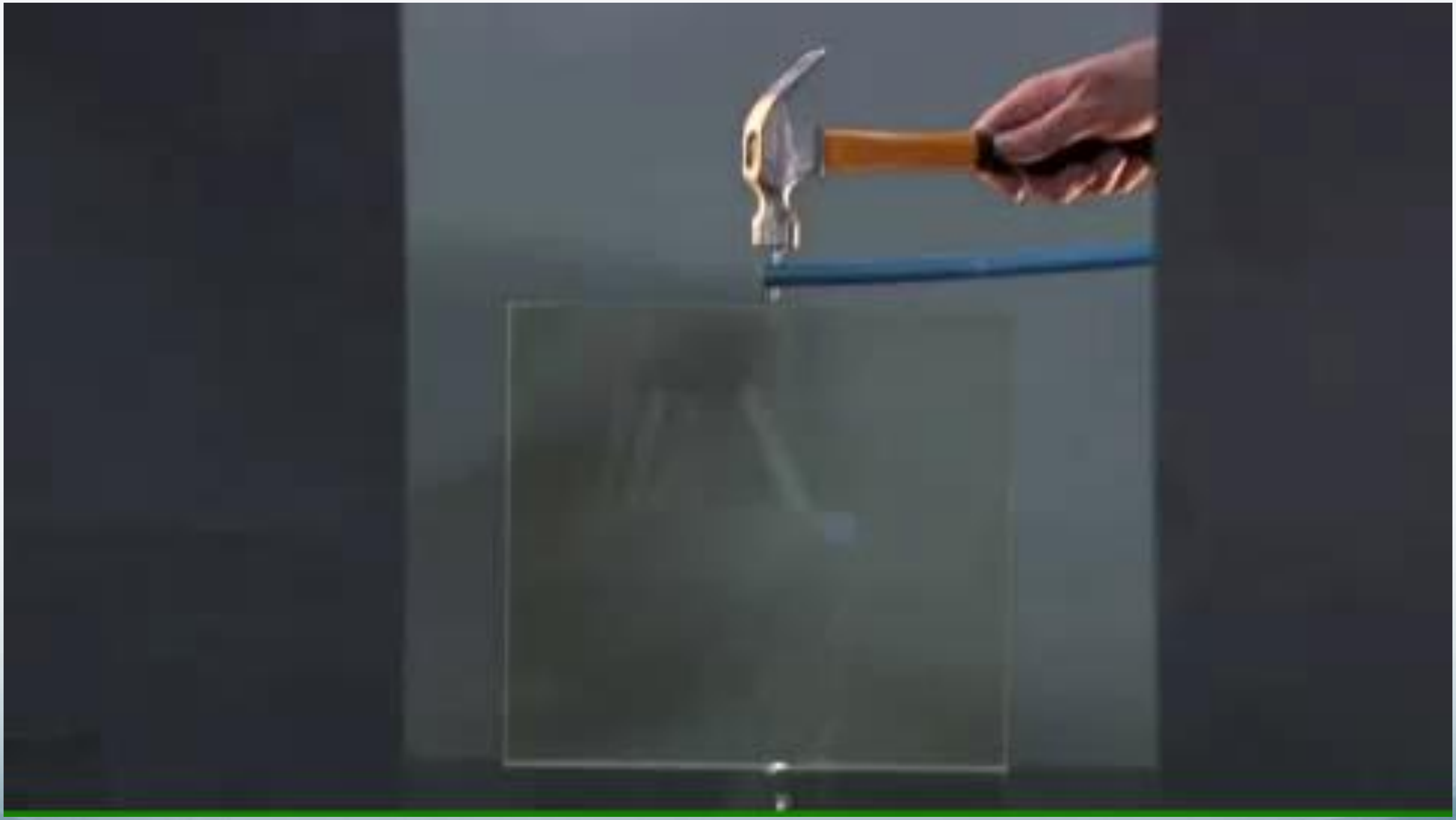


ISS MMOD shield 1.3 μm chromic acid anodized thermal control coating (T. Schneider/NASA)



PMMA (acrylic) charged by ~2 to 5 MeV electrons

Arcing Video



Impact of Charging on Spacecraft

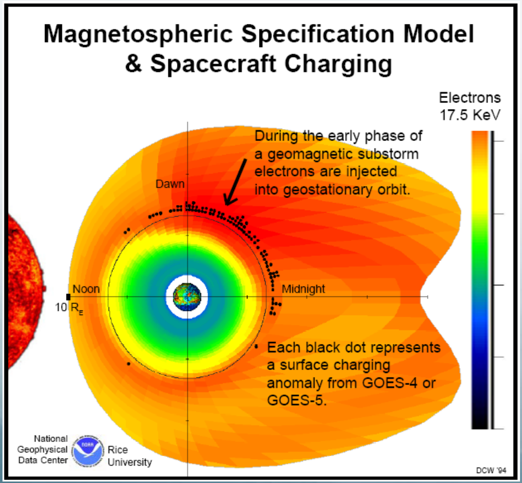
- Electrostatic discharge (ESD) currents
  - Compromised function and/or catastrophic destruction of sensitive electronics
  - Solar array string damage (power loss), solar array failures
  - Un-commanded change in system states (phantom commands)
  - Loss of synchronization in timing circuits
  - Spurious mode switching, power-on resets, erroneous sensor signals
  - Telemetry noise, loss of data

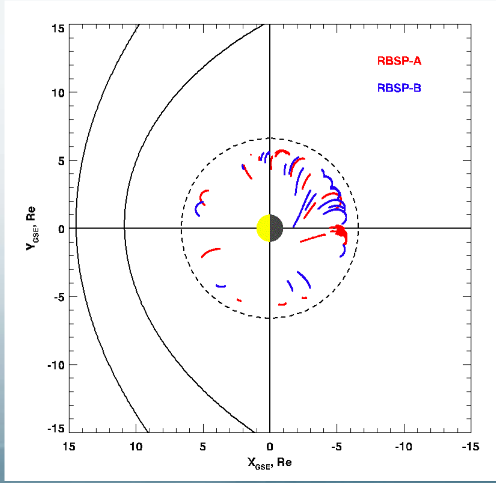
- Electromagnetic interference (EMI)
  - EMI noise levels in receiver band exceeding receiver sensitivity
  - Communications issues due to excess noise
  - Phantom commands, signals
- Material damage
  - ESD damage to mission critical materials including thermal control coatings, re-entry thermal protection systems, optical materials (dielectric coatings, mirror surfaces)
  - Re-attracted photo ionized outgassing materials deposited as surface contaminants
- Other
  - Compromised science instrument, sensor function
  - Modified “Ion line” charging signature in ion spectrum
  - Photoelectron contamination in electron spectrum
  - Parasitic currents and solar array power loss (LEO)

Surface Charging Locations

- GEO charging is more prevalent in the midnight to dawn sector.
- GTO, larger number in midnight-dawn sector, but sizable number at other local times
- Auroral charging occurs in the night time hemisphere of auroral regions.
- Internal charging independent of local time.

GOES 4, 5

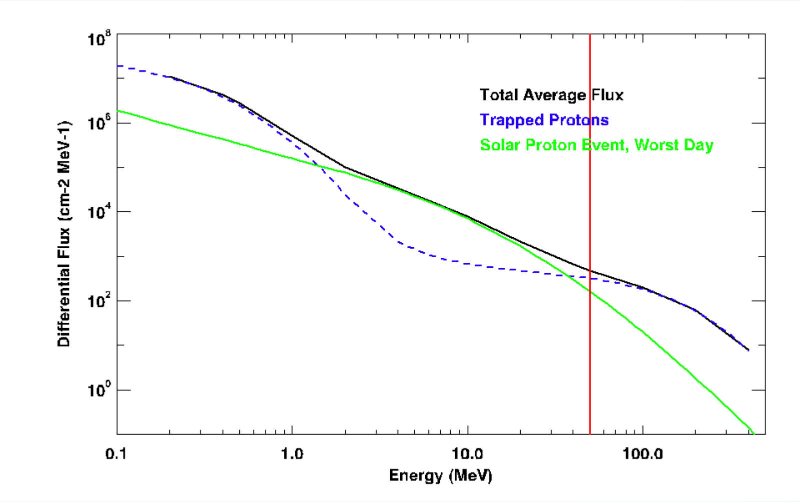


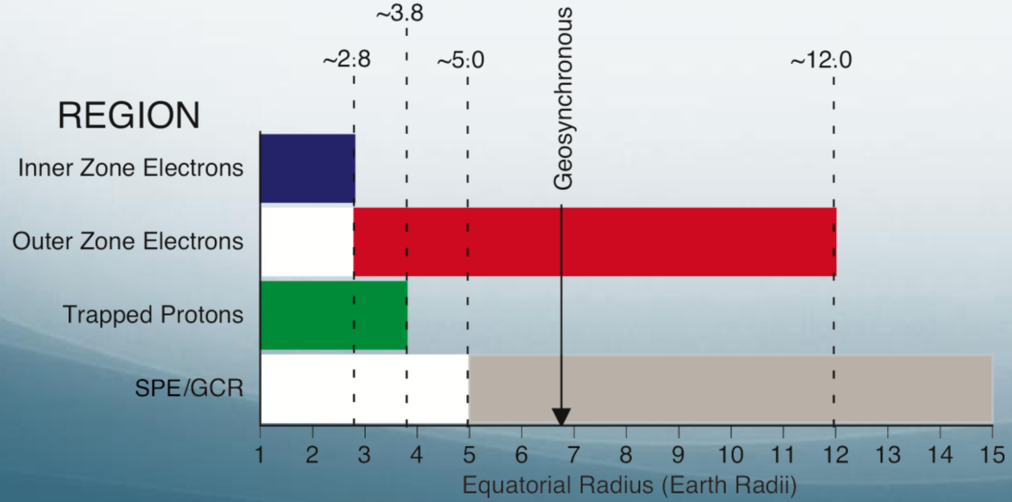


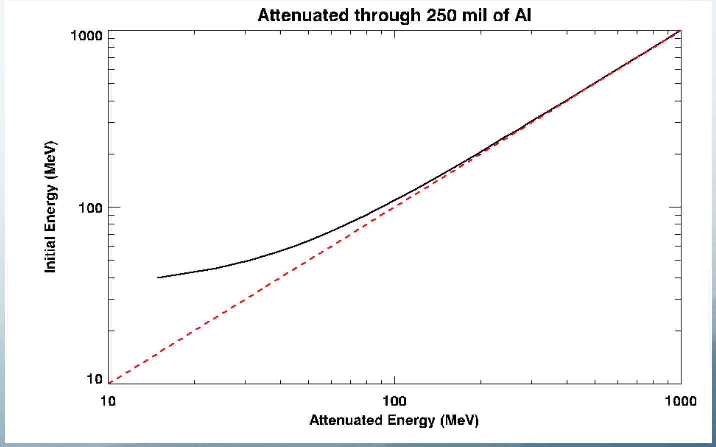
RBSP A, B

Radiation Effects

- Single event effects
- Total ionizing dose
- Displacement effects
- Typically mitigated through proper use of shielding material and part selection





