Space Weather Impacts on Satellites with Emphasis on Launch Vehicles

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CCMC Space Weather Course, NASA KSC

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Outline

- Todays presentation will discuss the impact of space weather on satellites with additional emphasis on launch vehicles

- Outline
  - General notes on space environments and effects
  - Environments of importance to satellites, launch vehicles
  - Ionizing radiation effects
  - Spacecraft charging effects
  - Meteors and orbital debris

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Space Weather and Spacecraft Operations

The primary approach for the spacecraft industry to mitigate the effects of space weather is to design satellites to operate under extreme environmental conditions to the maximum extent possible within cost and resource constraints

"Severe Space Weather Events--Understanding Societal and Economic Impacts Workshop Report," National Academies Press, Washington, DC, 2008
http://www.nap.edu/catalog/12507.html

This technique is rarely 100% successful and space weather will typically end up impacting some aspect of a space mission

- Some space weather issues are common to all spacecraft, e.g., space situational awareness is one example
- Specific details of space weather interactions with a spacecraft are often unique because spacecraft systems are unique, there is no "standard" space weather support to mission operations

Space Environment Effects

Mechanism	Effect	Source
Surface Charging	• Biasing of instrument readings • Power drains • Physical damage	• *Dense, cold plasma* • *Hot plasma*
Deep Dielectric Charging	• Biasing of instrument readings • Electrical discharges causing physical damage	• *High-energy electrons*
Structure Impacts	• Structural damage • Decompression	• *Micrometeoroids* • *Orbital debris*
Drag	• Torques • Orbital decay	• *Neutral thermosphere*
Total Ionizing Dose (TID)	• Degradation of microelectronics	• *Trapped protons* • *Trapped electrons* • *Solar protons*
Displacement Damage Dose (DDD)	• Degradation of optical components and some electronics • Degradation of solar cells	• *Trapped protons & electrons* • *Solar protons* • *Neutrons*
Single-Event Effects (SEE)	• Data corruption • Noise on images • System shutdowns • Electronic component damage	• *GCR heavy ions* • *Solar protons and heavy ions* • *Trapped protons* • *Neutrons*
Surface Erosion	• Degradation of thermal, electrical, optical properties • Degradation of structural integrity	• *Particle radiation* • *Ultraviolet* • *Atomic oxygen* • *Micrometeoroids Contamination*

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Space Environment Effects

Space Environmental Impacts on Space Systems			
Anomaly Diagnosis	Koons et al, 2000	NGDC DB, 2006	Satellite Digest, 2014
[redacted]			
ESD-Internal, surface, and indeterminate	54%	31%	10%
SEU (GCR, SPE, SAA, etc.)	28%	17%	5%
Radiation Dose	5%	---	---
Meteoroids and Orbital Debris	3%	---	5%
Atomic Oxygen	< 1%	---	---
Atmospheric Drag	< 1%	---	---
Design	---	---	25%
Other or Unknown	8%	52%	55%
[redacted]			

[*McKnight,* 2015]

2003 Halloween Storm Impacts on Spacecraft (1)

Oct 23: ***Genesis*** **satellite at L1 entered safe mode, normal operations resumed on Nov. 3.**
Midori-2 **(*ADEOS-2*) Earth-observing satellite power system failed, safe mode, telemetry lost (23:55), spacecraft lost**

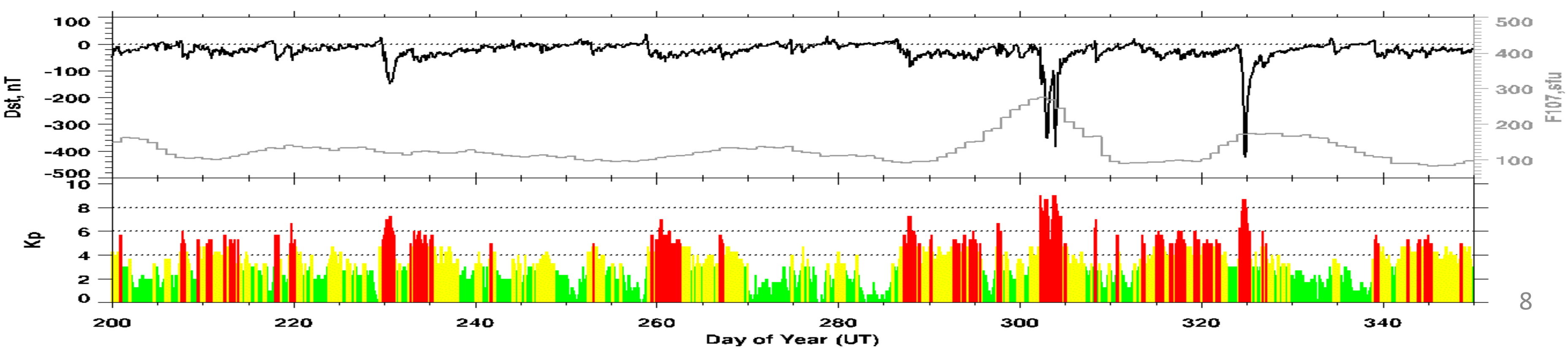
Oct 24: ***Stardust*** **comet mission went into safe mode due to read errors; recovered.**
Chandra X-ray Observatory **astronomy satellite observations halted due to high radiation levels (09:34EDT), restarted Oct. 25**
GOES-9, 10 and 12 **had high bit error rates (9 and 10), magnetic torquers disabled due to geomagnetic activity**

Oct 25: ***RHESSI*** **solar satellite had spontaneous CPU reset (10:42)**

Oct 26: ***SMART-1*** **had auto shutdown of engine due to increased radiation level in lunar transfer orbit (19:23)**

Oct 27: ***NOAA-17*** **AMSU-A1 lost scanner**
GOES-8 X-ray sensor turned itself off and could not be recovered

Oct 28-30: Astronauts on *Intl. Space Station* went into service module for radiation protection
Instrument on *Integral* satellite went into safe mode because of increased radiation
Chandra **observations halted again autonomously, resumed Nov 1**



2003 Halloween Storm Impacts on Spacecraft (2)

Oct 28: ***DMSP F16*** **SSIES sensor lost data twice, on Oct. 28 and Nov. 3; recovered. microwave sounder lost oscillator; switched to redundant system**

SIRTF**, in orbit drifting behind Earth, turned off science experiments and went to Earth pointing due to high proton fluxes, 4 days of operations lost**

Microwave Anisotropy Probe **spacecraft star tracker reset and backup tracker autonomously turned on, prime tracker recovered**

Oct 29: ***Kodama*** **data relay satellite in GEO; safe mode, signals noisy, recovery unknown**

RHESSI **satellite had 2 more spontaneous resets of CPU (28, 17:40; 29, 03:32).**

CHIPS **satellite computer went offline on Oct. 29 and contact lost with the spacecraft for 18 hr. When contacted the S/C was tumbling; recovered successfully. Offline for a total of 27 hrs.**

X-ray Timing Explorer **science satellite Proportional Counter Assembly (PCA) experienced high voltages and the All Sky Monitor autonomously shut off, both instruments recovered Oct 30 but PCA again shut down. PCA recovery delayed into November.**

adapted from Allen and Wilkerson, 2010
http://www.ngdc.noaa.gov/stp/satellite/anomaly/2010_sctc/docs/1-1_JAllen.pdf

2003 Halloween Storm Impacts on Spacecraft (3)

Oct 28-31: CDS instrument on *SOHO* spacecraft at L1 commanded into safe mode for 3 days

***Mars Odyssey* spacecraft entered safe mode, MARIE instrument had a temperature red alarm leading it to be powered off (Oct. 28). S/C memory error during downloading on 29 Oct corrected with a cold reboot on Oct. 31**

Both *Mars Explorer Rover* spacecraft entered "sun idle" mode due to excessive start tracker events

Oct 29: NASA's Earth Sciences Mission Office directed all instruments on 5 spacecraft be turned off or safed due to Level 5 storm prediction. Satellites affected include *AQUA, Landsat, TERRA, TOMS, and TRMM*

Oct 30: *ACE & Wind* solar wind satellites lost plasma observations

Electron sensors of *GOES* satellite in geosynchronous orbit saturated

Nov 2: *Chandra* observations halted again autonomously due to radiation. Resumption of observations delayed for days

Nov. 6: *Polar* TIDE instrument reset itself and high voltage supplies were disabled; recovered within 24 hr.

***Mars Odyssey* spacecraft commanded out of Safe mode; operations nominal.**

adapted from Allen and Wilkerson, 2010
http://www.ngdc.noaa.gov/stp/satellite/anomaly/2010_sctc/docs/1-1_JAllen.pdf

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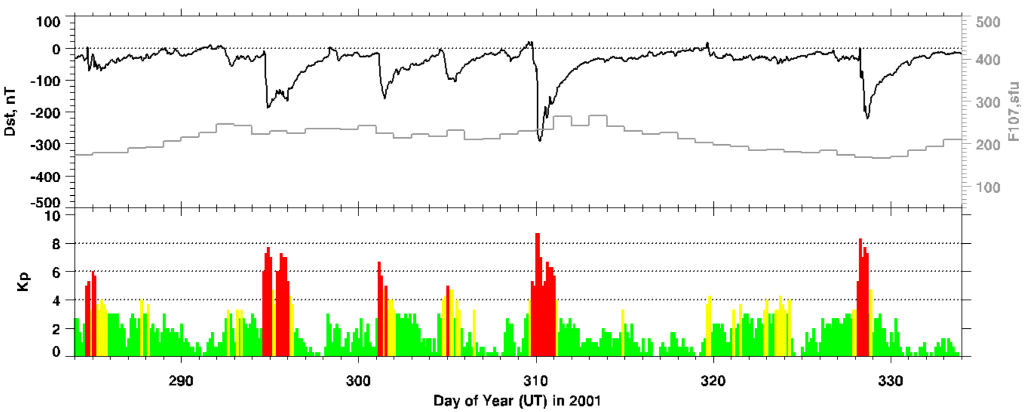
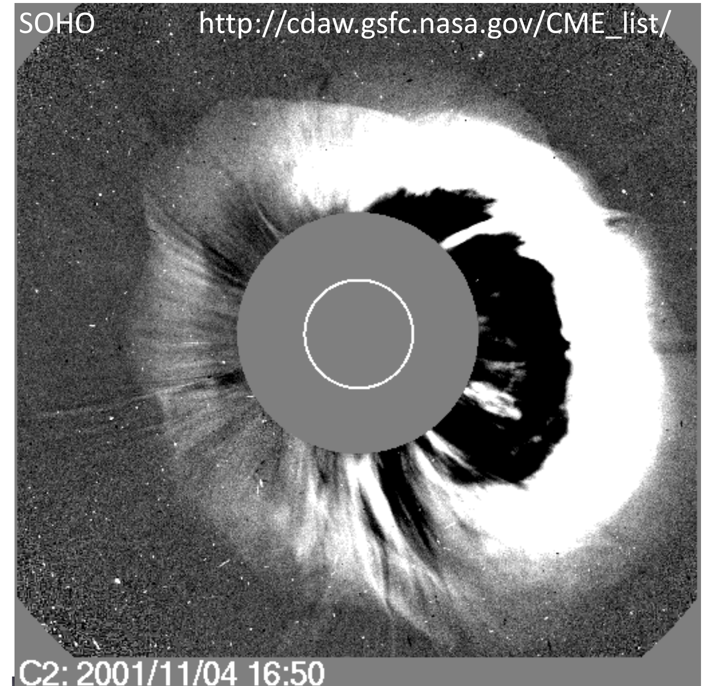
Space Weather and Climatology

- Space climatology:
  - Variability over months to years
  - Space environment effects on both satellites and launch vehicles are best mitigated by good design
  - Effects on launch vehicle will be present regardless of launch date and time

- Space weather:
  - Variability over minutes to days
  - Effects mitigated by design or operational controls
  - Design satellites to withstand mean, extreme space weather events that may occur during time on orbit
  - Launch operations may be deferred to avoid space weather effects during short flight (launch constraint)



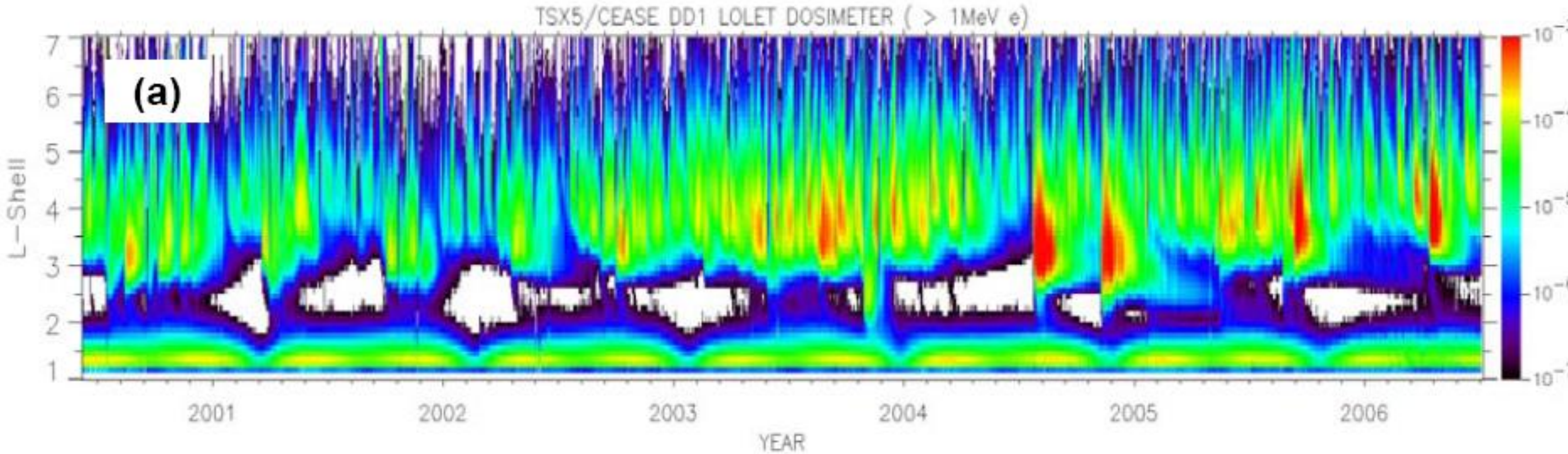


North Alabama, 5 Nov 2001 CST (GMT 309-310)

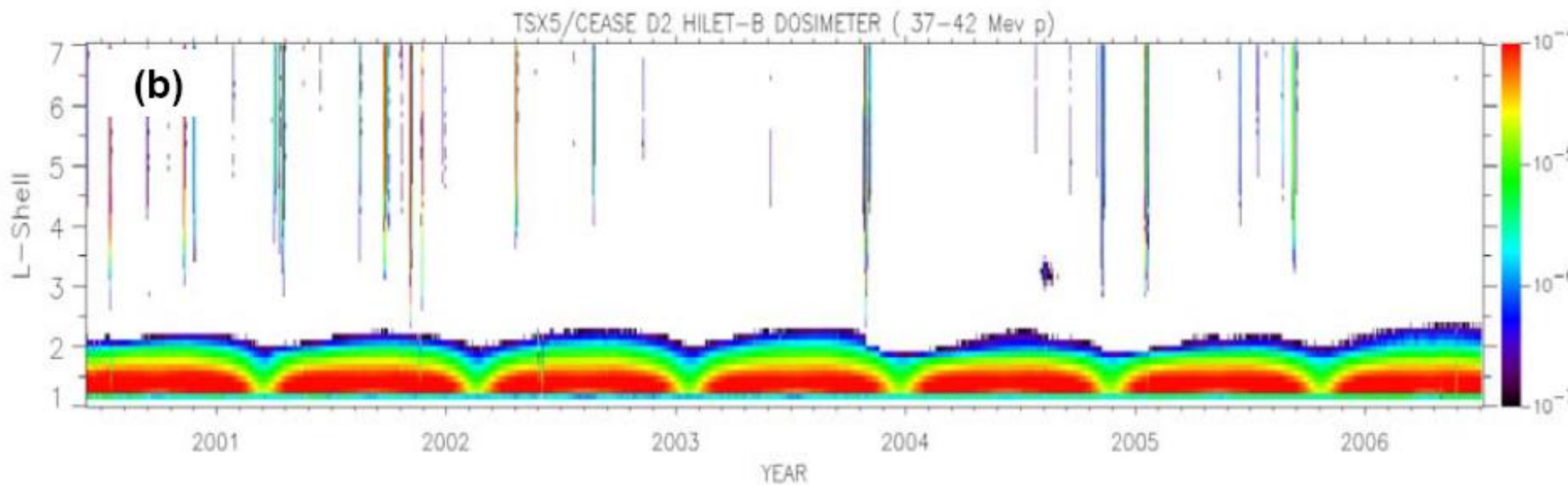
Radiation Belt Energetic Electrons and Protons

TSX-5 410 km x 1750 km x 69°

e-



p+

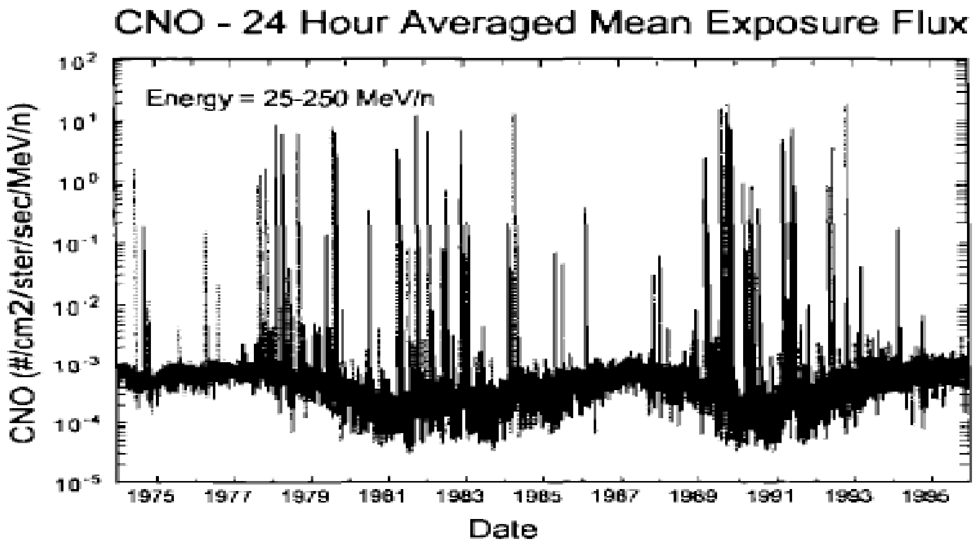


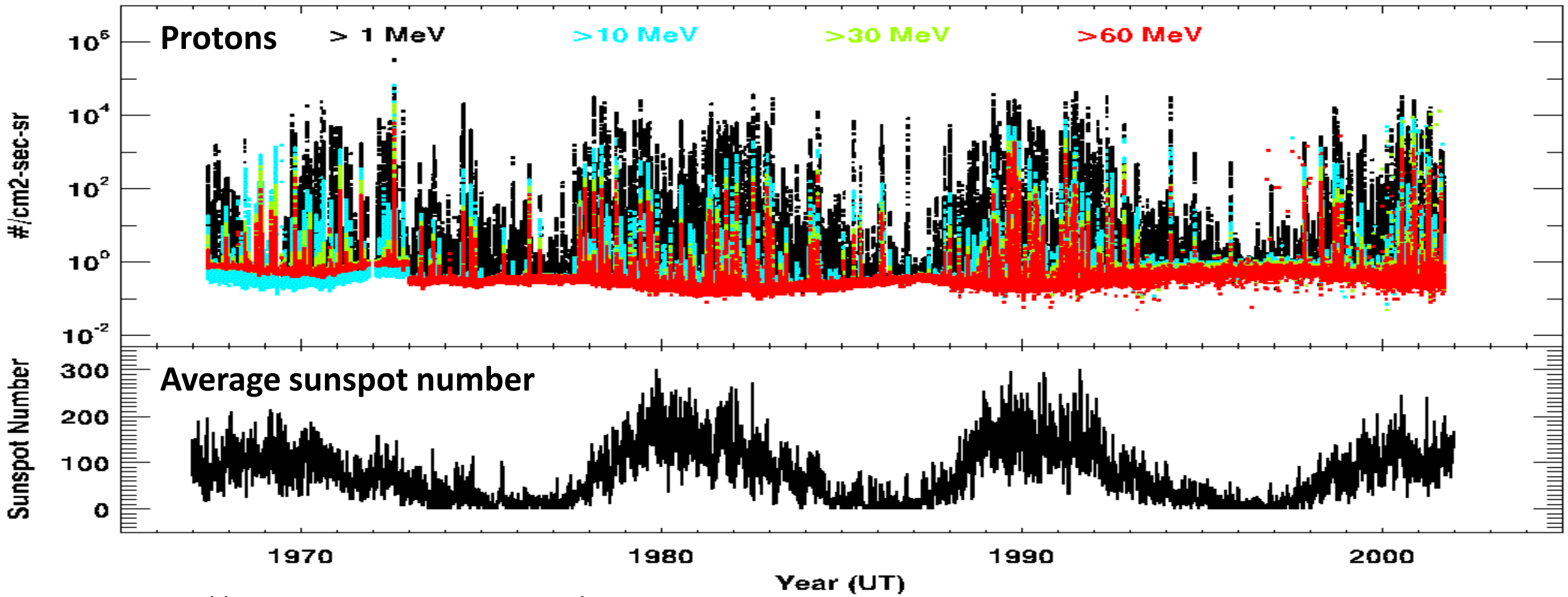
Dose rate [rad(Si) sec−1] averaged over five seconds for the entire TSX-5 mission from two CEASE dosimeter channels measuring mostly (a) >1 MeV electrons and (b) 37–42 MeV protons.

Metcalf et al., 2007

Solar Protons and Galactic Cosmic Rays

- GCR
  - Anti-correlated with solar cycle
  - Small flux variation
- SEP
  - Correlated with solar cycle
  - Large flux variation





http://omniweb.gsfc.nasa.gov/

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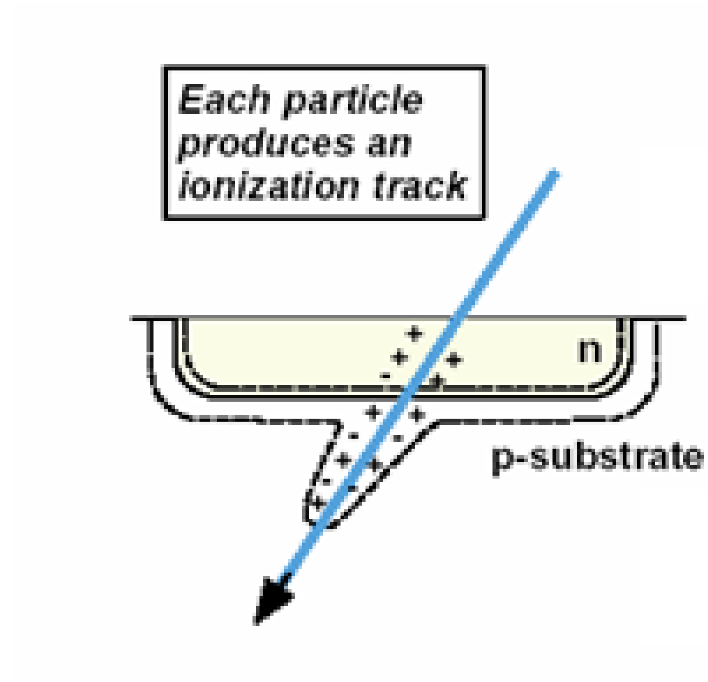
Single Event Effects (SEE)

Single event effect (SEE) : current generated by ion passing through the sensitive volume of a biased electronic device changes the device operating state

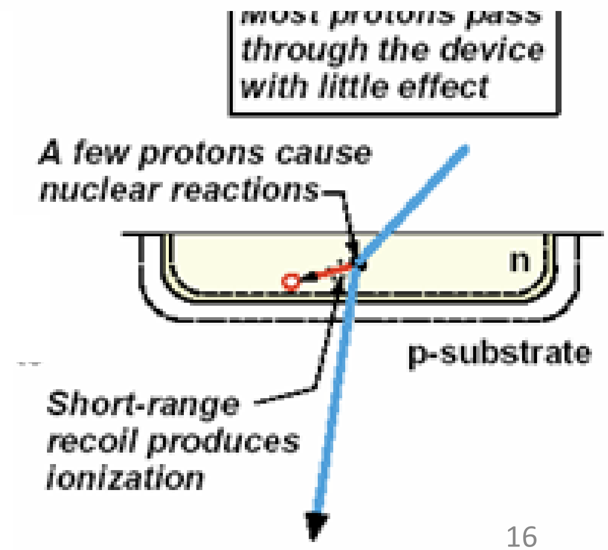
SEE Generated by Heavy Ions (Z=2-92)

- High linear energy transfer (LET) rate of heavy ions produces ionization along track as ion slows down
- Dense ionization track over a short range produces sufficient charge in sensitive volume to cause SEE
- SEE is caused directly by ionization produced by incident heavy ion particles



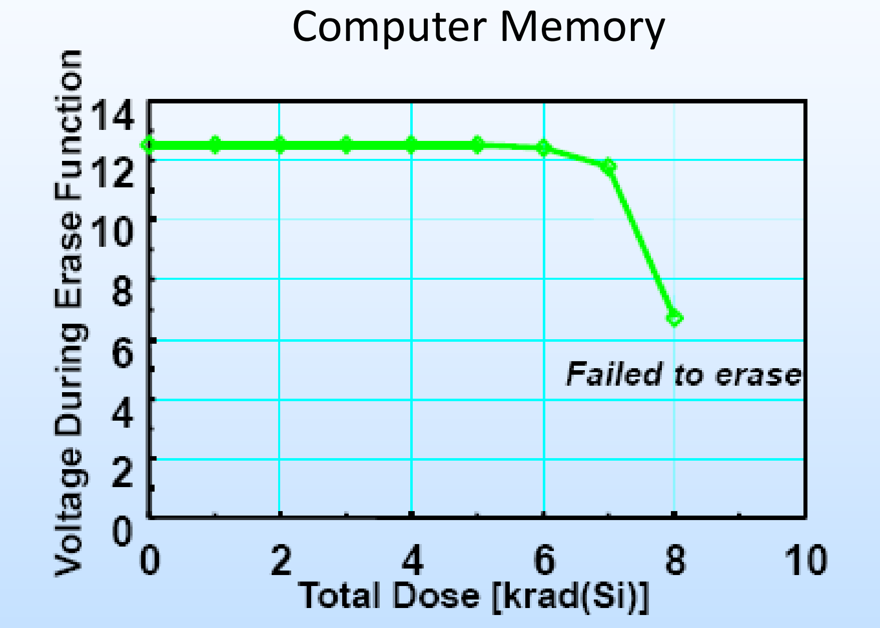
SEE Generated by Protons (Z=1)

- Proton LET is too low to generate SEE, but secondary heavy ions are produced in nuclear reactions with nuclei of atoms (usually silicon) inside electronics. Energy is transferred to a target atom fragment or recoil ion with high LET and charge deposited by recoil ion(s) is the direct cause of SEE.
- Only a small fraction of protons are converted to such secondary particles (1 in 10^4 to 10^5).