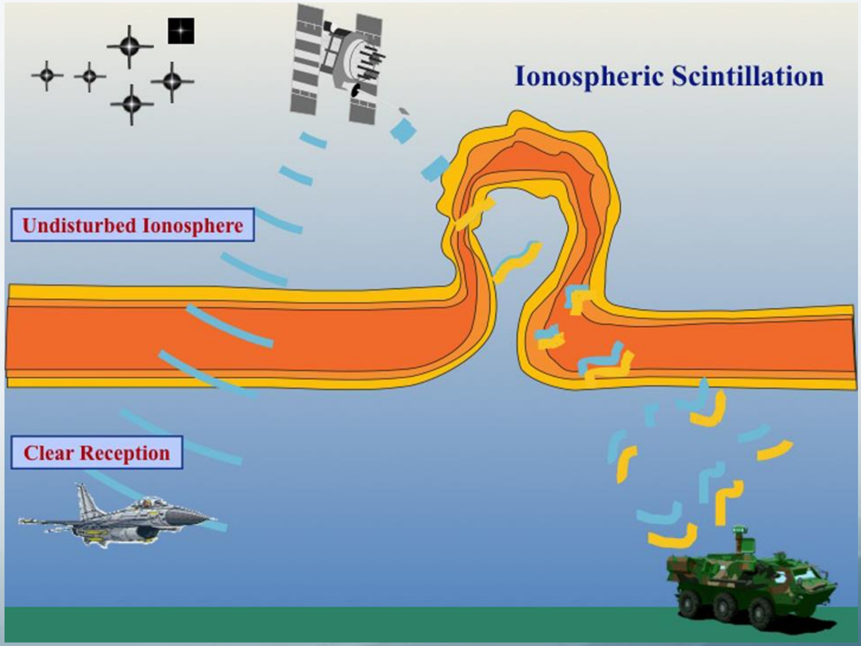


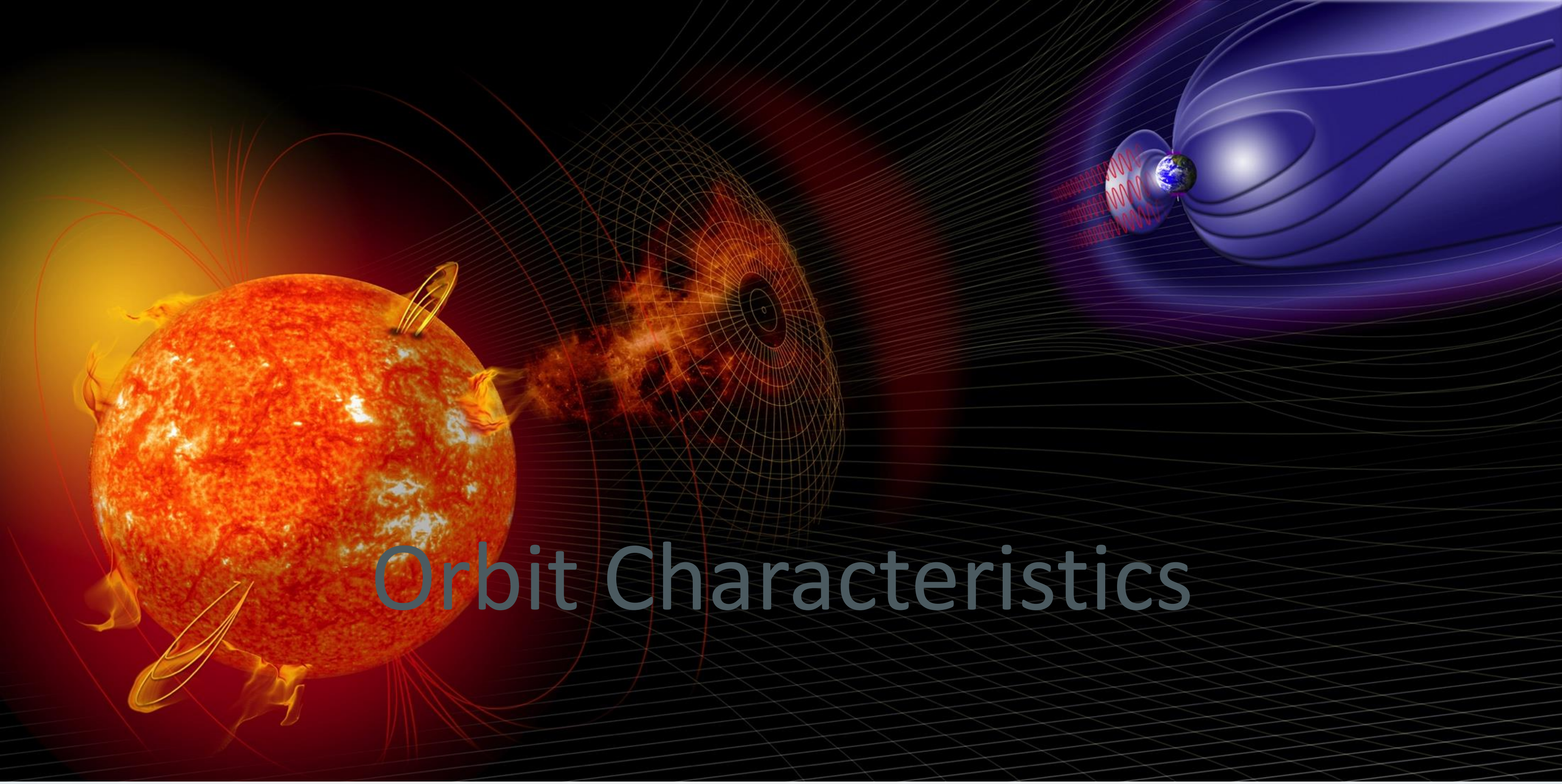
Scintillation

Scintillation is caused by an ionospheric disturbance that interferes with the communication from the satellite to ground (or vice versa).

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_o m_e}}$$

$$\omega_{pi} = \sqrt{\frac{n_i Z e^2}{\epsilon_o m_i}}$$

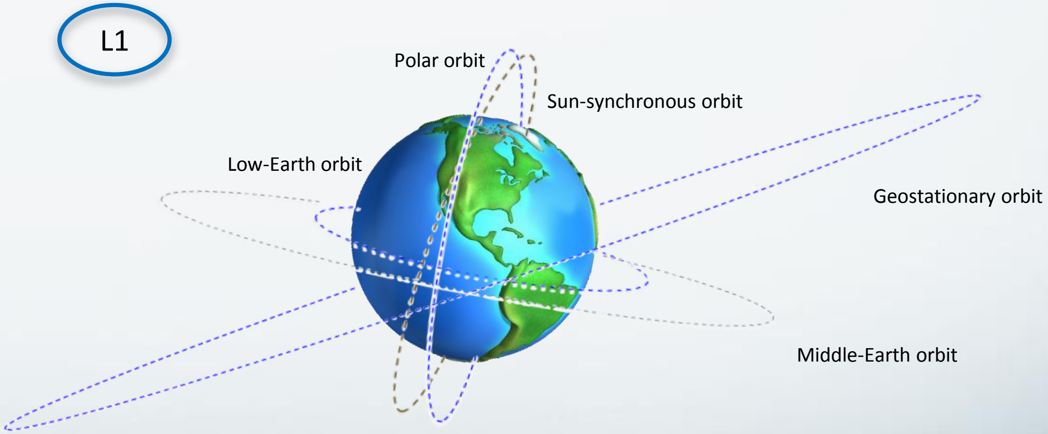




Orbit Characteristics

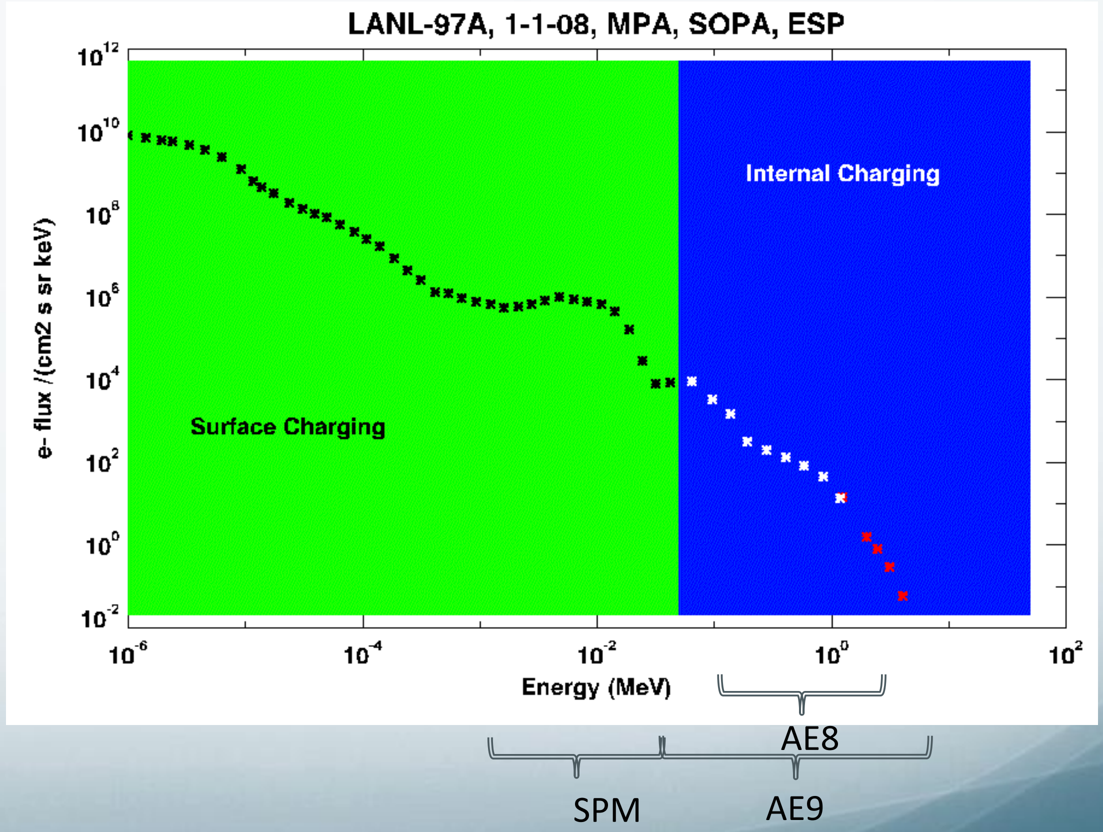
Different Orbits

- LEO
- Polar, sun-synchronous
- GEO
- MEO
- Radiation Belts
- L1, Interplanetary
- Lunar
- Jupiter, etc



GEO

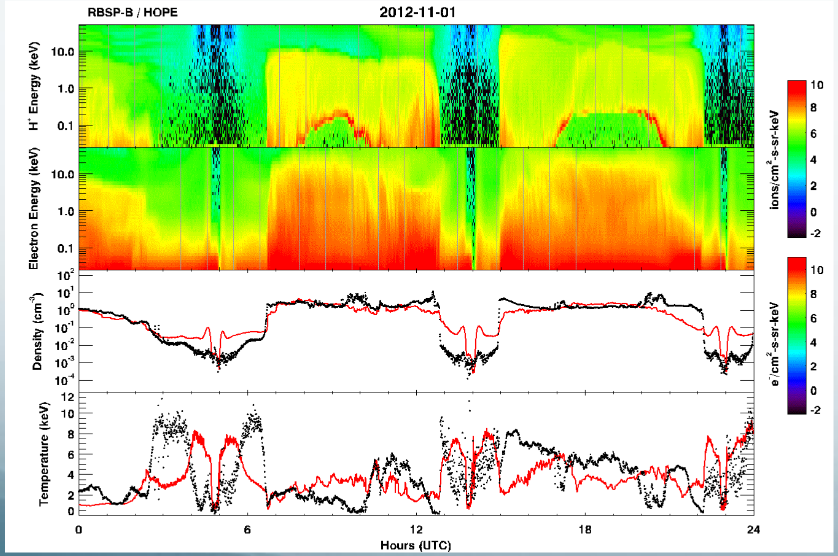
- Surface and Internal Charging
- Radiation