Total Ionizing Dose

- Cumulative ionizing damage due to proton and electron energy deposition in materials
  - Electron, hole pairs responsible for long term effects due to charge trapping at damage sites
  - Modifies electrical characteristics of electronic devices
  - Darkening, damage of materials (optics, fiber optics, dielectric filters)
  - Breaking bonds modifies chemical structure (polymers, epoxy binders)



LaBel, 2003

- Effects in electronics
  - Leakage currents
  - Threshold shifts
  - Timing changes
  - Functional failures

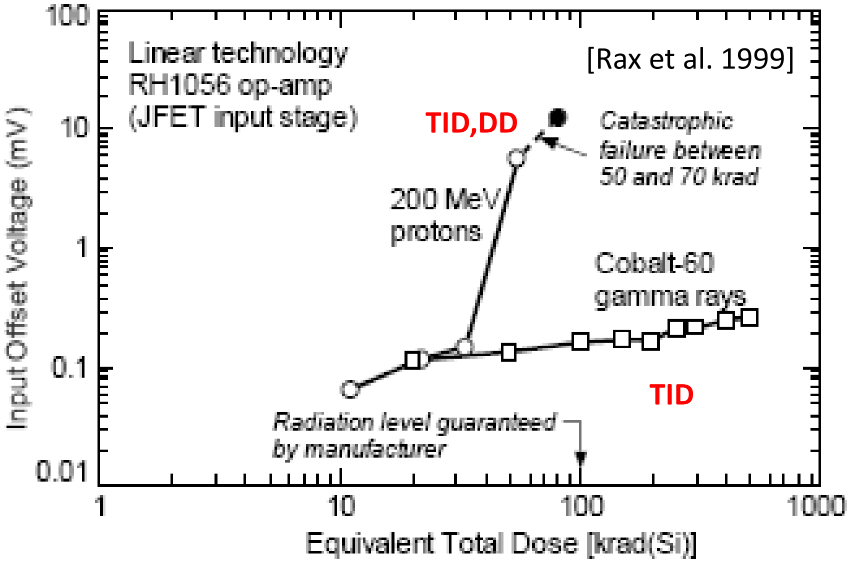
1 Gray = 1 Joule/kilogram = 100 rad

1 centiGray = 1 rad

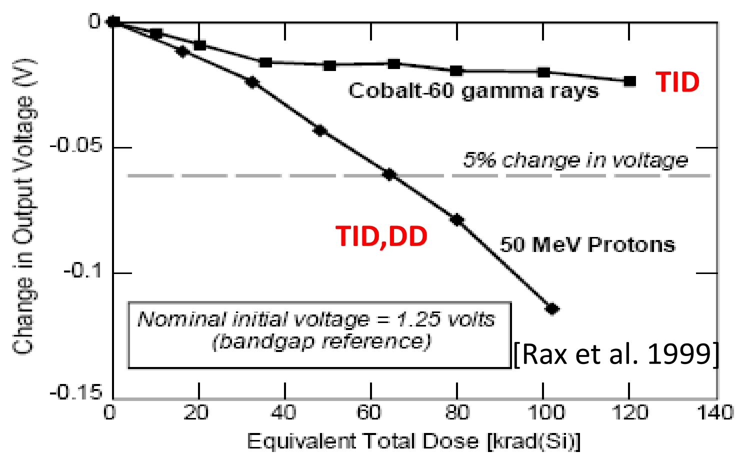
- Shielding partially mitigates the effects by reducing of low energy protons, electrons

Displacement Damage

- Cumulative non-ionizing damage due to proton, electron, and neutrons
  - Particle impact of displaces ion from lattice position
  - Creates charge trapping sites, modifies electrical behavior of material
- Effects in electronics
  - Accumulation of defect sites result in device degradation
  - Optocouplers, solar cells, imagers (e.g., CCD's), lnear bipolar devices
- Shielding partially mitigates the effects by reducing low energy protons, electron damage
  - High energy protons, neutrons are difficult to shield

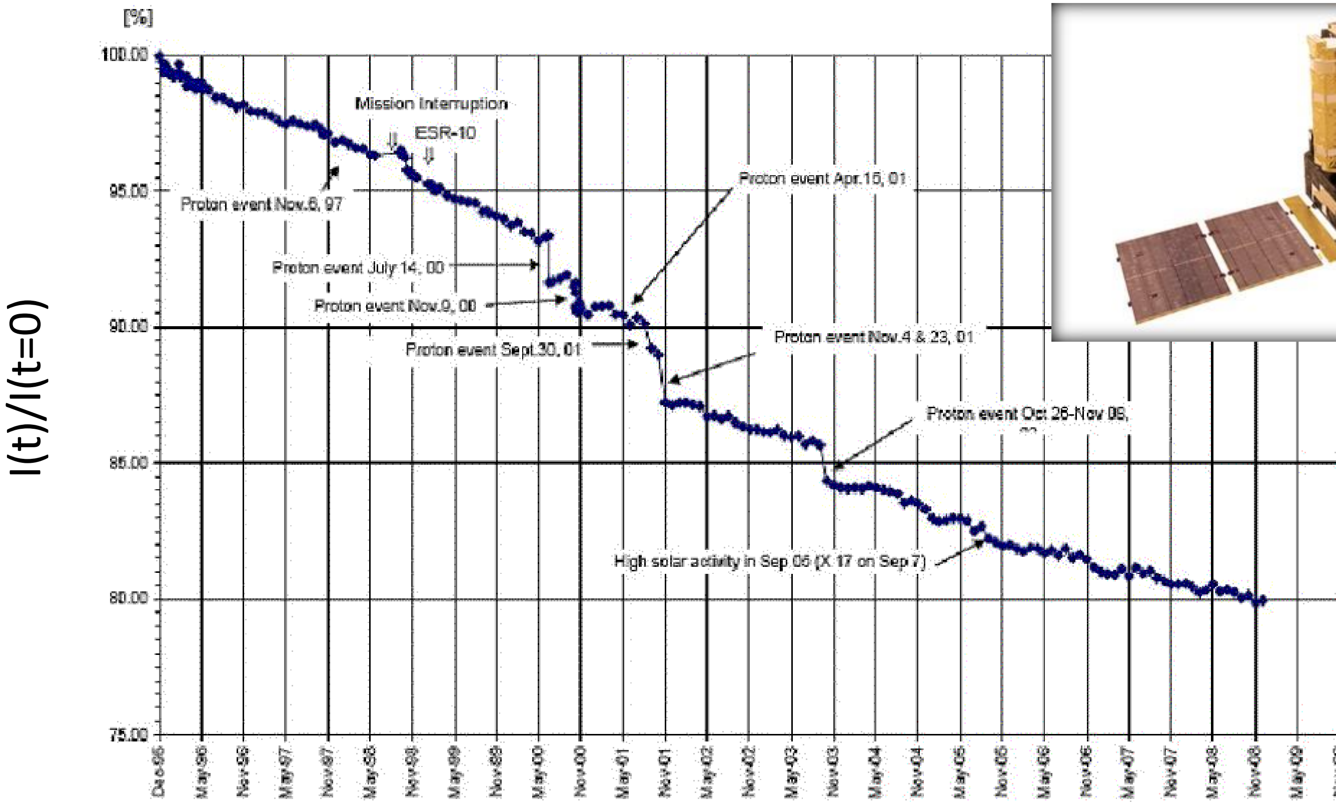


RH1056 op-amp degradation acceptable for gamma ray exposure, fails when exposed to protons

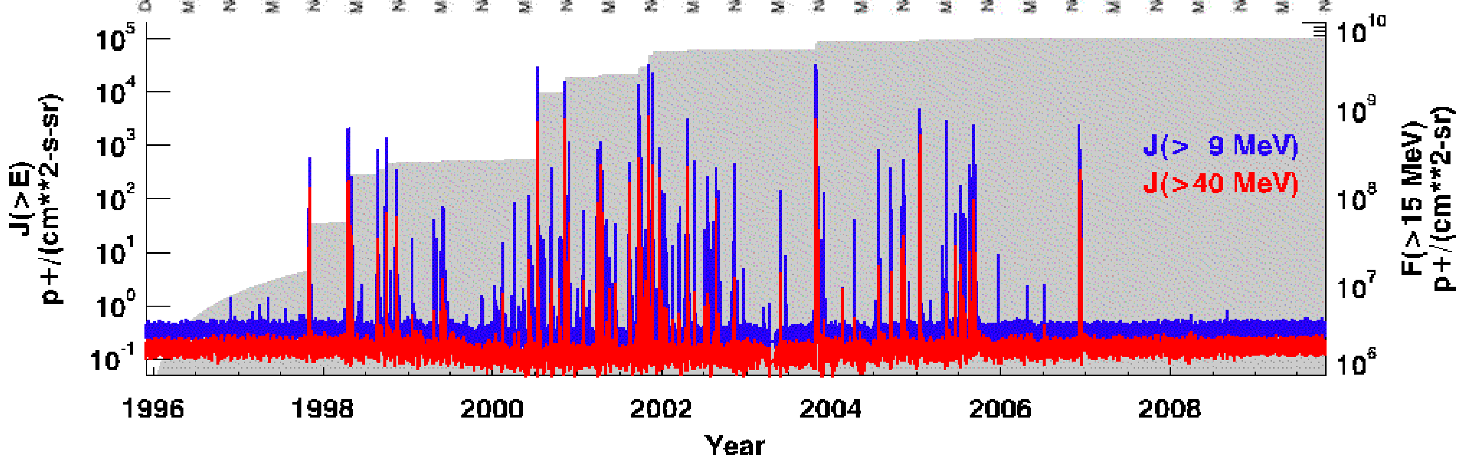


National LM117 output voltage modified by exposure to gamma rays, protons

ESA SOHO Solar Array Degradation

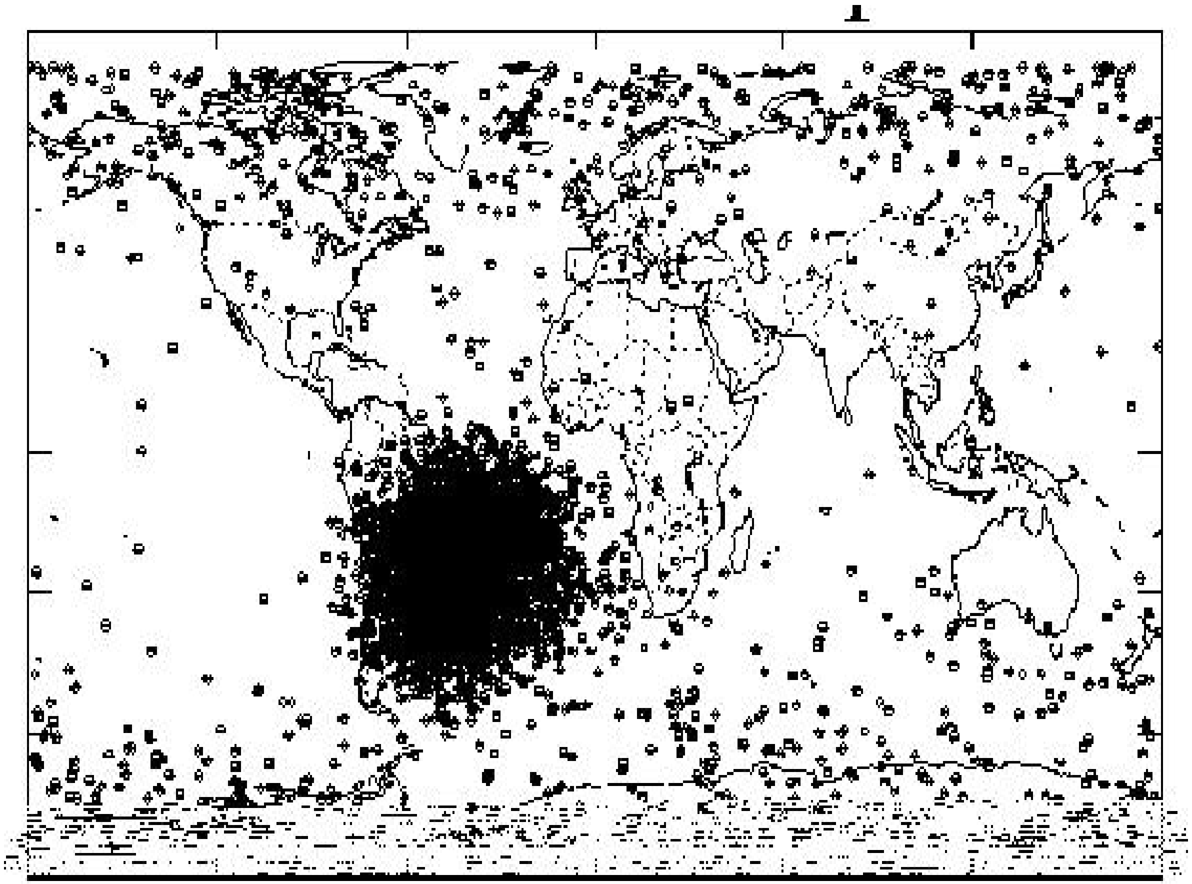


SOHO
Sun-Earth L1



UoSAT-3 Single Event Upsets

University of Surrey Satellite (UoSAT)

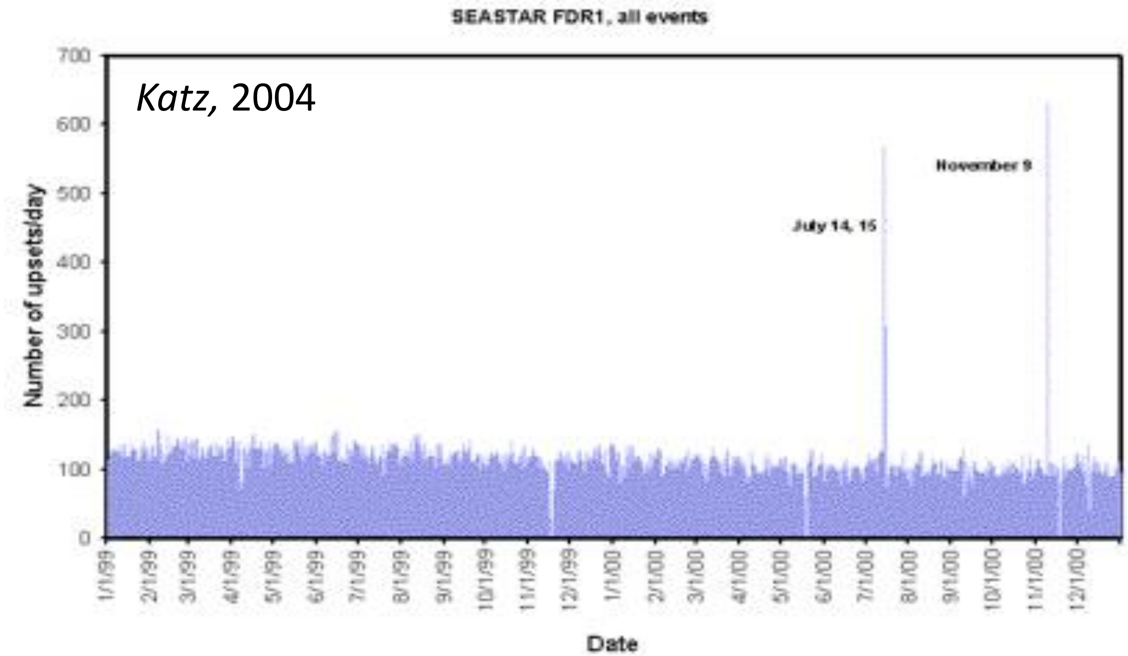


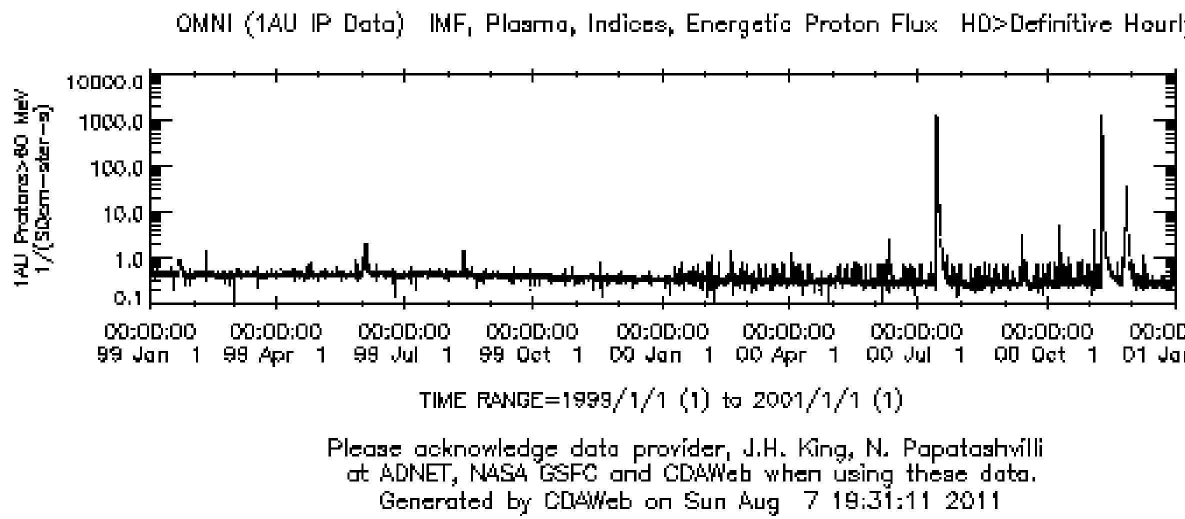
780 km, 98° inclination

[http://www.esa.int/TEC/Space_Environment/SEMQ95T4LZE_0.html]

SeaStar Satellite Single Event Upsets (SEU)

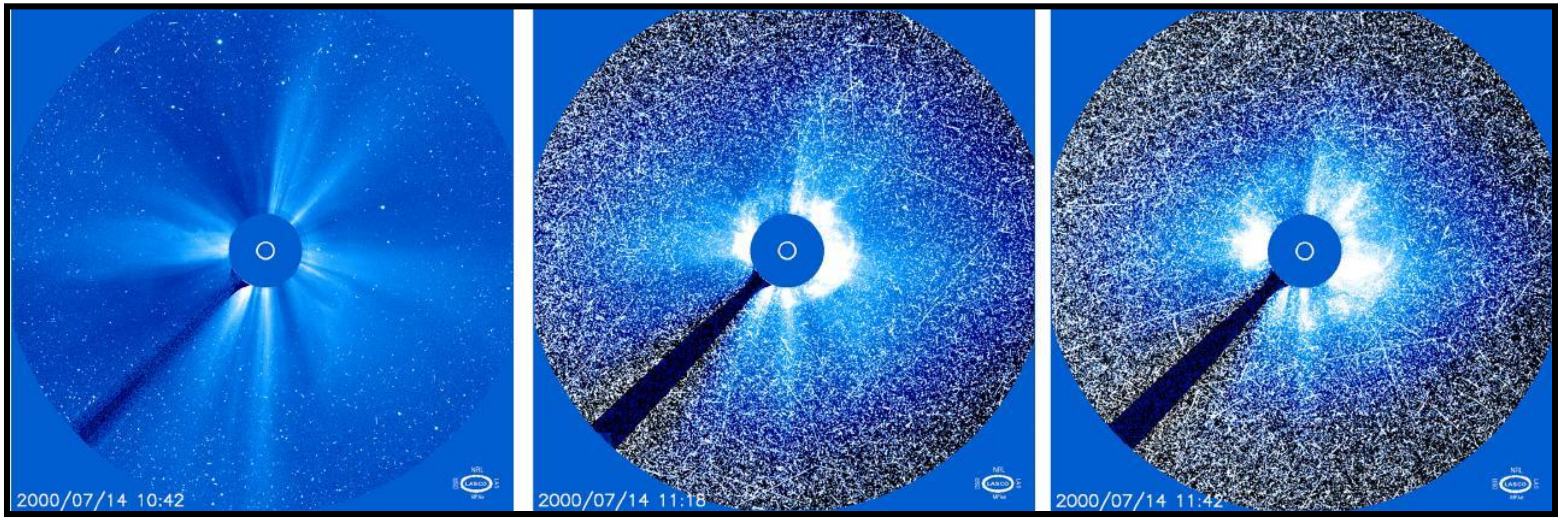
- SeaStar satellite
  - 705 km, 98.2° inclination
- Flight Data Recorder SEU counts
- Daily rate is just over 100 SEU per day
  - Slowly decreasing as background GCR flux decreases
- Two periods with enhanced SEU are due to solar proton events
  - 15-16 July 2000
  - 9 November 2000



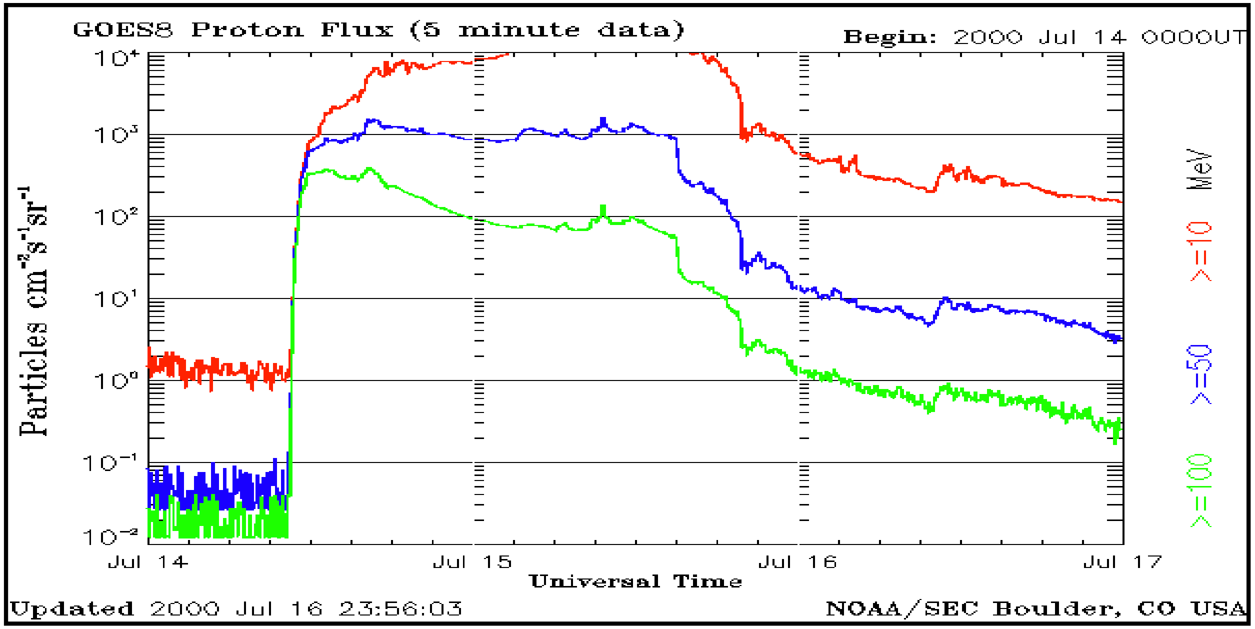


Solar Particle Events, CCD Imagers

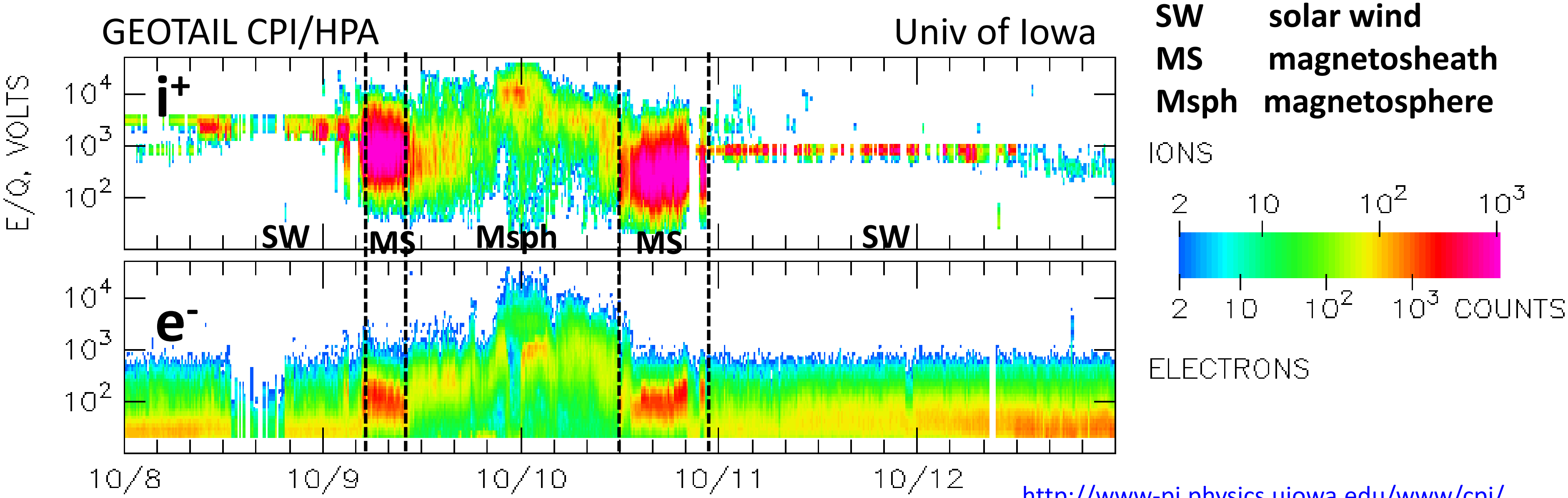
SOHO (L1) 14 July 2000 “Bastille Day Event”