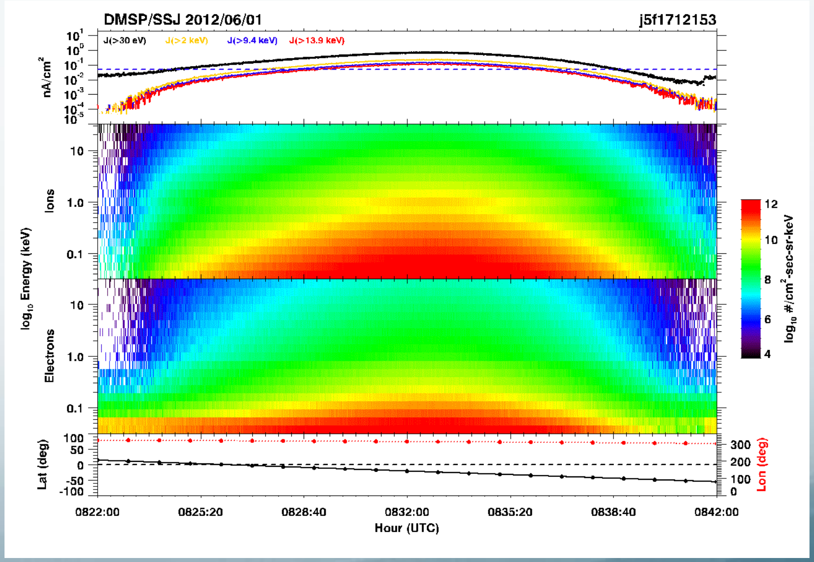
Radiation Belts

- Radiation, internal charging
- Always a problem

Radiation Belts

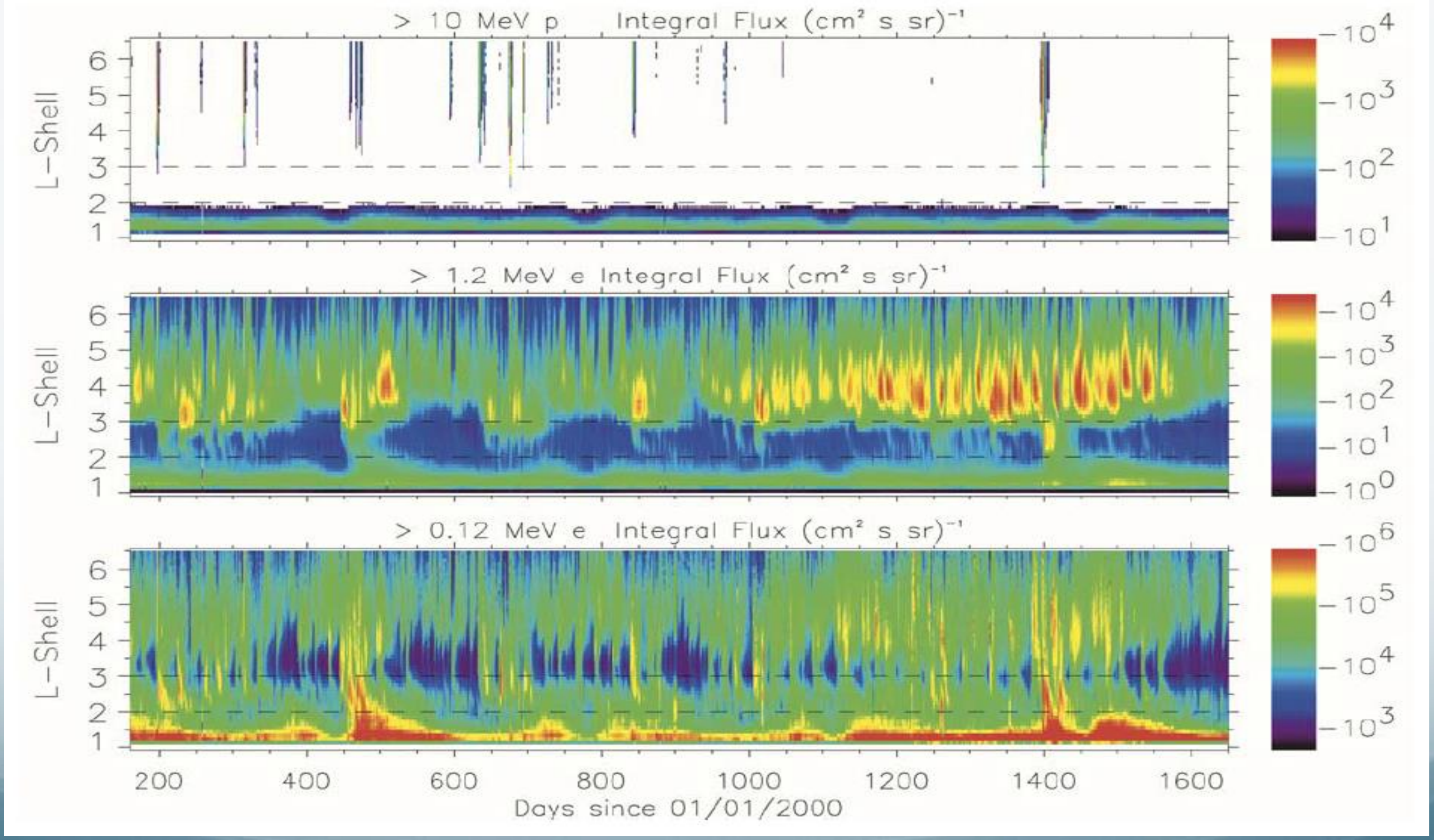


South Atlantic Anomaly



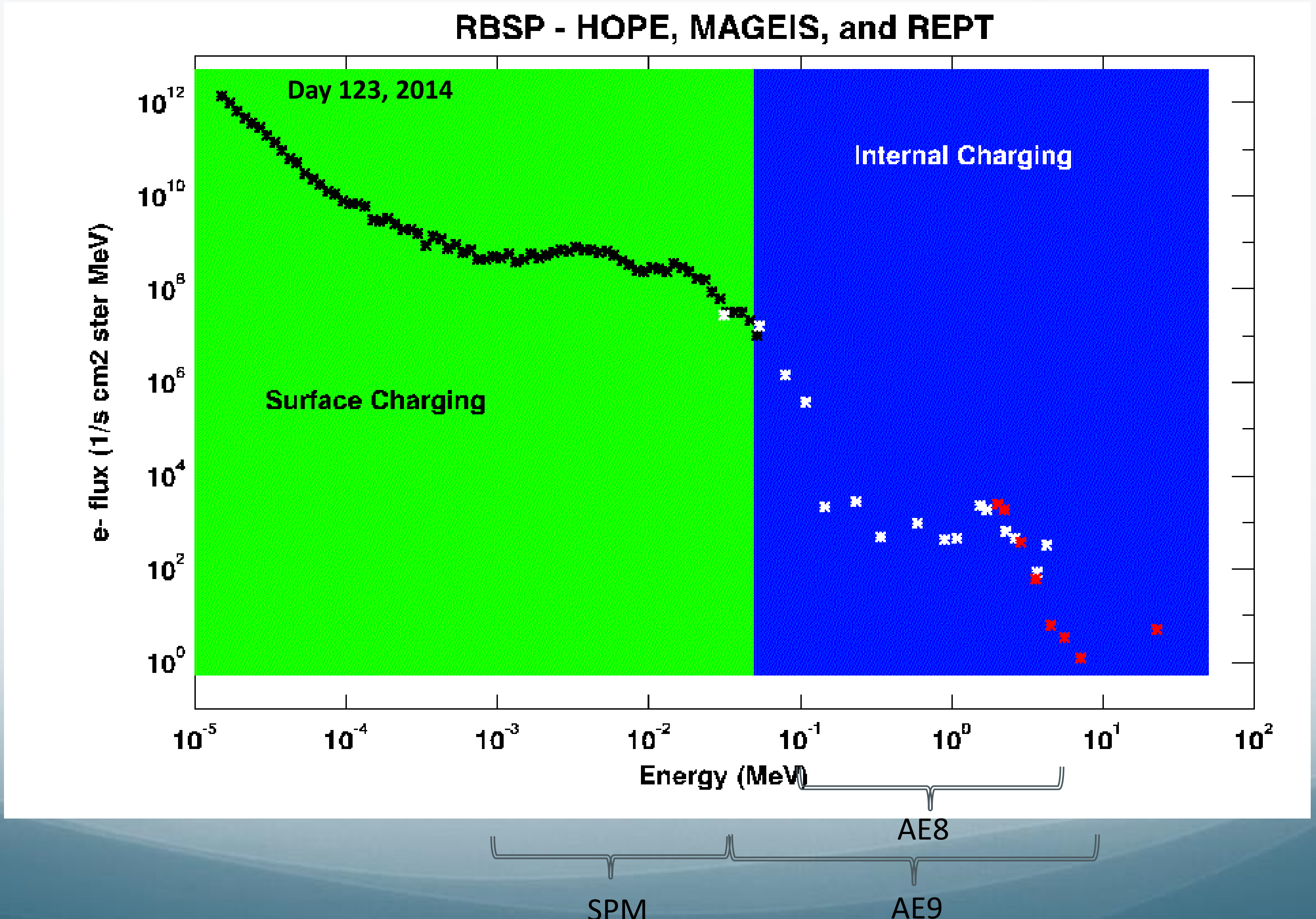
Relative stability of inner belt e-, proton populations compared to strong variability in outer belt electron populations

TSX-5: 410 km x 1710 km x 69⁰ inclination



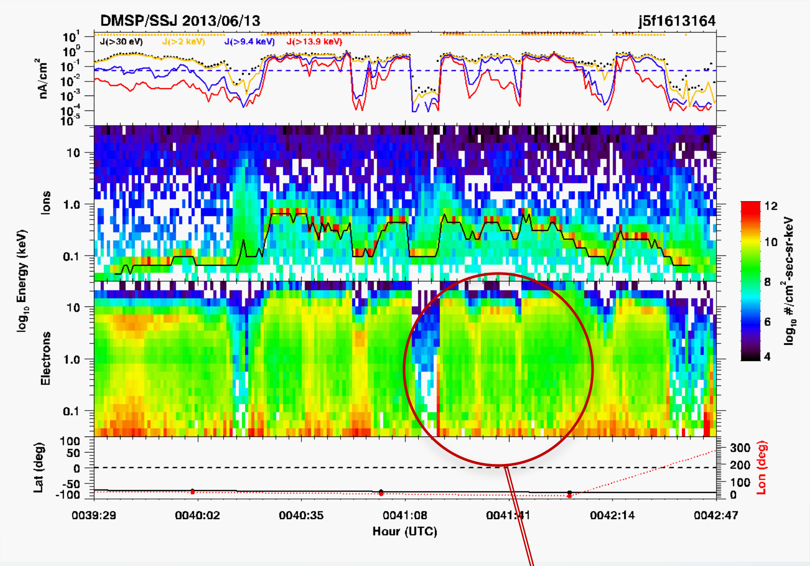
Brautigam et al., 2004

Radiation belts



Polar

- Surface, internal, radiation
- Rule of thumb
  - Satellite is in darkness
  - An intense, energetic electron (> 14 keV population) precipitation event is required (flux > 10^8 electrons cm^{-2} s^{-1} sr^{-1})
  - Locally depleted (< 10^4 cm^{-3}) ambient plasma density
- Fontheim distribution
  - power law, which models the backscattered and secondary electron fluxes, typically from 200 eV – 1 keV,
  - Maxwellian, which models the energetic part of the spectrum,
  - Gaussian, which models the inverted V part of the spectrum that represents the monoenergetic high energy beam.



Inverted V

Backscattered and secondary e- fluxes

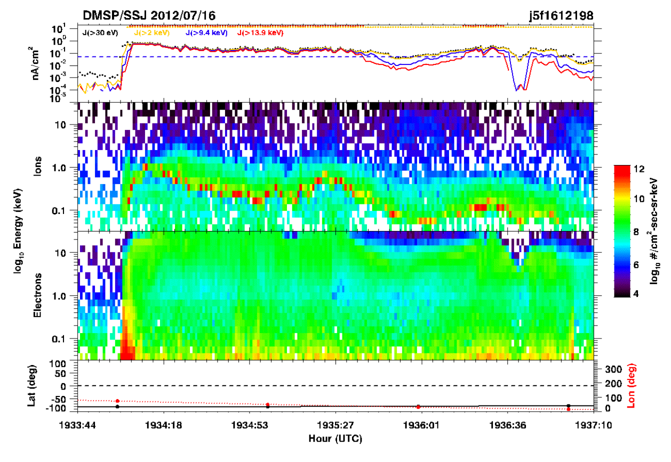
Energetic spectrum

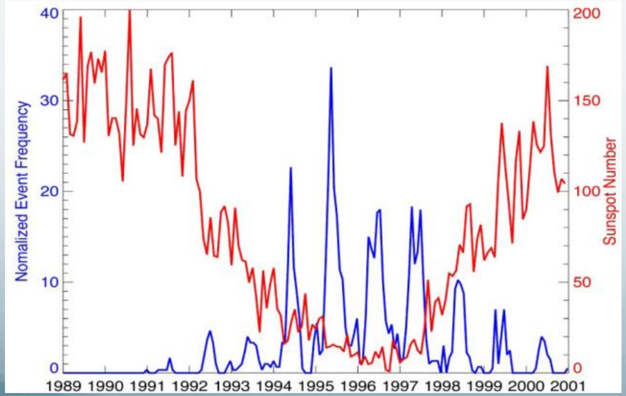
Monoenergetic high energy beam

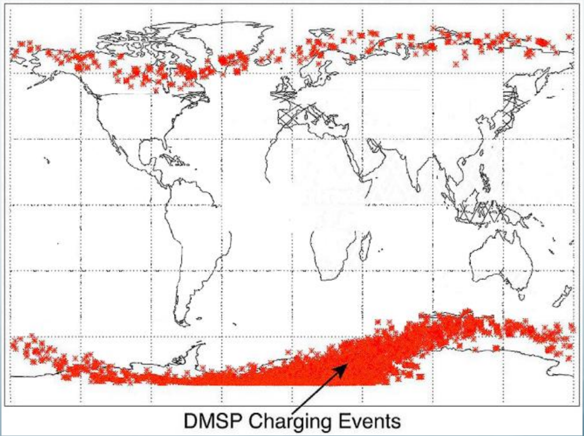
$$\varphi(E) = \alpha E^{-\alpha} + Cn\frac{E}{(kT)^{3/2}}e^{-E/kT} + EAe^{-\left[\frac{(E-E_0)}{\Delta}\right]^2}$$

Auroral Charging

Auroral charging is readily identified from the “ion line” signature that appears in ion electrostatic analyzer records. The ion line is the result of ambient low energy ions accelerated by the spacecraft potential from an initial energy E_0 ~ 0 eV to a final energy $E = E_0 + q\phi$ eV where q is the charge of the ion and ϕ the spacecraft surface potential in volts.