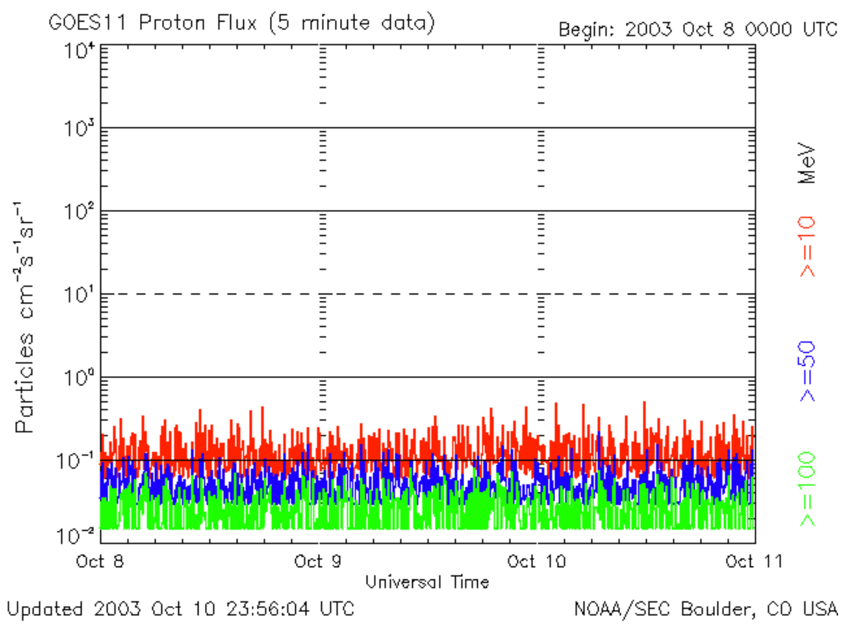
10:42 UT **11:16 UT** **11:42 UT**

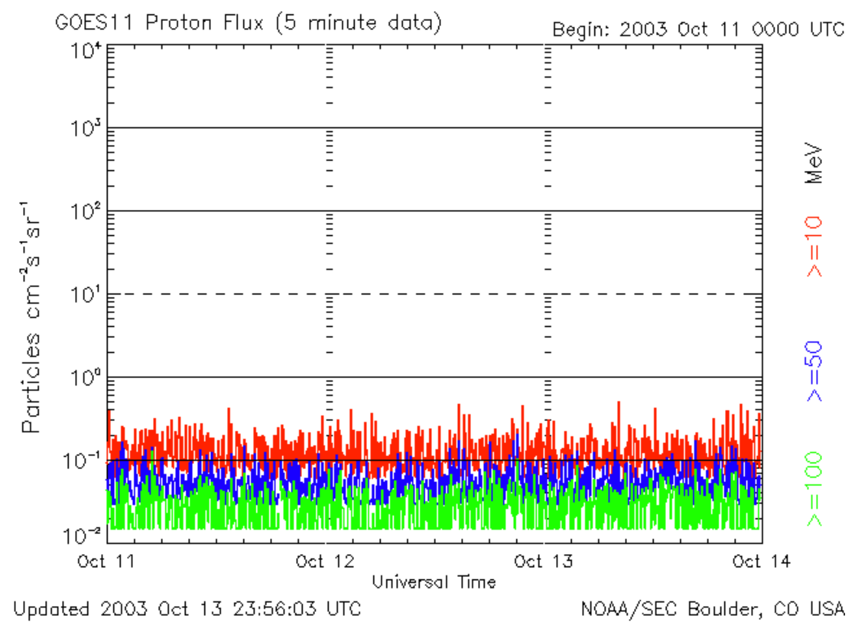


Impact on Science Data Quality

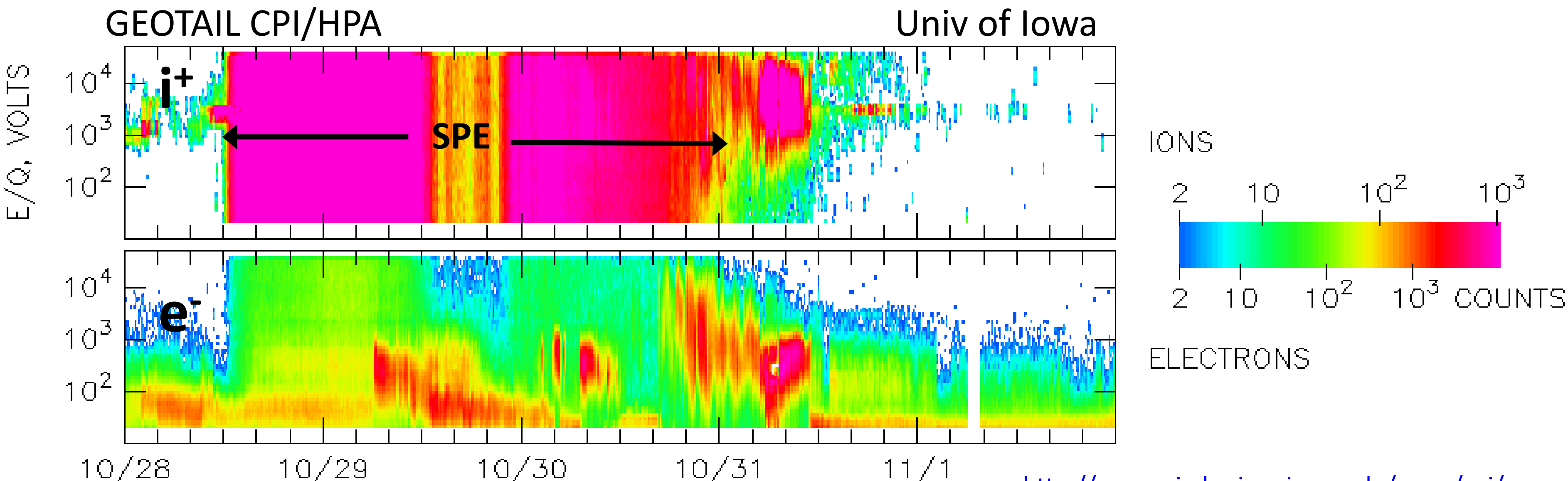


http://www-pi.physics.uiowa.edu/www/cpi/





SPE Data Contamination of Geotail CPI/HPA Data



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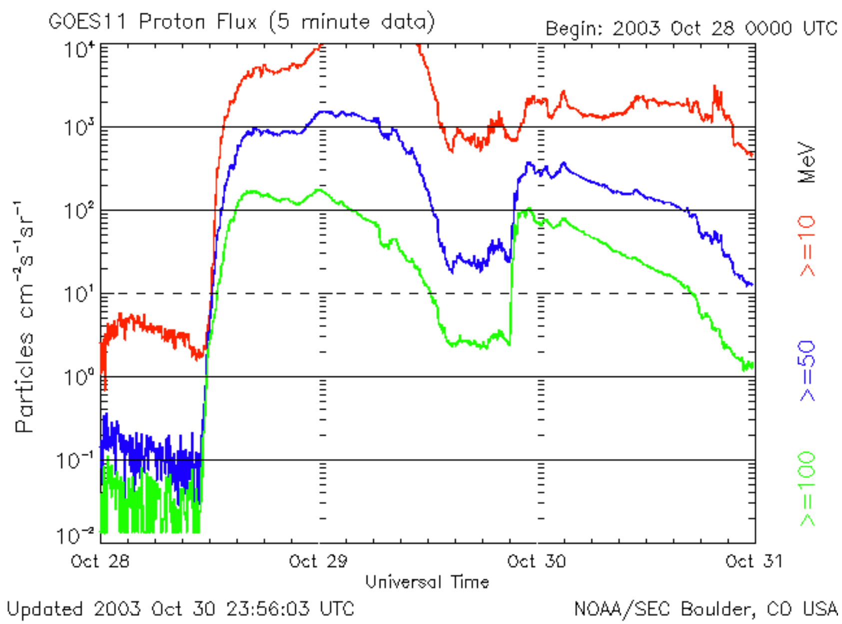
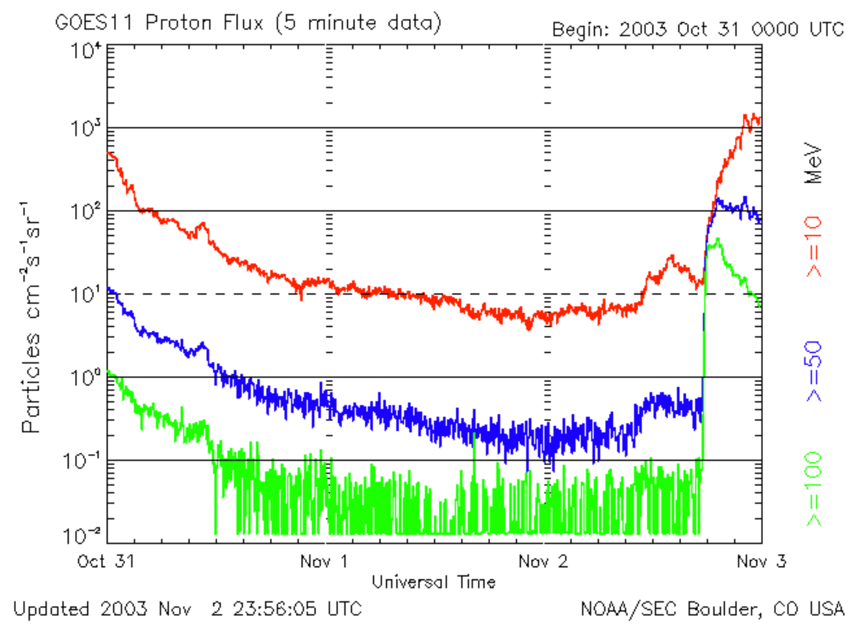




Chandra X-Ray Observatory
Solar Cycle 24 Radiation Interventions

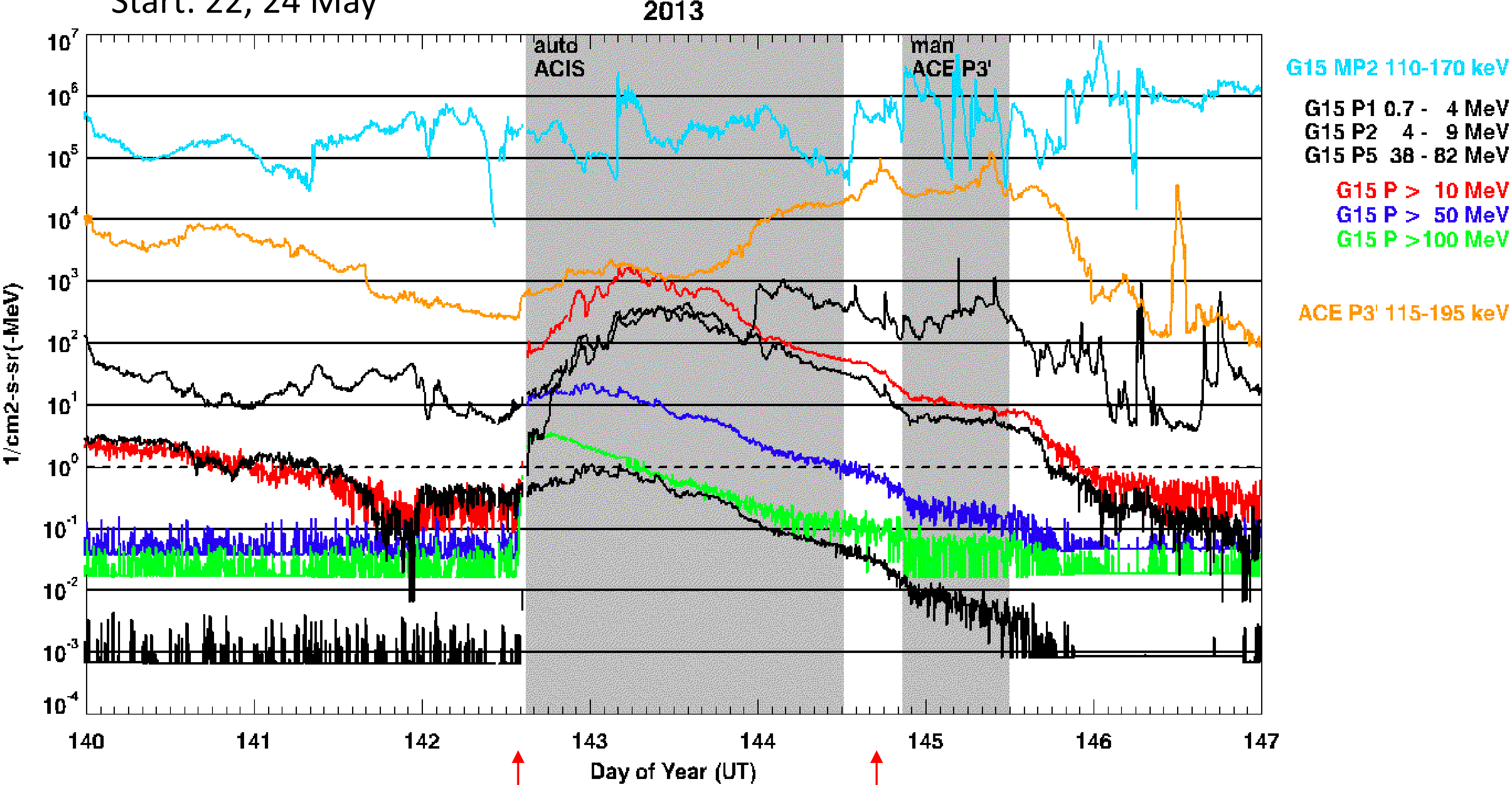
Event*	Start	End	Lost Science time	Auto/Manual	Cause (HRC/EPHIN/ACE)
3 *(+1)*	**2011**		**406 ks (113 hr)**	**2/1**	**2/0/1**
1**	Jun 7 15:23 UT	Jun 8 12:50 UT	74.9 (20.8)	Auto	HRC (hard)
2	Aug 4 07:03	Aug 7 10:25	270.4 (75.1)	Auto	HRC (hard)
3	Oct 24 18:27	Oct 25 22:35	61.1 (17.0)	Manual	ACE P3' (soft)
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)
3	**2013 Q2**		**283 ks (78 hr)**	**1/2**	**0/0/1**
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)

* Solar-cycle-24 radiation interventions: Chandra Radiation Central http://asc.harvard.edu/mta/RADIATION/

** First radiation interruption since 2006 December 13

Auto ACIS, Manual ACE P3’

Start: 22, 24 May



M5.0 flare
~1200 km/s CME
Peak ~13:32 UT

IP Shock at L1
~17:35 UT

Radioactive Sources and Launch Vehicle TID

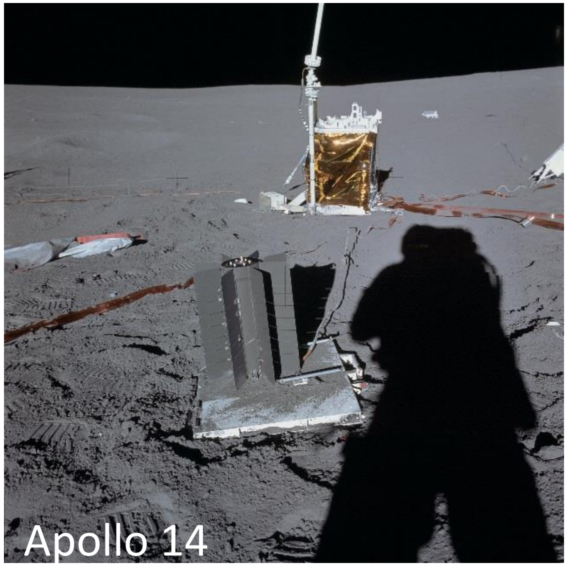
- Radioactive thermoelectric generators (RTG) used for space power sources produce greater TID in launch vehicle avionics than would be seen during flight from natural SPE, GCR, and trapped radiation sources

- Recent programs using RTG's include Galileo (1989), Ulysses (1990), Cassini (1997), Pluto New Horizons (2006), Mars Science Laboratory (2011)

- TID depends on how long the RTG will be in proximity of the launch vehicle avionics

- LV provider specifies TID limit at location of LV avionics for combined exposure period of pre-launch processing and launch window operations, examples:
  - Pluto New Horizons: two 30 day periods separated by one year (60 days total)
  - Mars Science Laboratory: 44 days

- US production of Pu-238 fuel has restarted so future RTG missions will be possible and perhaps more common than in recent years


Apollo 14


New Horizons at KSC

RTG Radiation Fields

- Pu-238 fuel decays emitting 4 to 6 MeV α-particles, range of α-particle is very short and easily stopped in fuel and container. No radiation issue for LV avionics
- Neutrons from spontaneous and induced fission and (α,n) reactions with low Z isotopes will penetrate fuel, housing to produce a radiation field surrounding the device (=DD)
- Pu-236 (trace impurity) radioactive decay products in Pu-238 fuel generate gamma-rays with energies to few MeV (=TID)
  - Ingrowth of impurity daughter products increases gamma-ray flux over time
  - Radiation threat due to penetrating gamma-rays increases over time since fuel was processed
- Verifying LV TID requirements requires measured radiation fields from **<u>flight</u>** RTG
  - Gamma intensity depends on age and purity of fuel
  - Don't let payload provider use design environments for TID verification!

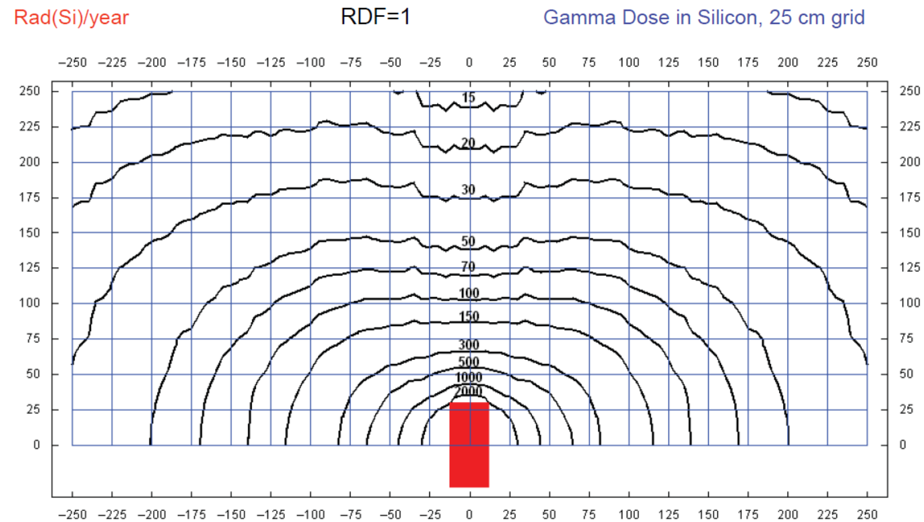


Figure 4.9-7 Contour Plot of One Year TID Levels of a Single, 8-module MMRTG (TBR)

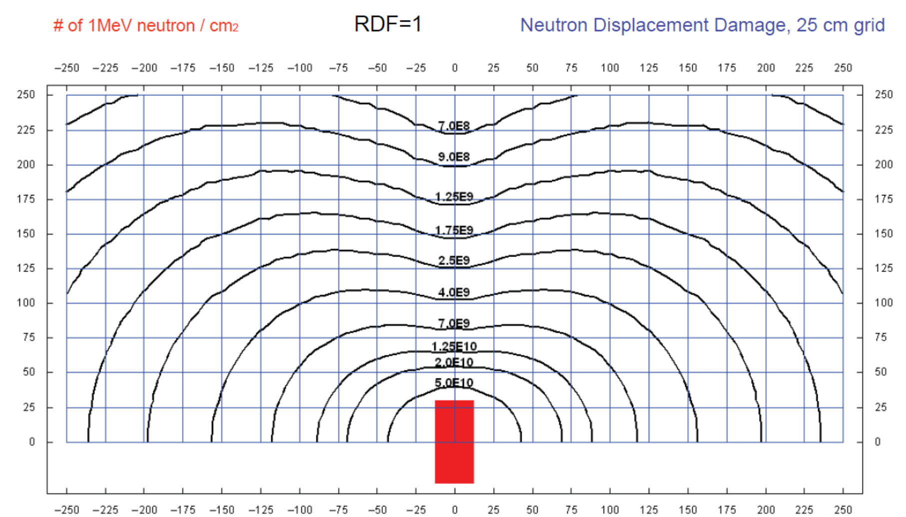


Figure 4.9-8 Contour Plot of One Year Displacement Damage Dose (in Equivalent 1 MeV neutrons/cm2 Fluence from a Single, 8-module MMRTG) (TBR)

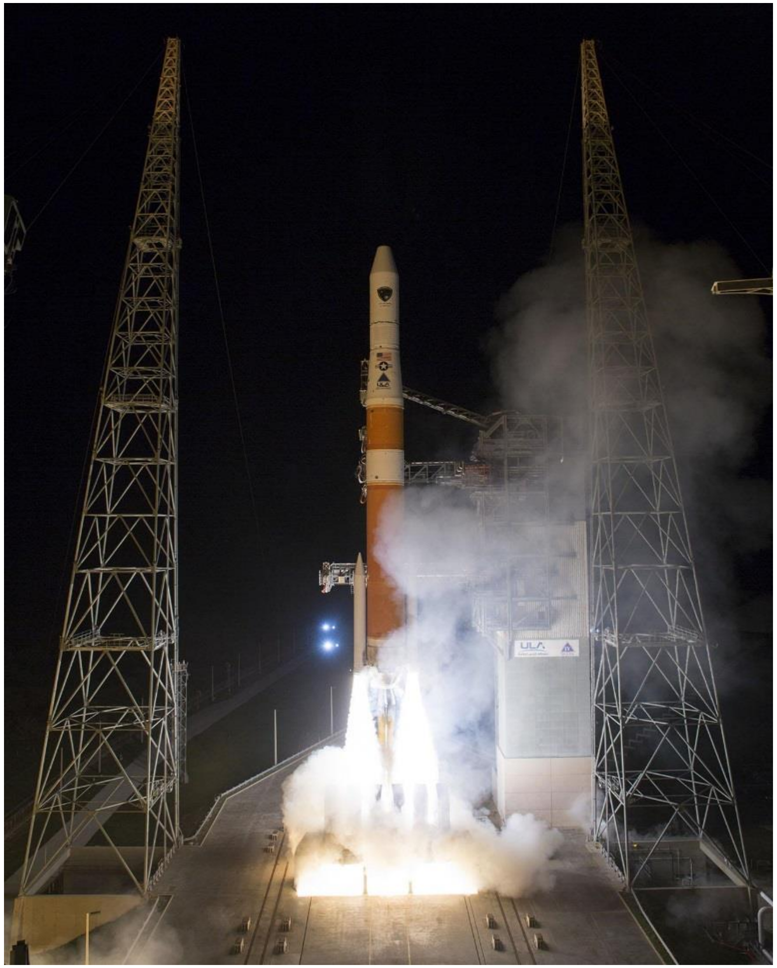
[Europa Clipper Mission, ERD (draft) Brinza, 2014]

Delta IV/GPS IIF-5: Launch Delay

- Cape Canaveral Air Force Station Delta IV launch operations on 20-21 February 2014 briefly delayed due to concern over solar proton event
- All system consoles reported GO at T-4 min hold except for Space Weather who reported a violation of launch criteria
- Launch teams determined the proton flux levels were very close to acceptable limit, represented no danger to LV, and decided Space Weather was GO
- Launch successful at end of window

  Window: 21 Feb, 01:40 UT – 01:59 UT

  Launch: 21 Feb, 01:59 UT

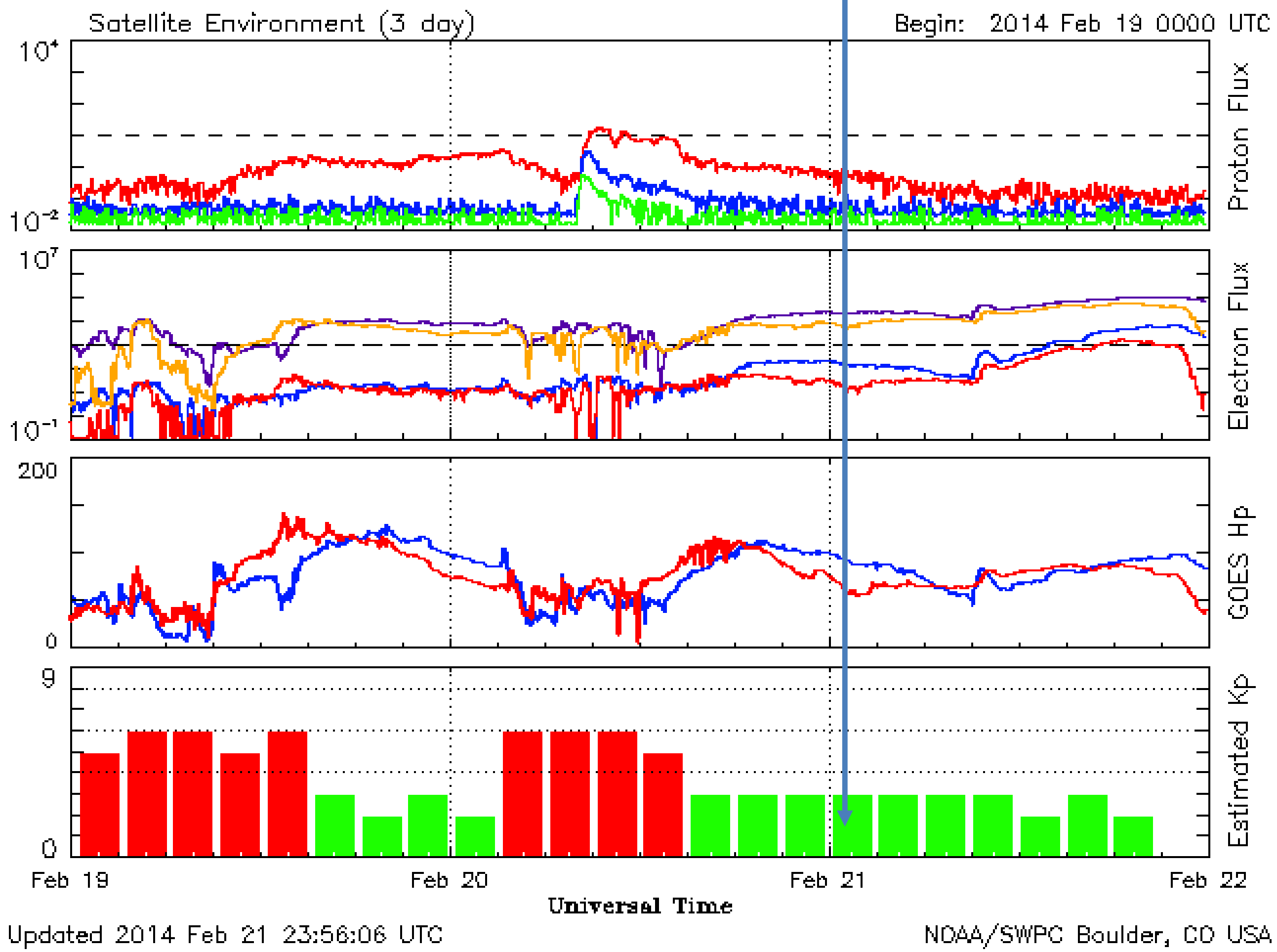


http://www.spaceflight101.net/delta-iv-gps-iif5-launch.html

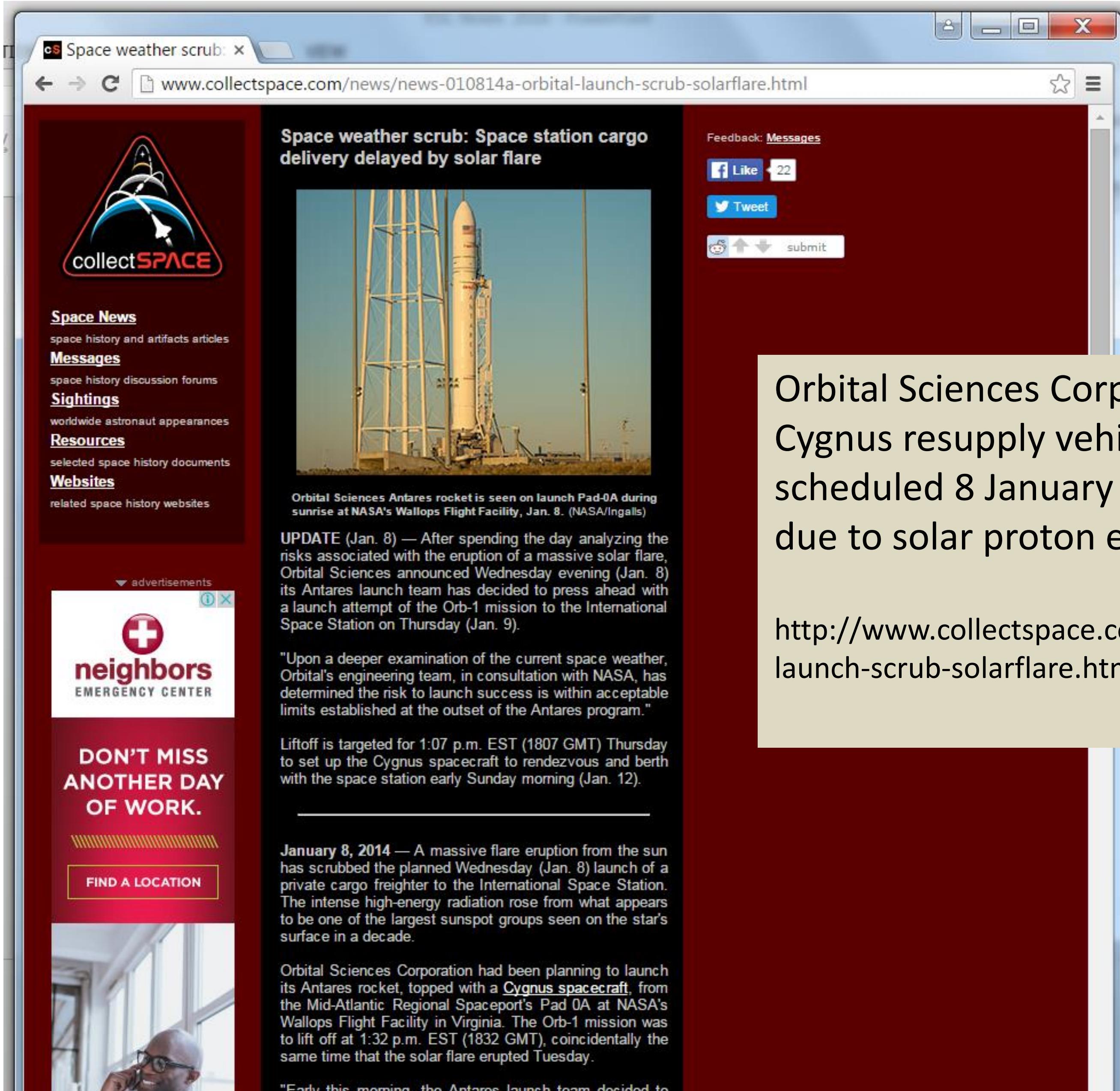
http://gpsworld.com/new-gps-iif-satellite-launched/

Delta IV/GPS IIF-5: Launch Delay

ULA Delta IV
GPS IIF-5
21 Feb, 01:59 UTC



ISS Commercial Resupply: Launch Delay



Space weather scrub:

www.collectspace.com/news/news-010814a-orbital-launch-scrub-solarflare.html

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space history and artifacts articles
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space history discussion forums
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Space weather scrub: Space station cargo delivery delayed by solar flare

Orbital Sciences Antares rocket is seen on launch Pad-0A during sunrise at NASA's Wallops Flight Facility, Jan. 8. (NASA/Ingalls)

UPDATE (Jan. 8) — After spending the day analyzing the risks associated with the eruption of a massive solar flare, Orbital Sciences announced Wednesday evening (Jan. 8) its Antares launch team has decided to press ahead with a launch attempt of the Orb-1 mission to the International Space Station on Thursday (Jan. 9).

"Upon a deeper examination of the current space weather, Orbital's engineering team, in consultation with NASA, has determined the risk to launch success is within acceptable limits established at the outset of the Antares program."

Liftoff is targeted for 1:07 p.m. EST (1807 GMT) Thursday to set up the Cygnus spacecraft to rendezvous and berth with the space station early Sunday morning (Jan. 12).

January 8, 2014 — A massive flare eruption from the sun has scrubbed the planned Wednesday (Jan. 8) launch of a private cargo freighter to the International Space Station. The intense high-energy radiation rose from what appears to be one of the largest sunspot groups seen on the star's surface in a decade.

Orbital Sciences Corporation had been planning to launch its Antares rocket, topped with a Cygnus spacecraft, from the Mid-Atlantic Regional Spaceport's Pad 0A at NASA's Wallops Flight Facility in Virginia. The Orb-1 mission was to lift off at 1:32 p.m. EST (1832 GMT), coincidentally the same time that the solar flare erupted Tuesday.