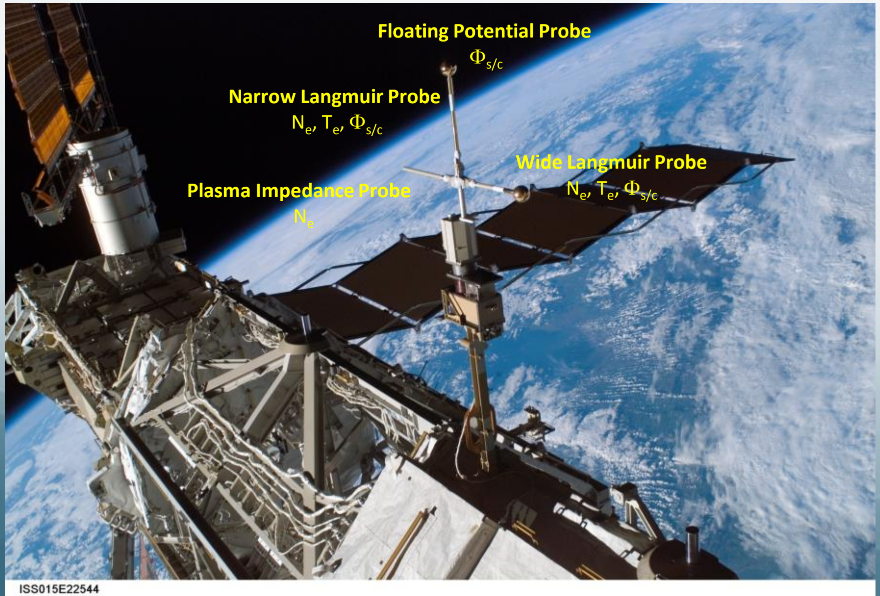


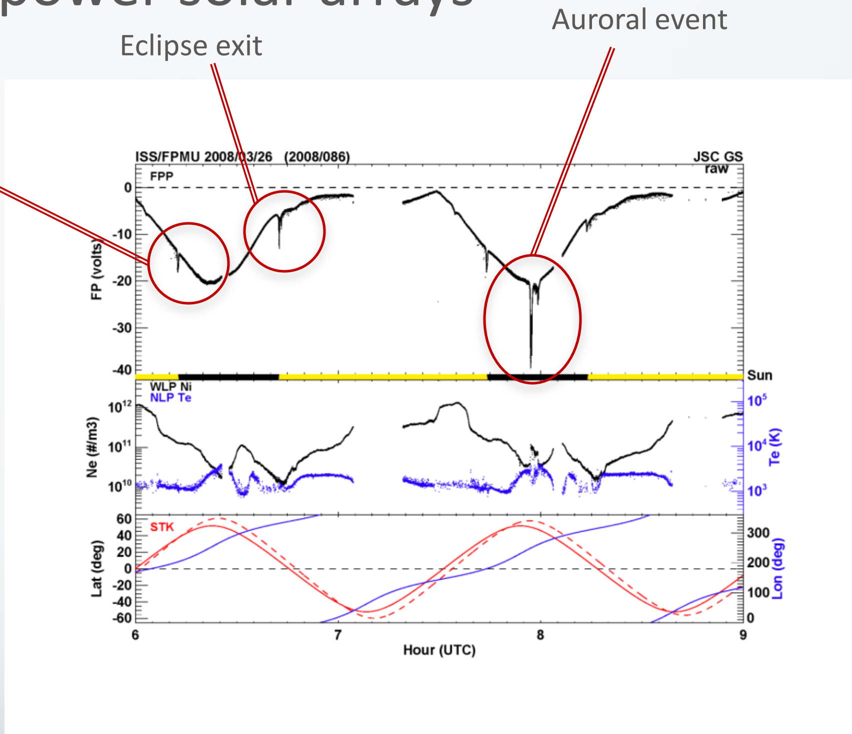


(from *Anderson*, 2001)

LEO

- Surface charging only with high power solar arrays
- Scintillation
- Atomic oxygen
- FPMU/ISS data





Mitigation Strategies

Environment Models

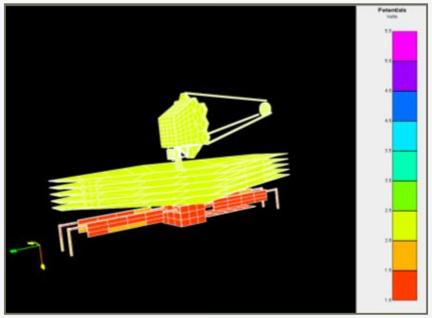
- IRI
  - Statistical
  - 50-2000 km
  - Monthly averages in the non-auroral ionosphere for magnetically quiet conditions
  - Uses data from ionosondes, ISR, topside sounders, satellite and rocket observations
  - Electron density, electron Temperature, ion temperature, ion composition (O^+, H^+, He^+, NO^+, O_2^+), ion drift, TEC
- AE8 / AP8
  - Statistical
  - e^- is 0.1-7 MeV
  - Protons is 0.1-400 MeV
- AE9 / AP9
  - Monte Carlo model
  - Electrons: 40 keV - 10 MeV
  - Protons: 100 keV – 2 GeV
  - Standard Plasma Model (SPM): electrons 1-40 keV, protons 1.15-164 keV

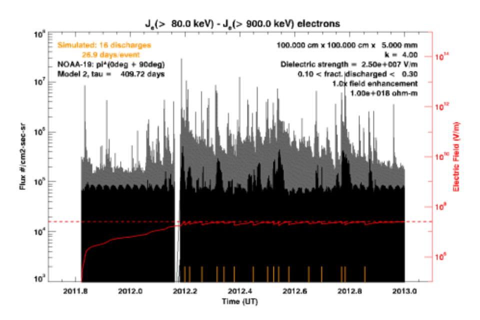
Analysis Models

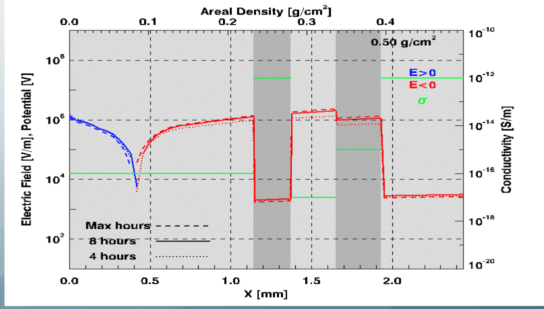
- Internal Charging - NUMerical Intergration (NUMIT)
  - 1D internal charging code that iteratively solves a set of equations.
  - Estimates currents, voltages, and electric fields as a function of depth in dielectrics
- Surface Charging - Nascap-2k
  - 3D analytic surface charging code that calculates the interaction of the spacecraft with the surrounding plasma environment
  - PIC calculations are used when required
  - Estimates surface currents, potentials, and electric fields on the outer surface of the spacecraft
- Radiation Effects
  - CRÈME – 1D radiation transport model (SEUs)
  - Novice – 3D radiation model that calculates dose

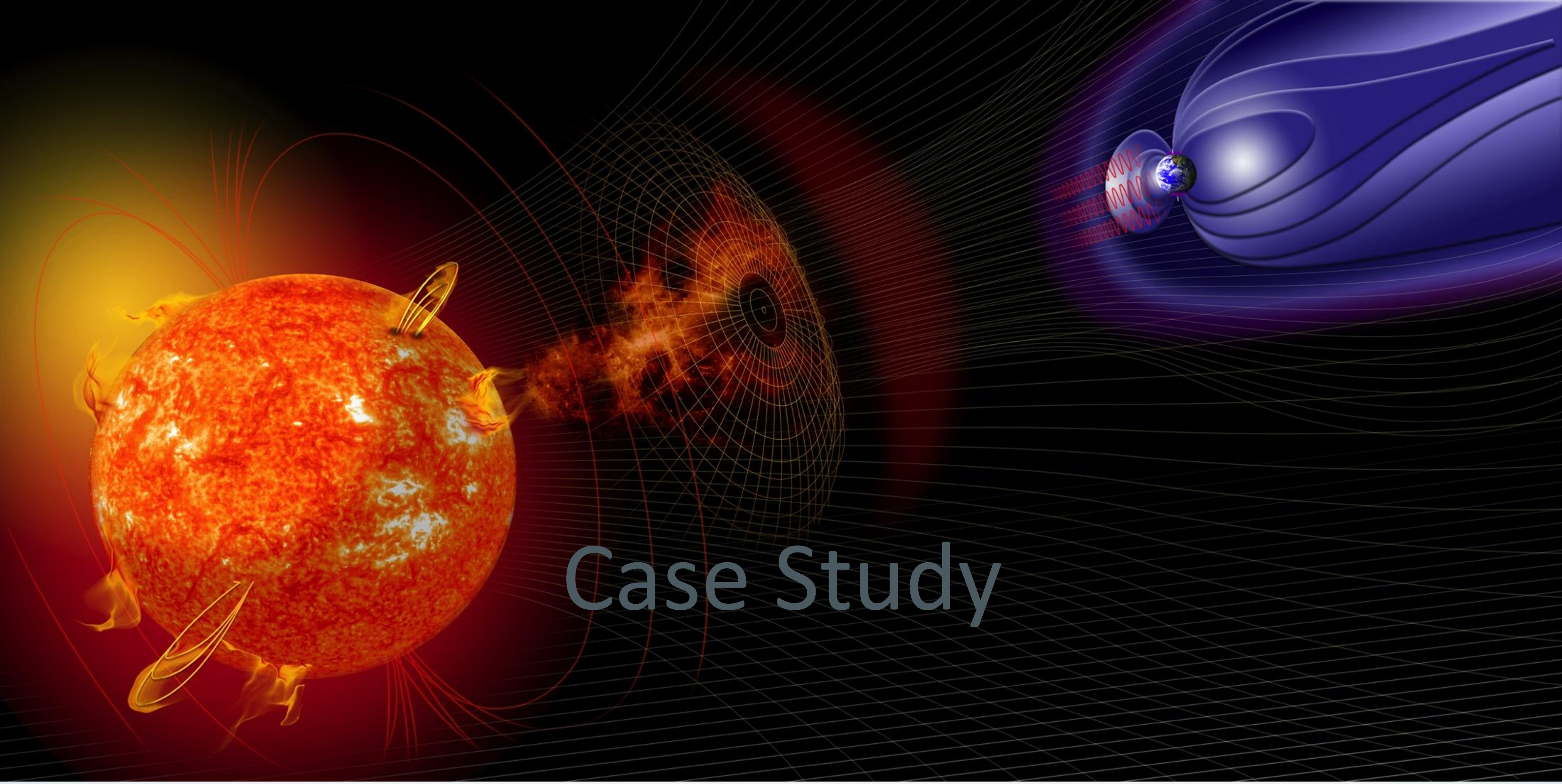
Mitigation Strategies

- Follow good EMC, grounding/bonding and charging design practices
  - Ground conductive materials to assure an equipotential (eliminate differential charging)
  - Use static dissipative materials when conductors can not be used
- Analyze spacecraft configuration in charging environment
  - Nascap-2k, In.cam, NUMIT
- Test insulating materials with electron beams at relevant energy (10's keV) and current (~1-10 nA/cm^2) to determine if (a) arcing will occur and (b) if it will result in damage









Case Study

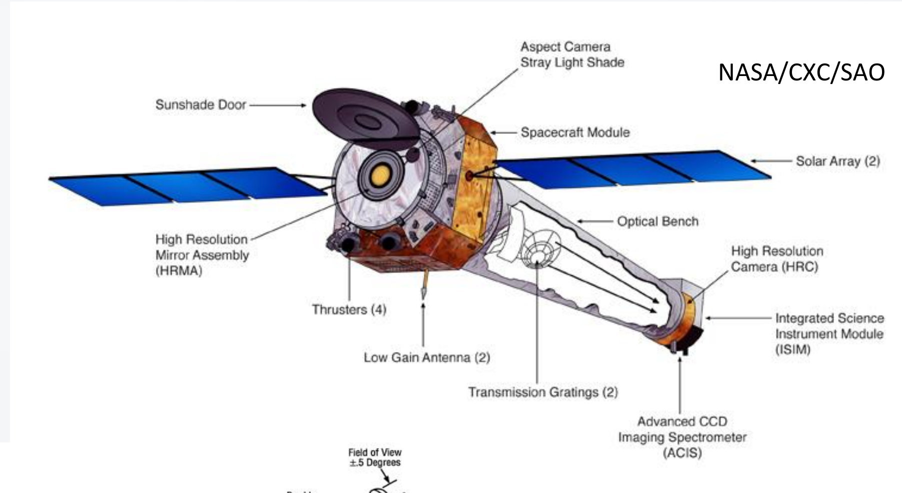
Chandra X-Ray Observatory (CXO)

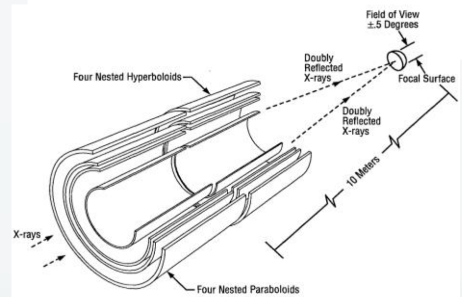
- Launched 23 July 1999 by STS-93
- Current orbit:

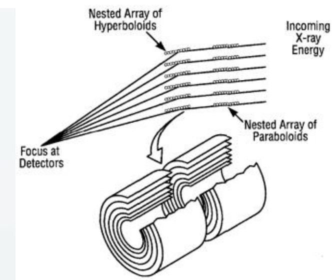
  ~1.5 Re x 22 Re x 67°, ~64.5 hour period

- Mission
  - 5-year primary science mission
  - Currently in 2nd 5-year extension
  - Planning for 3rd to 2019
- Advanced CCD Imaging Spectrometer (ACIS) is CXO's premier science most often requested in observatory proposals
  - Degradation of the 8 front illuminated ACIS CCD detectors was observed to be much worse than expected soon after launch, 2 back illuminated CCD's immune to damage
  - ~5 years worth of degradation in a single perigee passage
  - Damage mechanism identified as soft protons (~100 to 200 keV) depositing energy in CCD substrate
- ACIS cannot be operated in high flux, soft proton environment within the magnetosphere and solar particle events

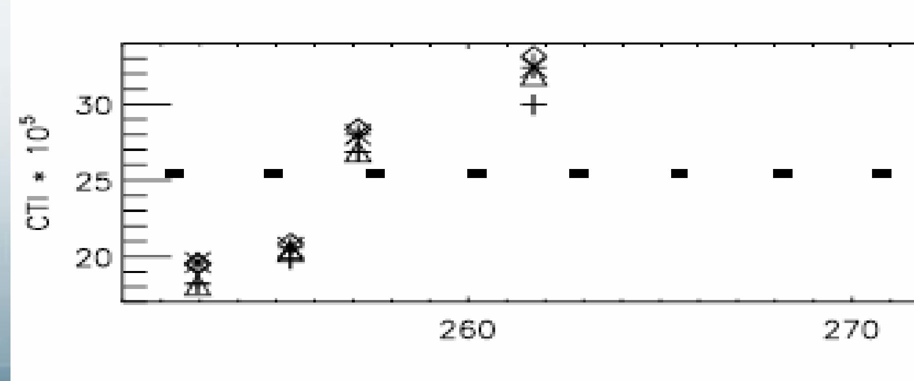
NASA/CXC/SAO







http://chandra.harvard.edu/about/top_ten.html



ACE Radiation Issue

- Chandra's Advanced CCD Imaging Spectrometer (ACIS) is susceptible to radiation degradation when exposed to energetic protons
  - Ion interactions with CCD material generates electron trapping sites in active region of CCD, increases the Charge Transfer Inefficiency (CTI)
  - Increased CTI results in reduction of CCD resolution
- Energetic proton sources
  - Cosmic ray background
    - Directly penetrate spacecraft hull, low flux
    - Manageable background degradation
  - 100 to 200 keV protons
    - High proton flux trapped in Earth's magnetic field (radiation belt, ring currents)
    - keV protons easily shielded, but scatter down the optical path onto CCD detector
    - Degradation only occurs on front illuminated CCD's
- Mitigation
  - Schedule observations in low proton flux environments
  - Move ACIS to shielded position during radiation belt passages

Environment Model

- **Proton flux model is required to determine safe locations along spacecraft orbit where ACIS detector can be used**
  - **Model must provide proton flux in outer magnetosphere, magnetosheath, and solar wind**
    - AP-8 is appropriate only for trapped protons in radiation belts
  - **Chandra approach was to create a database driven model**
    - MSFC/EV44 developed the CRM for Chandra program use
    - Empirical model of the free field outer magnetosphere, magnetosheath, and solar wind ion fluxes in energy range of interest to CXO

- **Applications for CRM**
  - **Mission planning**
    - CRM incorporated into the CXO off-line mission planning system to aid in determination of safing times for ACIS detector
    - CRM provides additional orbit “events” to those determined for radiation belt passage using AP-8 model
  - **Near-real-time environment tool**
    - Assess the ion fluence for individual orbits
    - Tool for management of the CTI ACIS degradation

Data Sources

Geotail

Energetic Particle and Ion Composition (EPIC) Ion composition Spectrometer (ICS) instrument

Polar

Comprehensive Energetic Particle and Pitch Angle Detector (CEPPAD) Imaging Proton Spectrometer (IPS) instrument

EPIC/ICS Energy Bands

Channel/ Species	Energy Band (keV/e)	Sector (deg)	Time Resolution Original[a] (sec)	Time Resolution Database[b] (sec)
P2/H$^+$	58.1 - 77.3	22.5	6	288
P3/H$^+$	**77.3 - 107.4**	**22.5**	**48**	**288**
P4/H$^+$	**107.4 - 154.3**	**22.5**	**48**	**288**
P5/H$^+$	**154.3 - 227.5**	**22.5**	**48**	**288**
P6/H$^+$	227.5 - 341.6	22.5	48	288
P7/H$^+$	341.6 - 522.5	22.5	48	288
P8/H$^+$	522.5 - 813.5	22.5	48	288
P9/H$^+$	813.5 - 1560.8	22.5	96	288
P10/H$^+$	560.8 - 3005.4	22.5	96	288

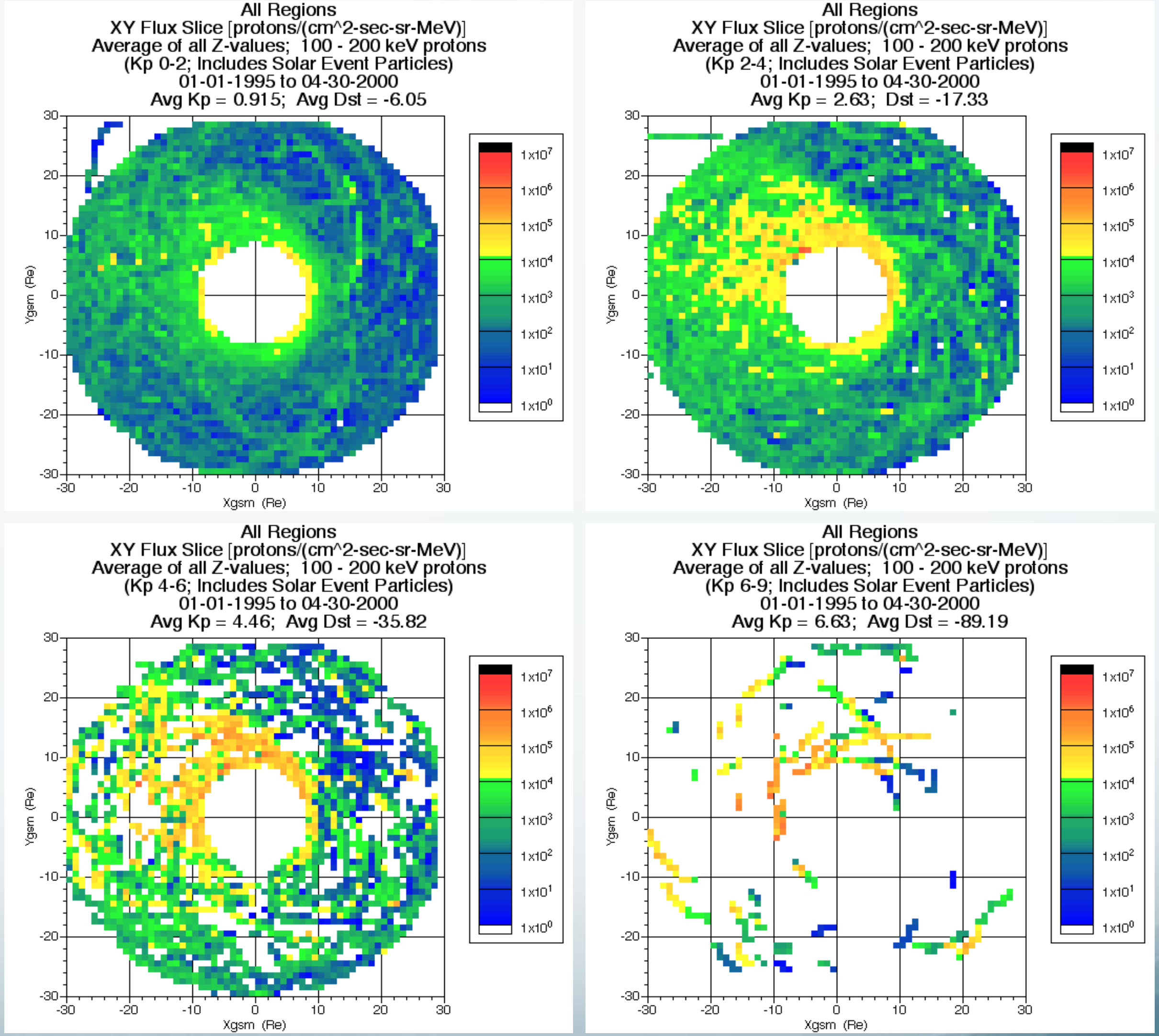
[a]Time resolution of original data.
[b]Time resolution of spin averaged data obtained from Principle Investigator.

CEPPAD/IPS Energy Bands

Channel/ Species	Energy Thresholds (keV) Set 1 Min	Set 1 Mid	Set 2 Min	Set 2 Mid
0/H+	16.8	18.9	13.9	15.6
1/H+	21.2	24.4	17.5	19.9
2/H+	27.9	32.4	22.6	26.2
3/H+	37.5	43.1	30.3	35.4
4/H+	49.6	57.2	41.4	48.1
5/H+	65.9	76.0	55.9	55.2
6/H+	**87.7**	**102.0**	**75.9**	**88.4**
7/H+	**118.0**	**138.0**	**103.0**	**121.0**
8/H+	**161.0**	**188.0**	**142.0**	**168.0**
9/H+	**221.0**	**259.0**	**198.0**	**234.0**
10/H+	303.0	355.0	277.0	327.0
11/H+	417.0	489.0	387.0	459.0
12/H+	574.0	674.0	543.0	643.0
13/H+	791.0	929.0	762.0	903.0
14/H+	1091.0	1281.0	1071.0	1269.0
15/H+	1505.0	2000.0	1505.0	2000.0

Proton Flux Observations

- Data sets are sparse at high geomagnetic activity
  - Kp < 4 well represented
  - Kp > 4 is sparse
- Example here is
  - Geotail Energetic Particles and Ion Compsition (EPIC) Ion Composition Spectrometer (ICS) records mapped onto equatorial plane
  - 1 Jan 1995 – 30 Apr 2000
- Sparse data utilized through mapping scheme

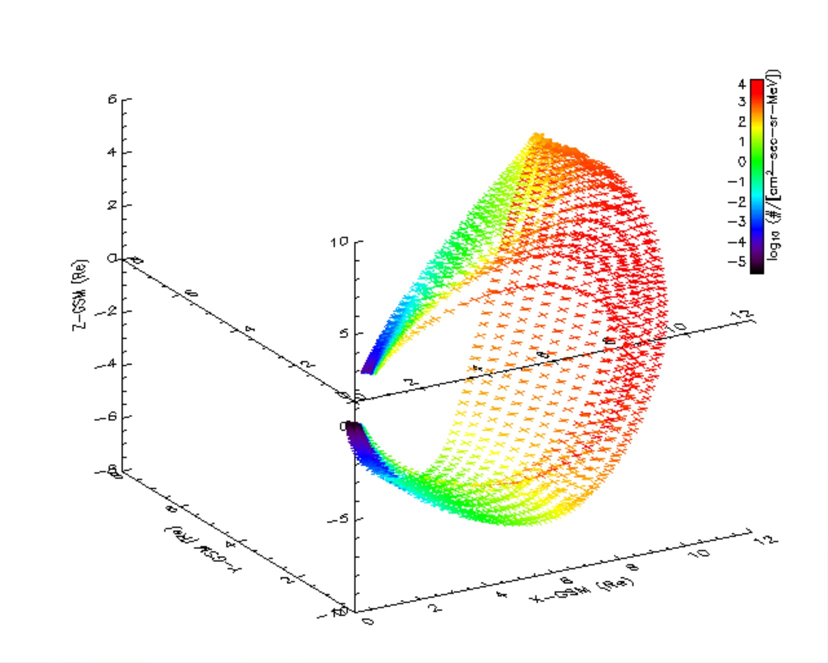


Proton Flux Correlation with Kp. EPIC/ICS ion flux values are projected onto the $Z_{GSM} = 0$ plane. The "hole" in the center is the perigee altitude of the Geotail spacecraft.