Feedback: Messages
Like 22
Tweet
submit

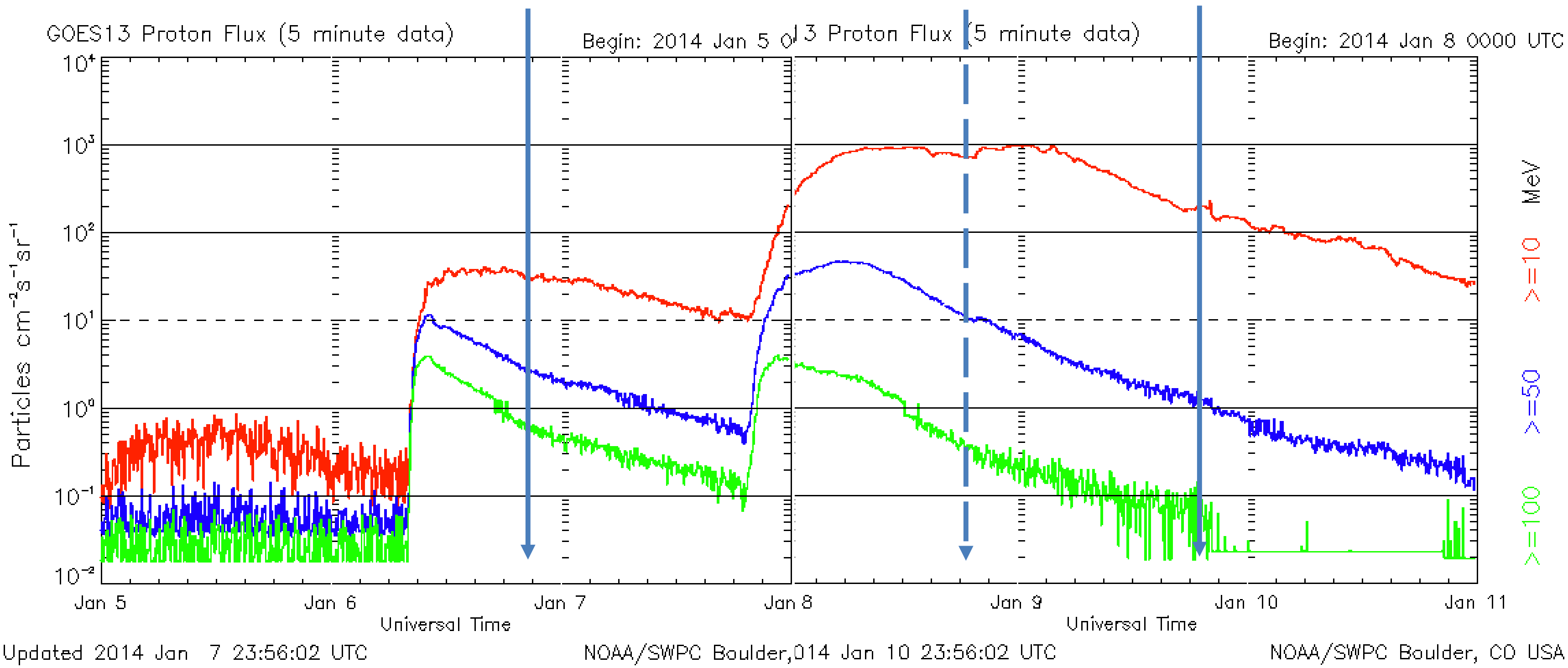
Orbital Sciences Corporation Antares launch of Cygnus resupply vehicle to ISS from Wallops scheduled 8 January 2014 delayed 24 hours due to solar proton event

http://www.collectspace.com/news/news-010814a-orbital-launch-scrub-solarflare.html

Launch Delay of ISS Commercial Resupply Mission

SpaceX, Falcon 9
Thiacom 6 satellite
6 Jan, 22:06 UT

Orbital ATK, Antares
Cygnus (ISS cargo resupply)
1st window: 8 Jan, 18:32 UT, launch delayed
2nd window: 9 Jan, 18:07 UT. launched

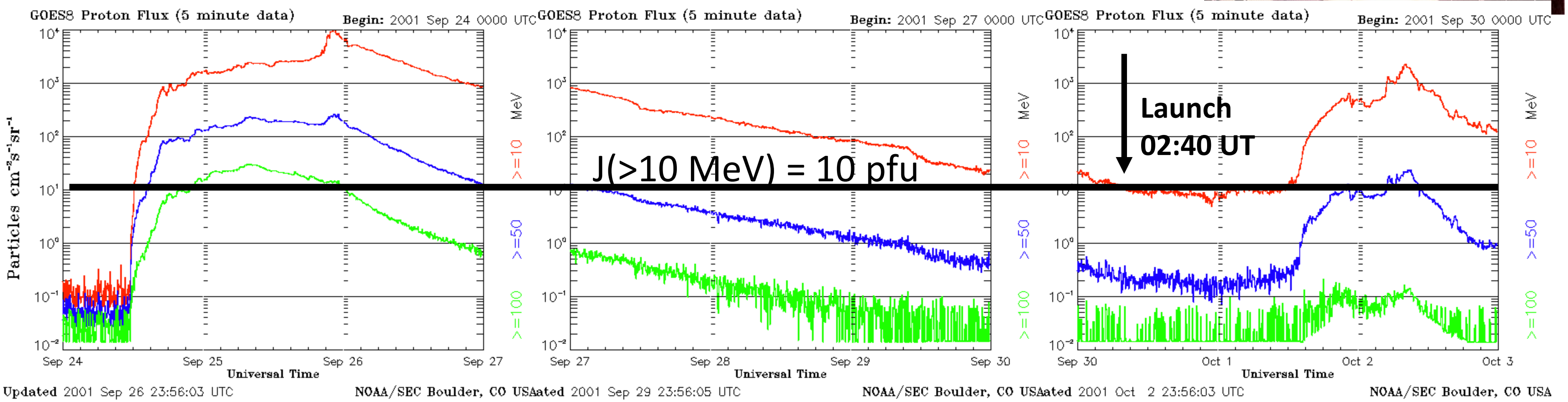


NASA/DOD Kodiak Star: Launch Delay

Kodiak Star scheduled for September 2001 launch from Kodiak Launch Complex (Alaska) on Athena (Lockheed Martin) rocket

Launch criteria: J(>10 MeV) < 10 particles/cm^2-s-sr

- 16 Sep: launch operations start, launch approved for 21 Sep
- 21 Sep: scrub due to terrestrial weather
- 22 Sep: scrub due to range tracking radar hardware problems, next attempt deferred to 24 Sep
- 24 Sep: scrub due to solar proton event
- 25 Sep: scrub due to solar proton event, next attempt deferred to 27 Sep
- 27 Sep: scrub due to solar proton event, terrestrial weather, next attempt deferred to 29 Sep
- 29 Sep: attempt begins with radar issues and proton flux out of limits; radar problem is corrected
- 30 Sep: proton flux decreases to less than constraint value allowing launch at 02:40 UT on 30 Sep



http://www.spaceflightnow.com/athena/kodiakstar/status.html

Sardonia and Madura, 2002

Outline

- Todays presentation will discuss the impact of space weather on satellites with additional emphasis on launch vehicles

- Outline
  - General notes on space environments and effects
  - Environments of importance to satellites, launch vehicles
  - Ionizing radiation effects
  - **Spacecraft charging effects**
  - Meteors and orbital debris

Potential Distributions on Spacecraft Surfaces

- **Electrostatic potentials**
  - Due to net charge density on spacecraft surfaces of or within insulating materials due to current collection to/from the space environment
  - Examples include
    - Plasma currents to surface
    - Secondary electron currents
    - Photoelectron currents
    - Solar array current collection
    - Active current sources (Electron, ion beams, electric thrusters, plasma contactors)
    - Energetic (~MeV) electrons
- **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

$$\frac{\mathrm{dQ}}{\mathrm{dt}} = \mathrm{C}\frac{\mathrm{d}\phi}{\mathrm{dt}} = \sum_{\mathrm{k}} \mathrm{I}_{\mathrm{k}}$$ **~ 0 at equilibrium**

Internal (deep dielectric) charging

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

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

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

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!

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

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

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

Surface Charging Current Balance

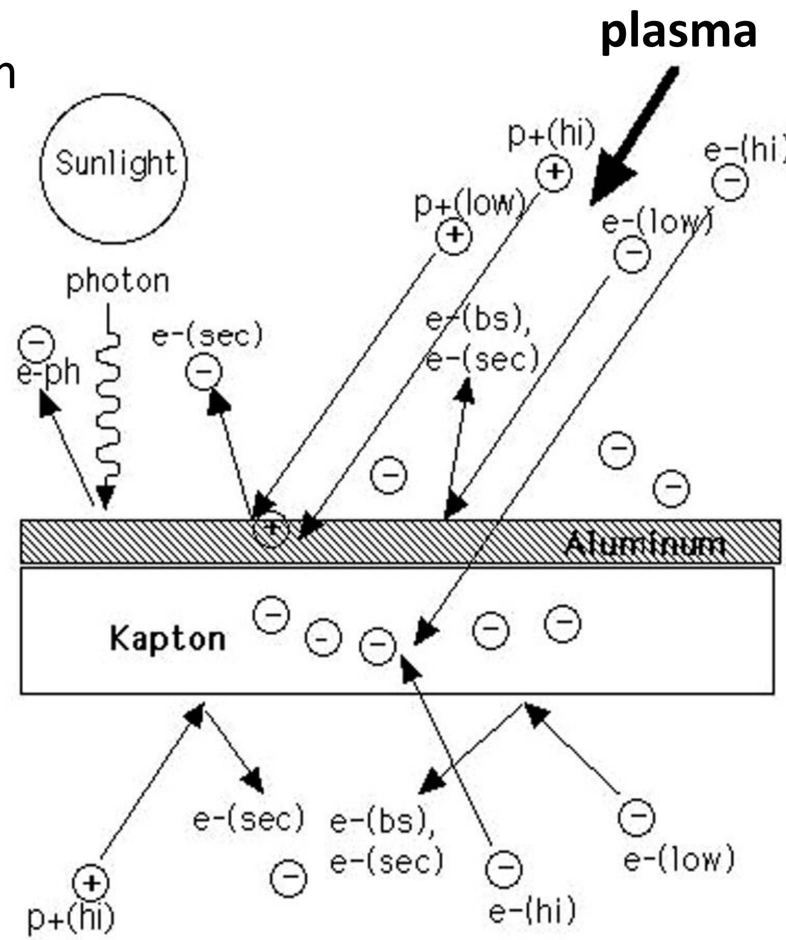
Time dependent current balance

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

Currents

$$\frac{dQ}{dt} = \sum_k I_k =$$

$+I_i(V)$	**incident ions**
$-I_e(V)$	**incident electrons**
$+I_{bs,e}(V)$	**backscattered electrons**
$+I_c(V)$	**conduction currents**
$+I_{se}(V)$	**secondary electrons due to I_e**
$+I_{si}(V)$	**secondary electrons due to I_i**
$+I_{ph,e}(V)$	**photoelectrons**
$+I_b(V)$	**active current sources (beams, thrusters)**



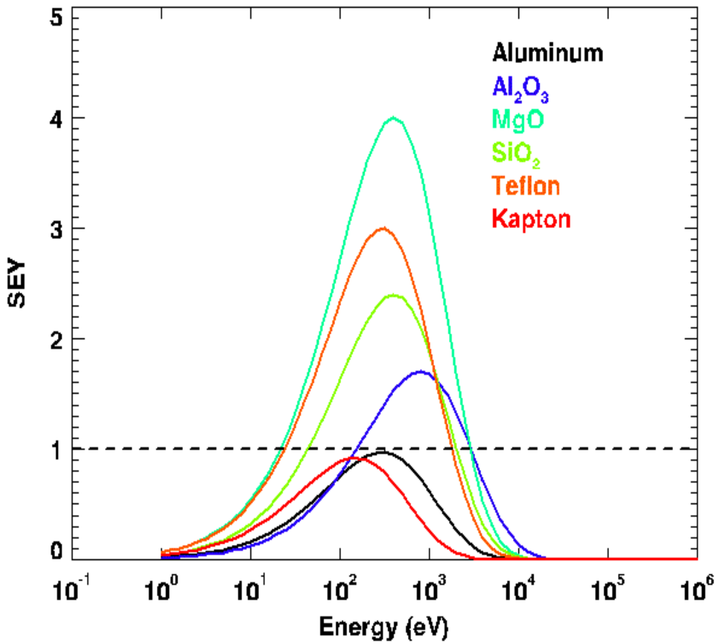
(Garrett and Minow, 2004)

Secondary Electron Yields

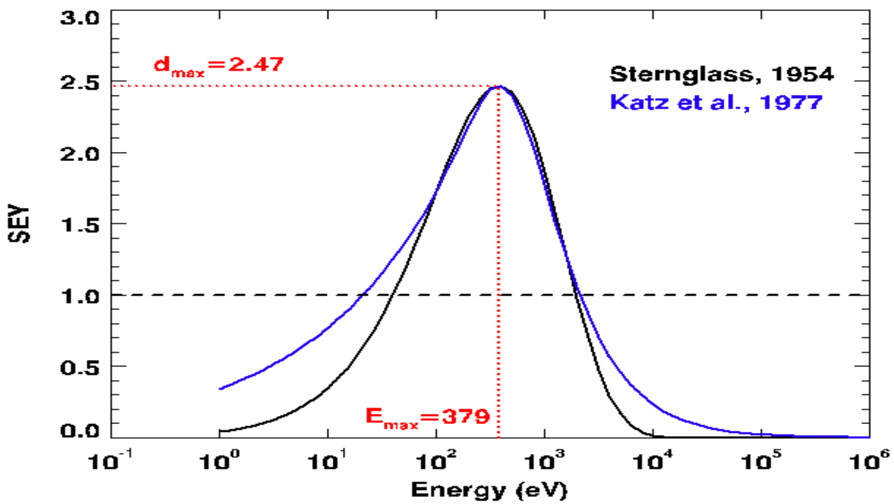
Charging is suppressed when SEY > 1

$$\frac{dQ}{dt} = \sum_k I_k = +I_i - I_e + I_{se} + I_{ph,e}$$

$$= +I_i - I_e(1-\delta) + I_{ph,e}$$



δ_m, E_m from Hasting and Garrett, 1996



Sternglass, 1954

$$\delta_e(E,\theta) = \delta_{e,max}\frac{E}{E_{max}}\exp(2-2\sqrt{E/E_{max}})\exp[2(1-\cos\theta)]$$

Katz et al., 1977; Whipple, 1981

$$\delta_e(E,\theta) = \frac{1.114\delta_{e,max}}{\cos\theta}\left[\frac{E}{E_{max}}\right]^{0.35}\left\{1-\exp\left[-2.28\cos\theta\left[\frac{E_{max}}{E}\right]^{1.35}\right]\right\}$$

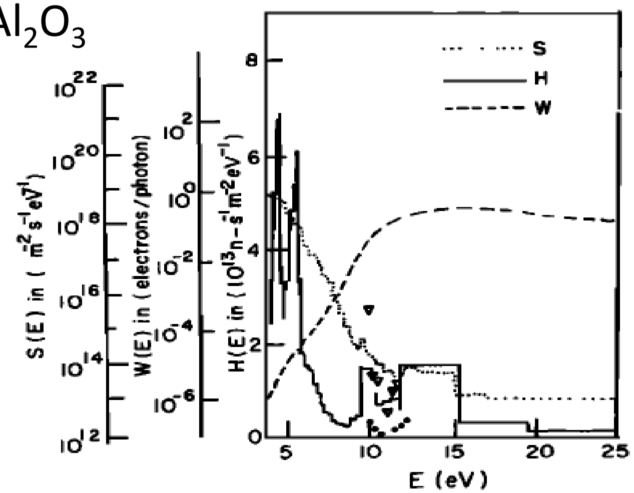
Photoemission Yields

- Photoemission is an important factor in controlling surface charging

Material	Saturation Photocurrent Density
Al2O3	4.2 nA/cm^2
Au	2.9 nA/cm^2
Stainless steel	2.0 nA/cm^2
Graphite	0.4 nA/cm^2

[from Garrett, 1981]