Field Line Mapping

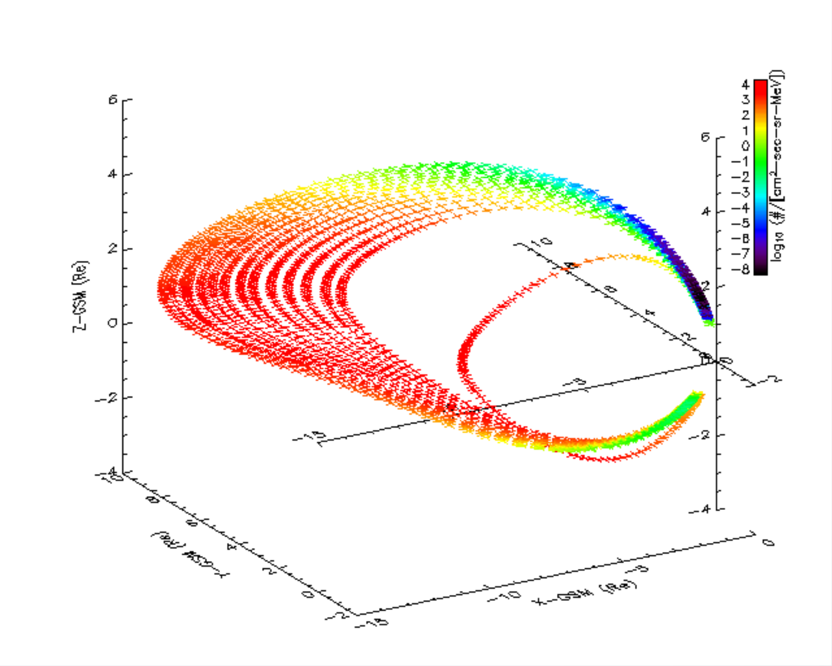
1999/200 Kp = 3.5 Dst = -20 nT

Solar wind proton flux=1×10^4 #/cm2-sec-sr-MeV Region =magnetosphere



Day

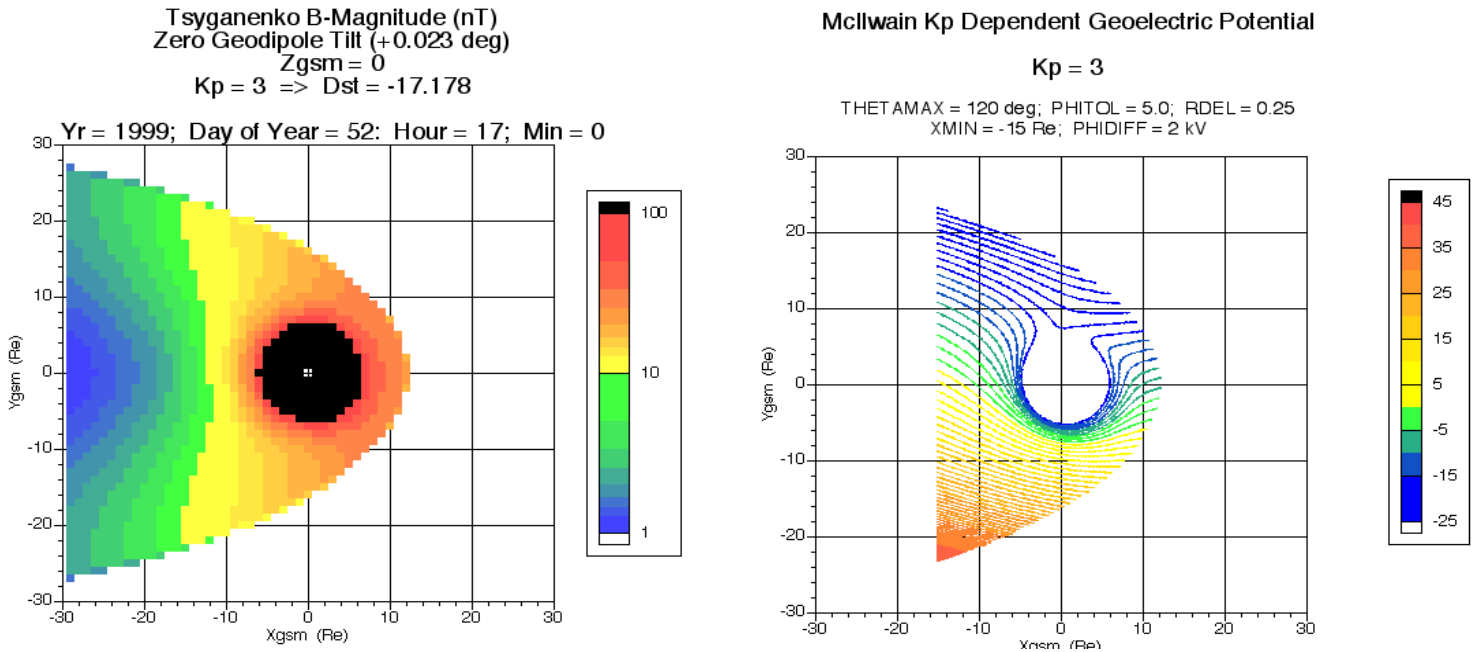
- X_{GSE} = 9 R_e, Y_{GSE} = 1 R_e, Z_{GSE} = 0 R_e
- Total flux points: 2191
- Restricted mapping points: ~393



Night

- X_{GSE} = -9 R_e, Y_{GSE} = -1 R_e, Z_{GSE} = 0 R_e
- Total flux points: 1978
- Restricted mapping points: ~579

Streamline Mapping

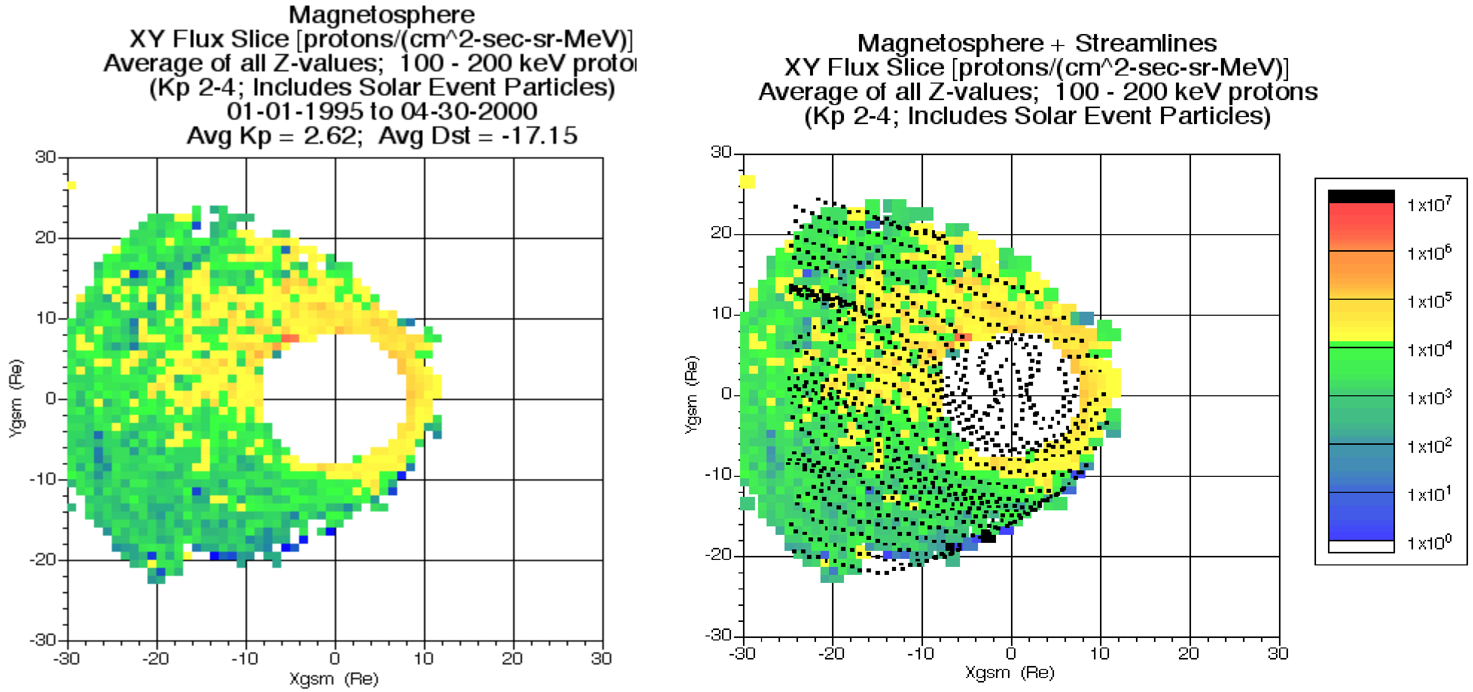


(a) **(b)**

Magnetic and Electric Potential Models. (a) Tsyganenko magnetic field intensity |B| (nT) and (b) geoelectric potential (kV) in the $Z_{GSM} = 0$ plane. These values will be used to compute an example set of streamlines shown in later figures.

- ExB drifts computed from magnetic field and Kp dependent electric potential models

Streamline Mapping



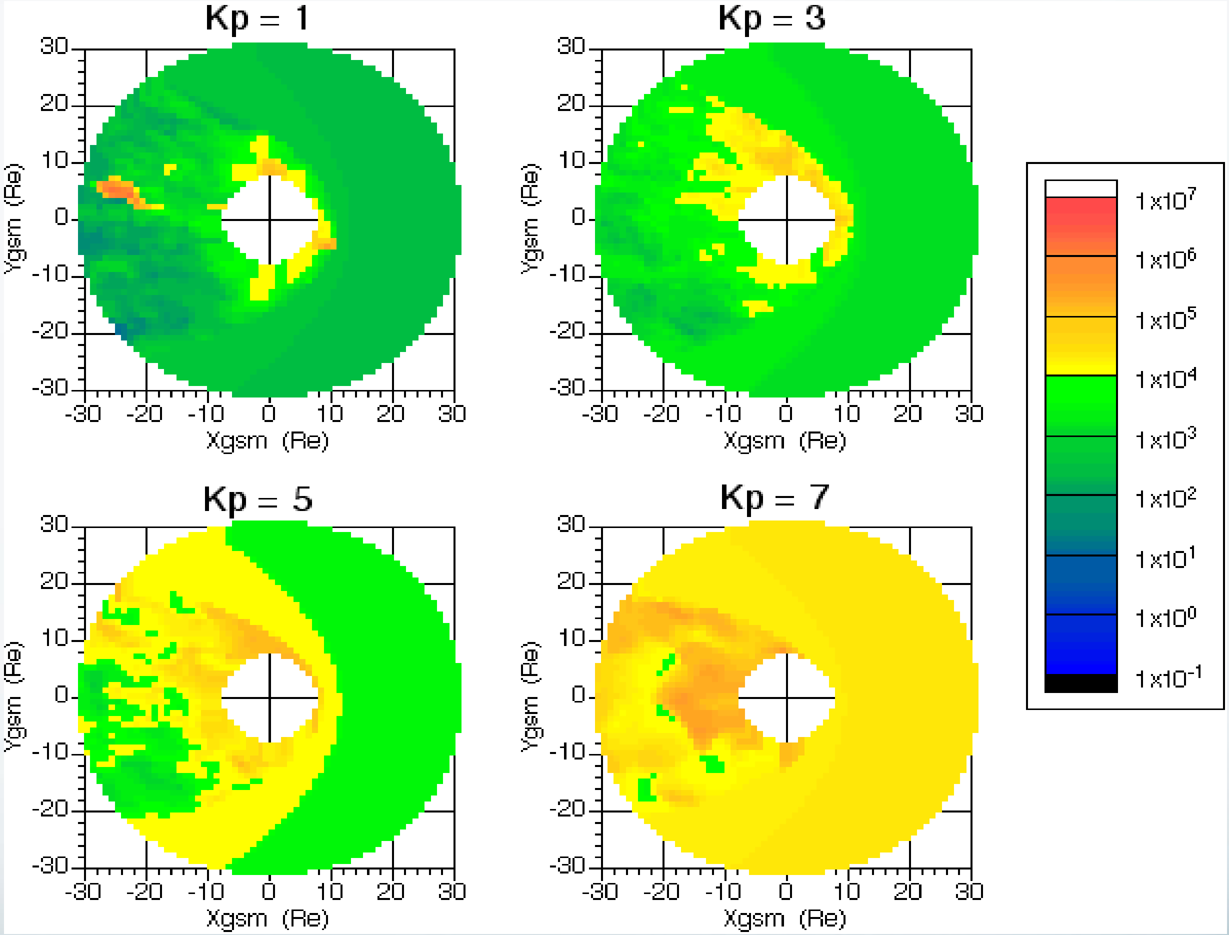
(a) **(b)**

Streamline Overlay on Magnetospheric Ion Flux Distributions. (a) Ion flux within the magnetosphere are projected onto the Zgsm = 0 plane. (b) Streamlines shown in Figure 2a are plotted over the ion flux distribution.

Example CRM Output

- Equatorial plane projection of CRM output for range of Kp values

- Model includes magnetosheath and solar wind



Ion Flux (protons/cm2-sec-sr-MeV) Output from CRM for a Range of K_p Values. Note the inward motion of the model magnetopause for higher Kp values (a property of the Tsyganenko magnetic field model) and the increase in flux.

Energetic Ions for Chandra X-Ray Observatory (CXO)

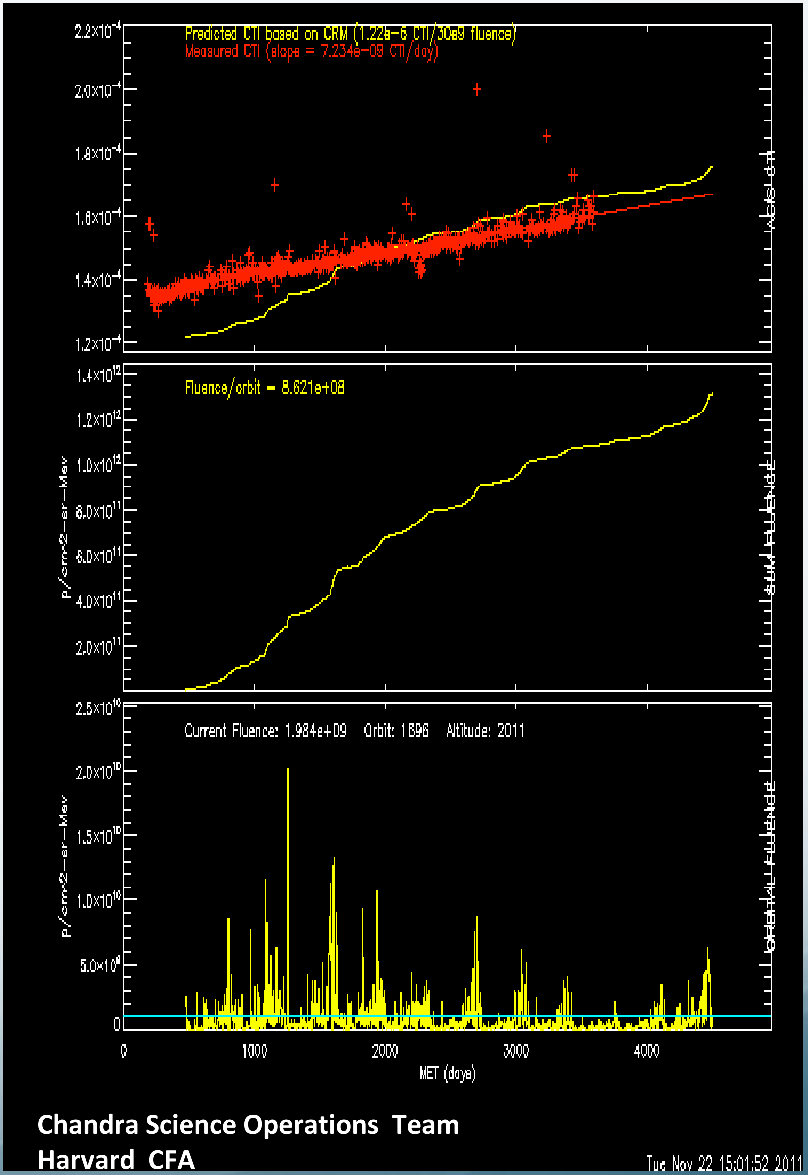
- NASA's CXO operations team utilizes real time L1 energetic ion measurements as a component of a radiation protection program to minimize exposure of the Advanced CCD Imaging Spectrometer (ACIS) detector to < 1 MeV protons with special emphasis on 100-200 keV protons

- NOAA "strawman" low energy ion measurements support CXO's real time monitoring requirements:
  - At least 4 differential channels from 50 keV to 1 MeV. One example is:

    50 – 100 keV, **100 – 200 keV**, 200 – 500 keV,

    500 – 1000 keV
  - 5 minute average (20 minutes every 4 hours)
  - Accuracy ≤20%
  - Latency ≤5 minutes (2 hour latency, 6 hour gap)

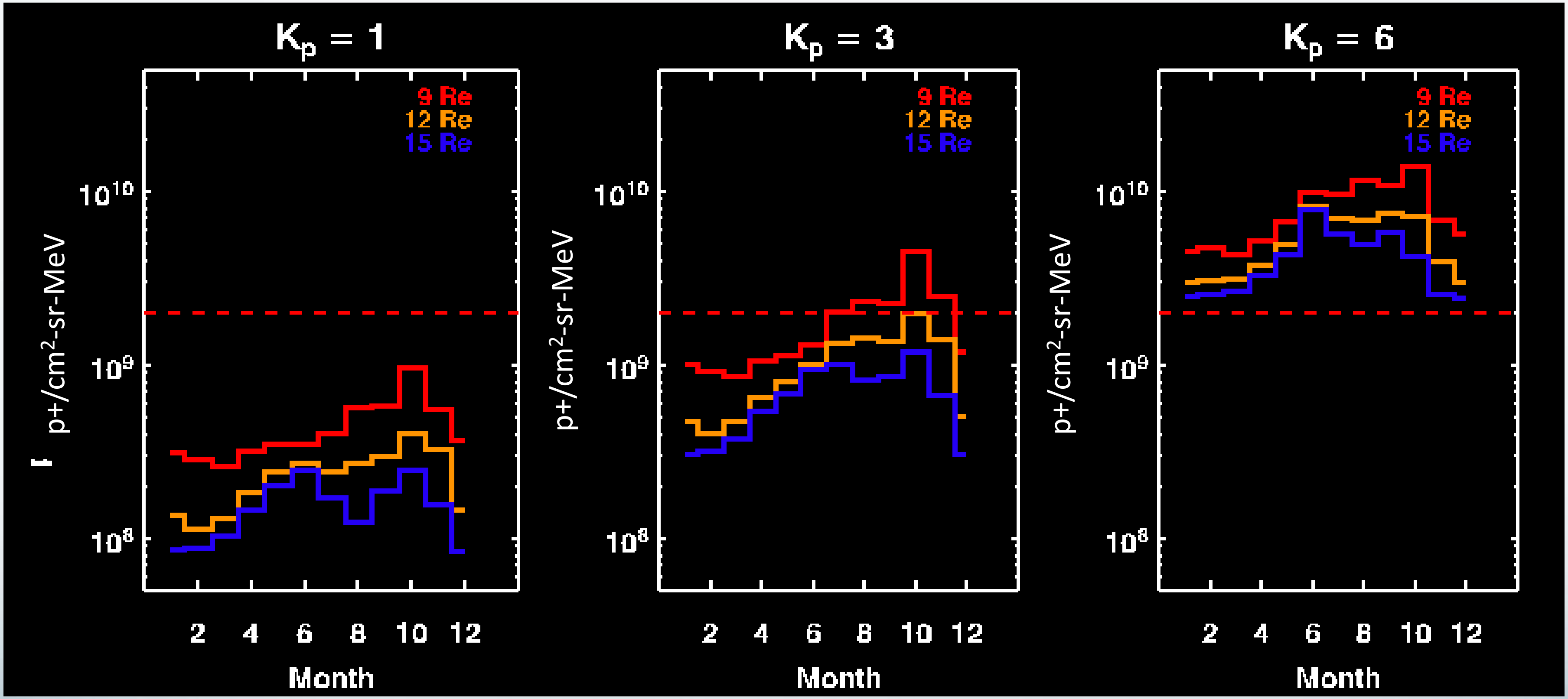
- CXO operations currently expected to continue into at least 2020 with study in progress to determine feasibility of operations to ~2025



Chandra Science Operations Team
Harvard CFA

Fluence Scheduling

Average fluence (100-200 keV protons) per orbit for 2000

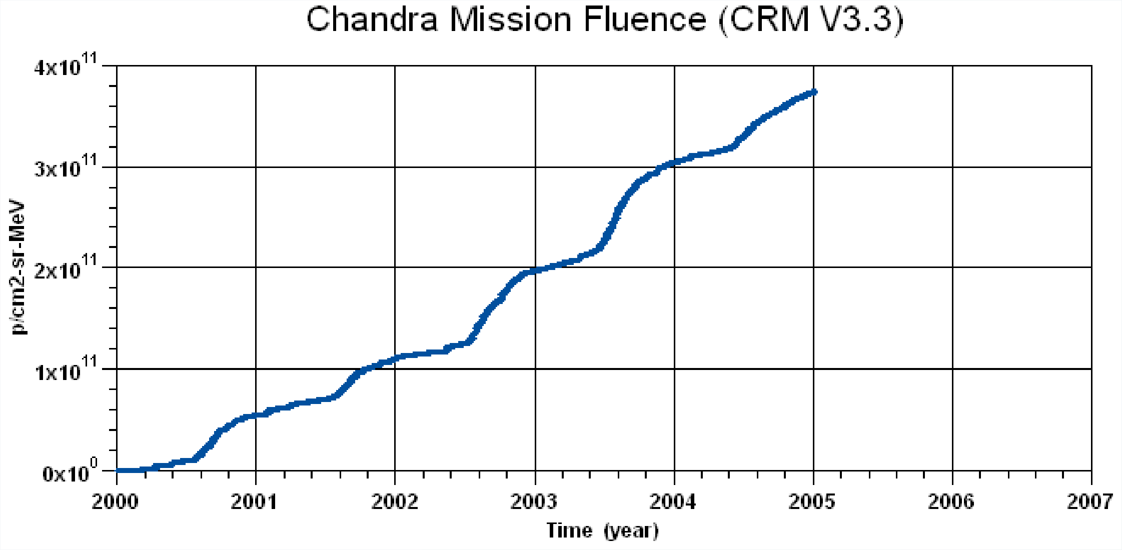


Fluence level to meet ACIS

5% CTI increase per year

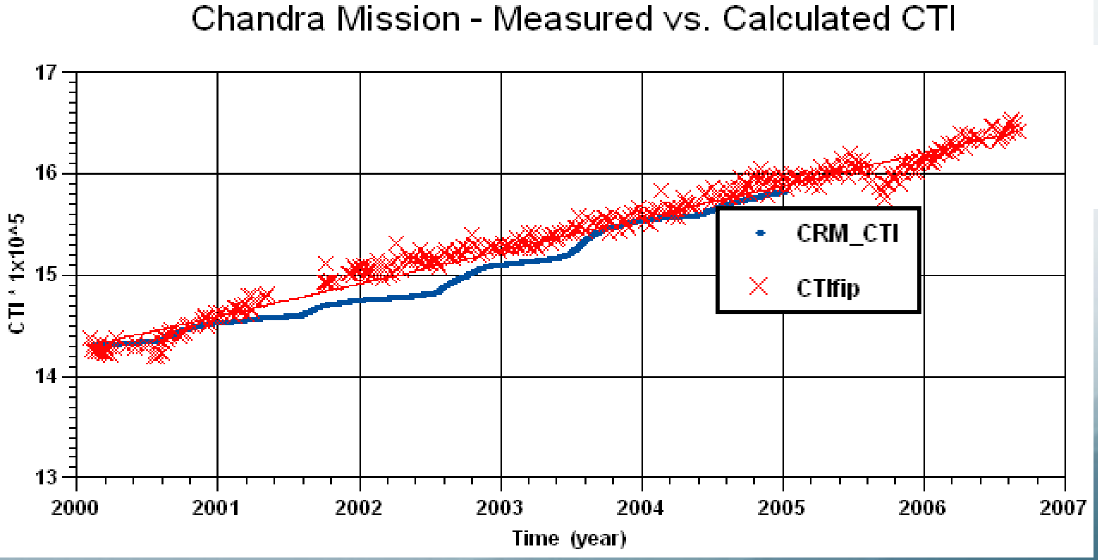
Mission Fluence, CTI Estimate

- CRM Mission fluence

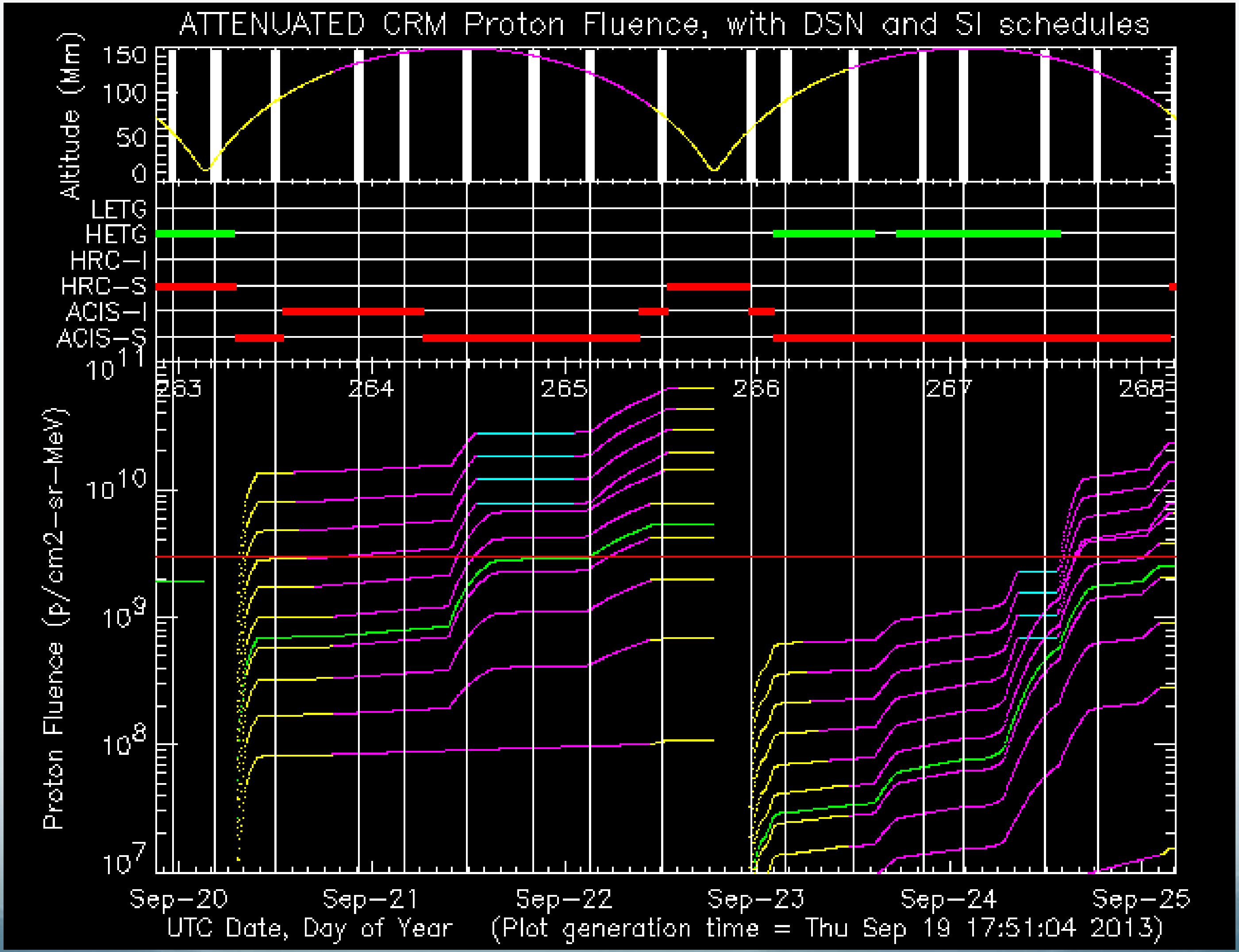


4.06E-17 (CTI/(#/cm^2-sr-MeV))

- Measured CTI and CRM predicted CTI
  - CTI increase ~ 2.3%/yr
    Requirement < 5%/yr



CRM Situational Awareness



http://asc.harvard.edu/mta/alerts/rad_summ.html

CXO Radiation Mitigation Strategy

- Schedule science operations to avoid high soft proton flux in the Earth's ring currents using Chandra Radiation Model, AP-8/AE-8
- Real time radiation monitoring using in-situ (autonomous) and other data sources (manual), move ACIS to protected position during periods of high particle flux
- CXO Monitoring and Trends Analysis (MTA) Team utilizes data from a variety of sources for real-time monitoring of CXO radiation environment:

Satellite	Instrument	Species	Energy	Notes
CXO (NASA)	EPHIN rates	H^+, e^-	H^+ 25 – 41 MeV e^- 2.6 – 6.2 MeV	In-situ, autonomous ACIS safing
	HRC rates	H^+	>10's MeV	In-situ, autonomous ACIS safing
	ACIS rates	H^+	>10's MeV	In-situ, autonomous ACIS safing
GOES (NOAA)	EPS P2 (P4GM proxy)	H^+	4 – 8 MeV	NOAA real time (5 min), manual
	EPS P5 (P41GM proxy)	H^+	38-80 MeV	NOAA real time (5 min), manual
	EPS E	e^-	>2 MeV	NOAA real time (5 min), manual
ACE (NASA)	P3'	H^+	115 – 195 keV	NOAA real time (5 min), manual
XMM (ESA)	Radiation Monitor	H^+, e^-	H^+ >1 MeV e^- > 130 keV	ESA real time (2 to 60 minutes), manual

ACE Real Time Data Issue

- Deep Space Climate Observatory (DSCOVR) will replace ACE in late 2015 (no earlier than early Nov)
  - DSCOVR will become the primary NOAA space weather plasma data source from L1
  - ACE RTSW coverage will be discontinued (NASA will continue to downlink science data)
  - DSCOVR carries a MAG/SWEPAM type cold solar wind plasma and magnetic field instrument
  - No replacement for non-thermal EPAM, SIS energetic particle instruments on DSCOVR
- The ACE/EPAM RTSW records are the only real-time data for detecting ~100-200 keV proton events in interplanetary space that impact the ACIS instrument
- CXO strategy is to
  - Develop contingency plans to operate without ACE RTSW data
  - Work with NOAA SWPC for option of continued ACE RTSW data

Chandra Solar Cycle 24 Radiation Interventions

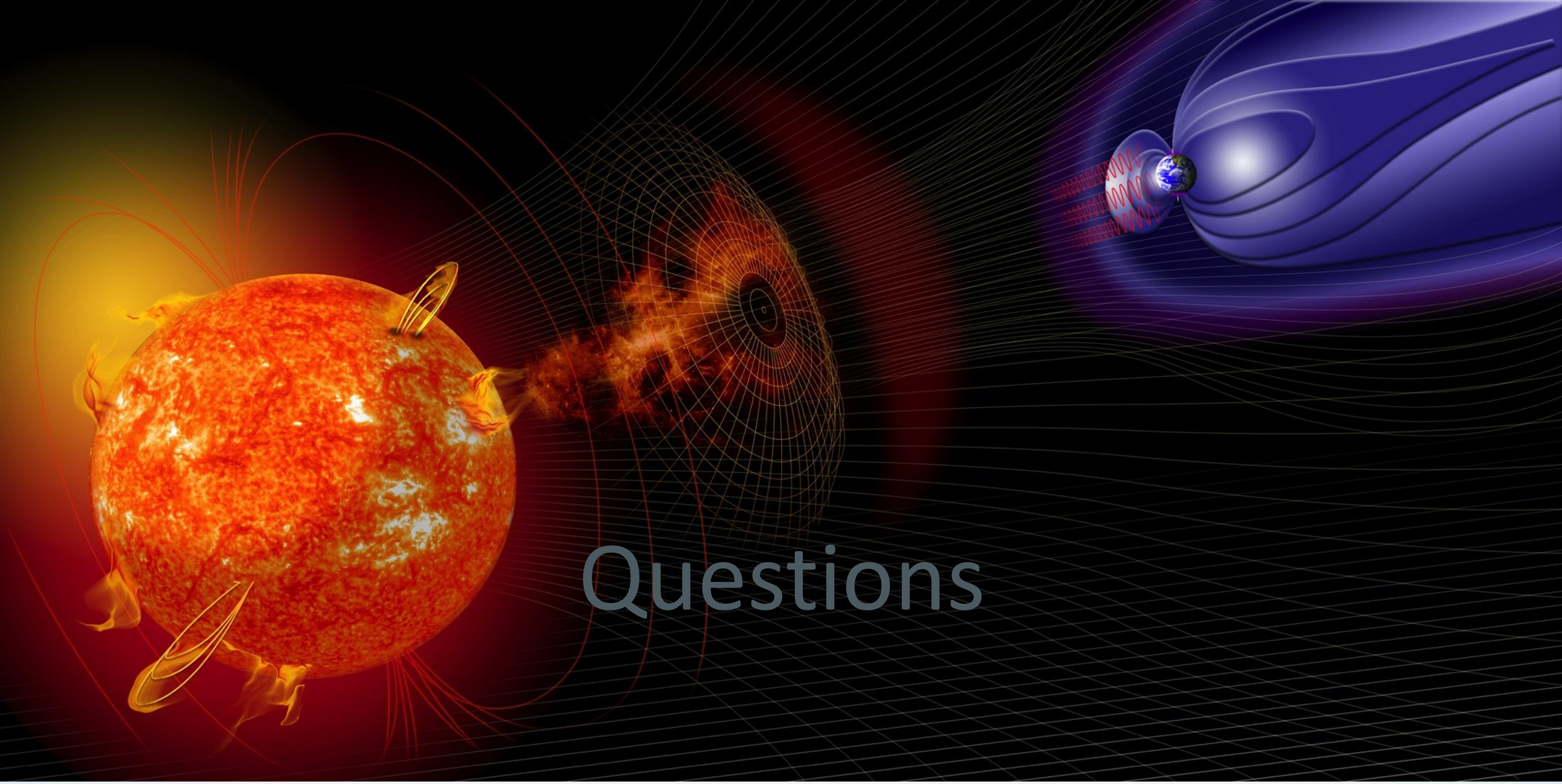
Event	Start	End	Lost Science time	Auto/Manual	Cause (HRC/EPHIN/ACE)
3 (+1)	**2011**		**406 ks (113 hr)**	**2/1**	**2/0/1**
1**	Jun 7 15:23 UT	Jun 8 12:50 UT	74.9 (20.8)	Auto	HRC (hard)
2	Aug 4 07:03	Aug 7 10:25	270.4 (75.1)	Auto	HRC (hard)
3	Oct 24 18:27	Oct 25 22:35	61.1 (17.0)	Manual	ACE P3' (soft)
4	Oct 26 11:40	Oct 28 12:33	154 (42.8)	Auto	Command Telemetry Unit (SEU)
10	**2012**		**1,246 ks (346 hr)**	**7/3**	**5/2/3**
5	Jan 23 06:00	Jan 26 08:27	192.1 (53.4)	Auto	HRC (hard)
6	Jan 27 19:39	Jan 30 02:20	163.4 (45.4)	Auto	HRC (hard)
7	Feb 27 03:24	Feb 27 20:23	61 (16.9)	Manual	ACE P3' (soft)
8	Mar 7 05:30	Mar 13 05:14	440 (122.2)	Auto	HRC (hard)
9	Mar 13 22:41	Mar 14 13:57	53.3 (14.8)	Auto	HRC (hard)
10	May 17 02:18	May 18 04:52	93.8 (26.1)	Auto	E1300 (hard)
11	Jul 12 19:59	Jul 14 00:09	61.7 (17.1)	Auto	E1300 (hard)
12	Jul 14 21:08	Jul 16 05:16	80.1 (22.3)	Manual	ACE P3' (soft)
13	Jul 19 11:44	Jul 20 04:09	56.5 (15.7)	Auto	HRC (hard)
14	Sep 3 12:57	Sep 4 12:41	44.5 (12.4)	Manual	ACE P3' (soft)

Solar Cycle 24 Radiation Interventions

Event	Start	End	Lost Science time	Auto/Manual	Cause
4	**2013**		**367 ks (102 hr)**	**1/3**	
15	Mar 17 12:32	Mar 19 05:58	105.7 (29.4)	Manual	ACE P3' (soft)
16	May 22 14:49	May 24 12:22	123.6 (34.3)	Auto	ACIS (hard)**
17	May 24 20:41	May 25 11:56	54.0 (15.0)	Manual	ACE P3' (soft)
18	Oct 02 02:04	Oct 03 13:27	83.3 (23.1)	Manual	ACE P3' (soft)
4	**2014**		**545 ks (151 hr)**	**2/2**	
19	Jan 07 20:39	Jan 12 01:54	364.5 (101.3)	Auto	SCS-107
20	Sep 12 11:51	Sep 13 12:48	89.0 (24.7)	Manual	SCS 107
21	Dec 22 04:52	Dec 22 23:26	65.1 (18.1)	Manual	ACE P3' (soft)
22	Dec 23 11:33	Dec 23 18:59	26.0 (7.2)	Manual	ACE P3' (soft)
2	**2015 (through Q3)**		**132 ks (37 hr)**	**0/2**	
23	Mar 17 04:34	Mar 19 08:04	131.8 (36.6)	Manual	ACE P3' (soft)
24	Jun 22 22:40	Jun 23 21:40	82.0 (22.8)	Manual	ACE P3' (soft)

* First radiation interruption since 2006 December 13 **First ACIS trigger event

Source: Chandra Radiation Central http://asc.harvard.edu/mta/RADIATION/



Questions