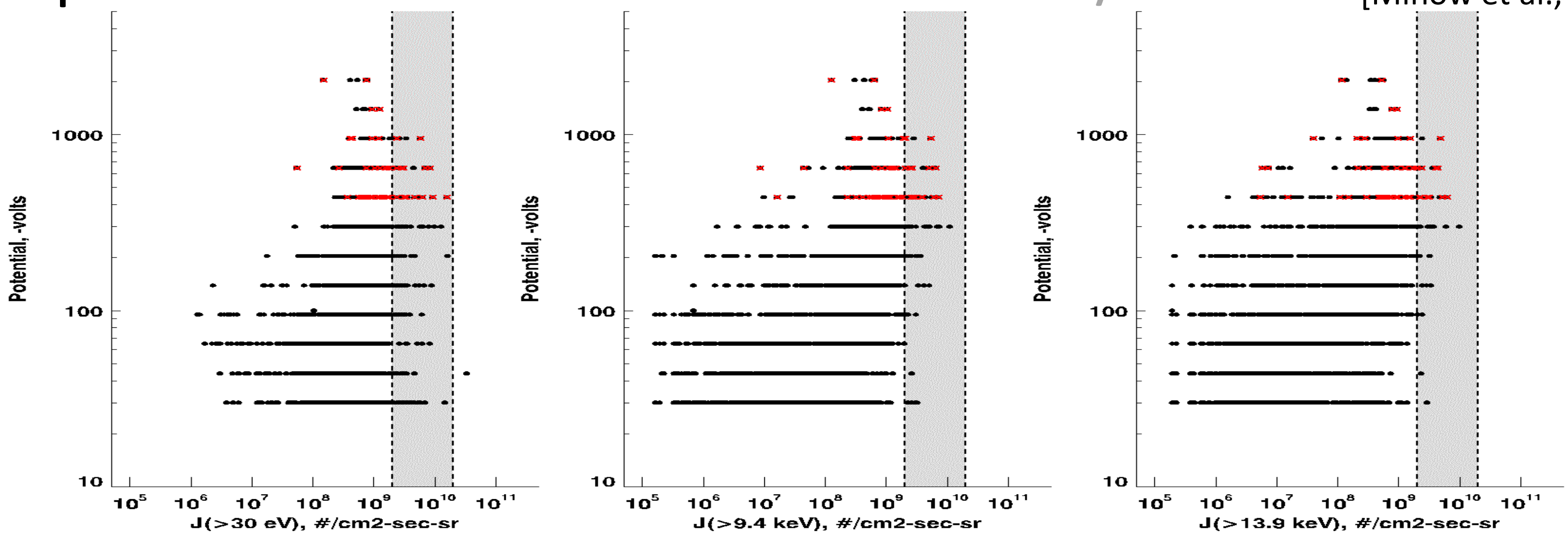
Al_2O_3



[Grard, 1973]

All potentials in event **Maximum Potential** **1-10 nA/cm^2**

[Minow et al., 2014]



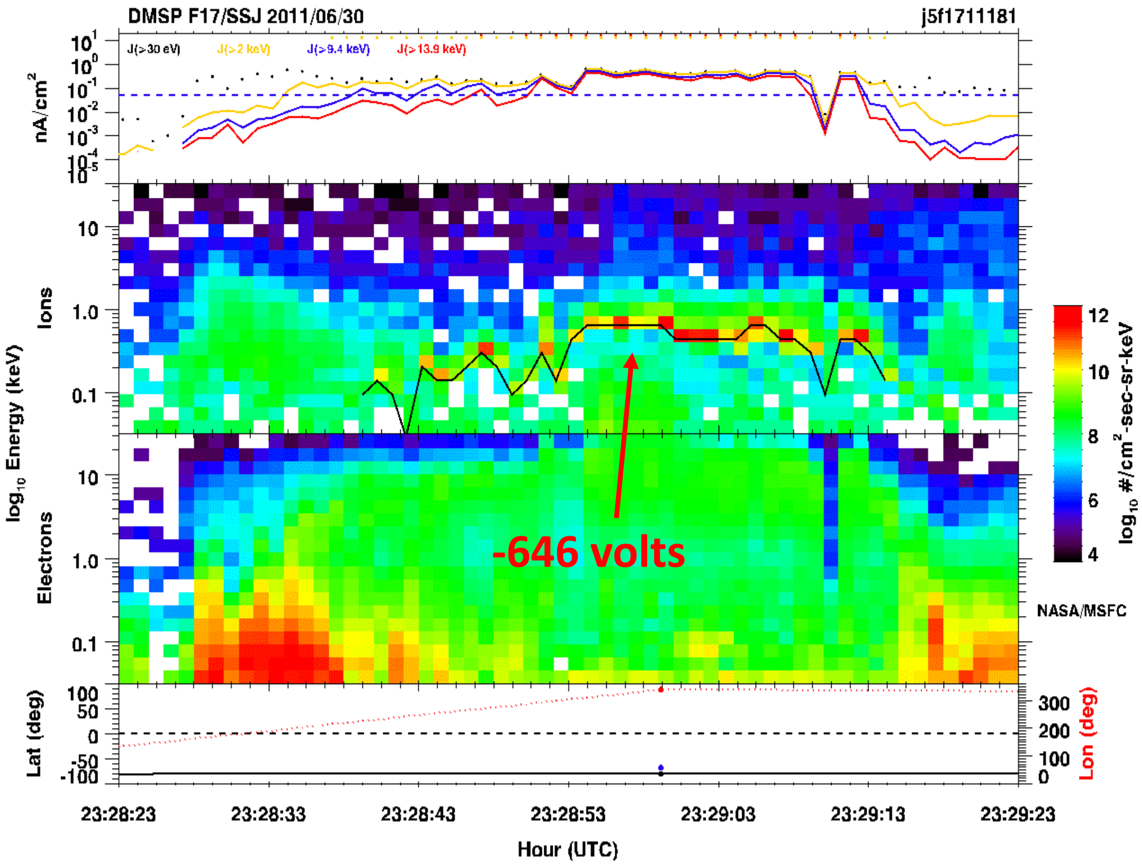
“Ion Line” Charging Signature, $\phi_{s/c} < 0$

- Low energy background ions accelerated by spacecraft potential show up as sharp “line” of high ion flux in single channel

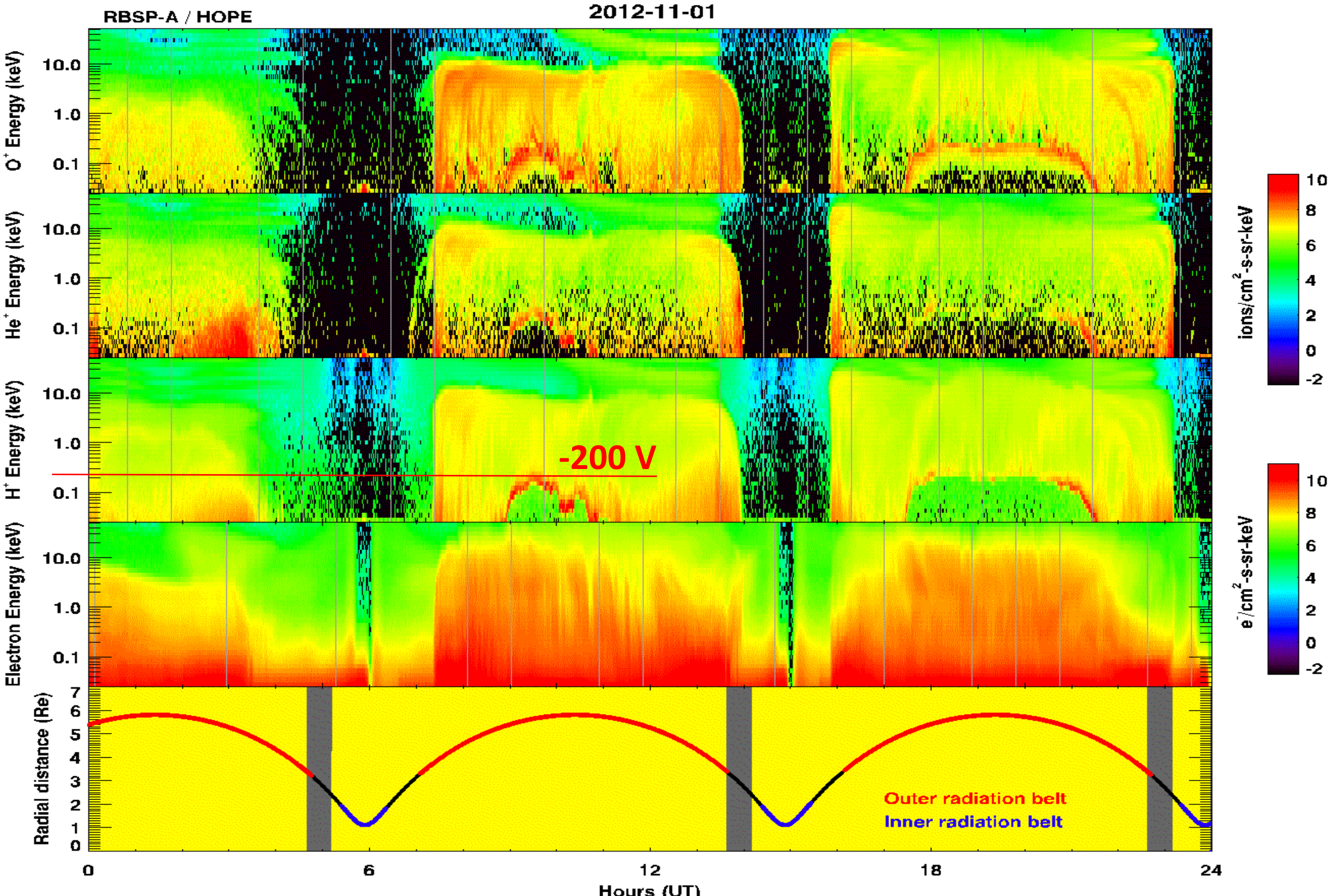
$$E = E_0 + q\Phi$$

- Assume initial energy $E_0 \sim 0$ with single charge ions (O^+, H^+) and read potential (volts) directly from ion line energy (eV)

- Accuracy of potential measurement set by energy width and separation of the energy channels used to infer the potential



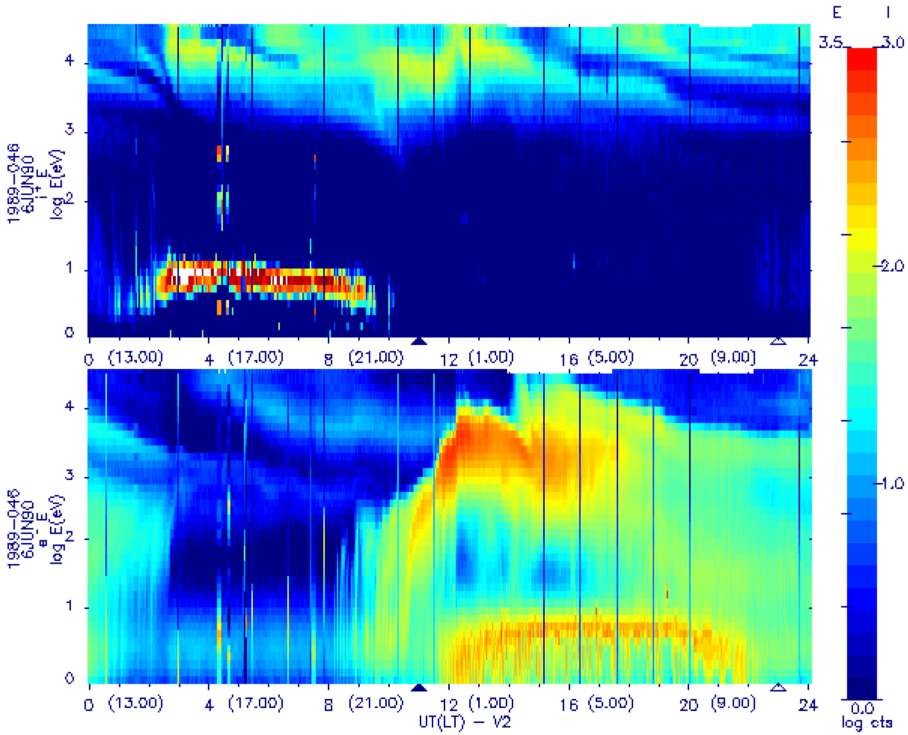
Van Allen Probe-A (GTO)



[*Parker and Minow*, 2014]

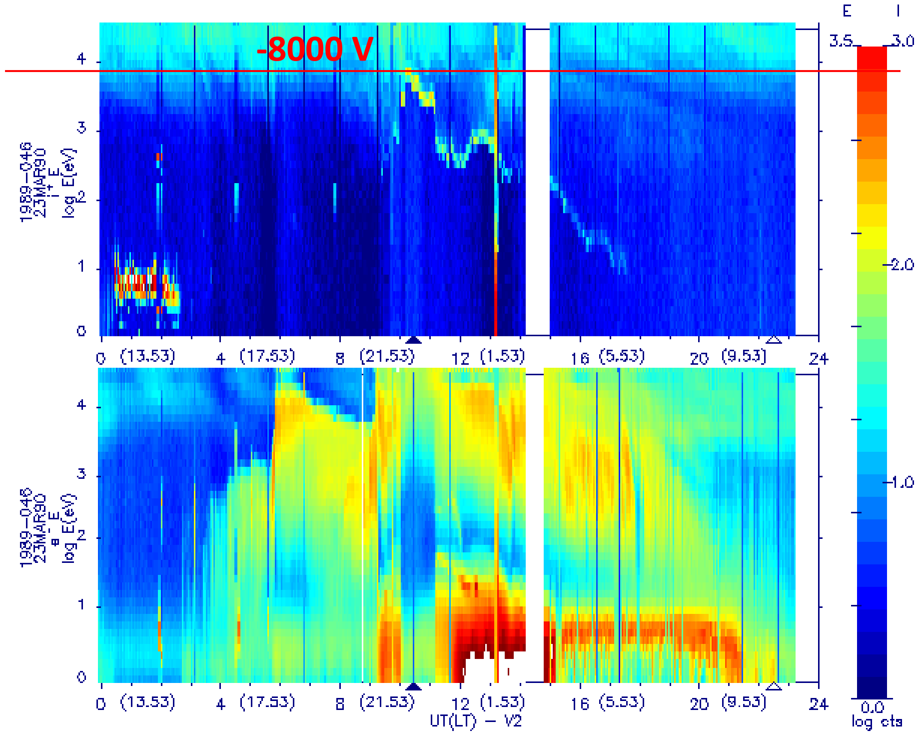
Los Alamos GEO Spacecraft

LANL 1989-046 6 June 1990



no charging

LANL 1989-046 23 March 1990

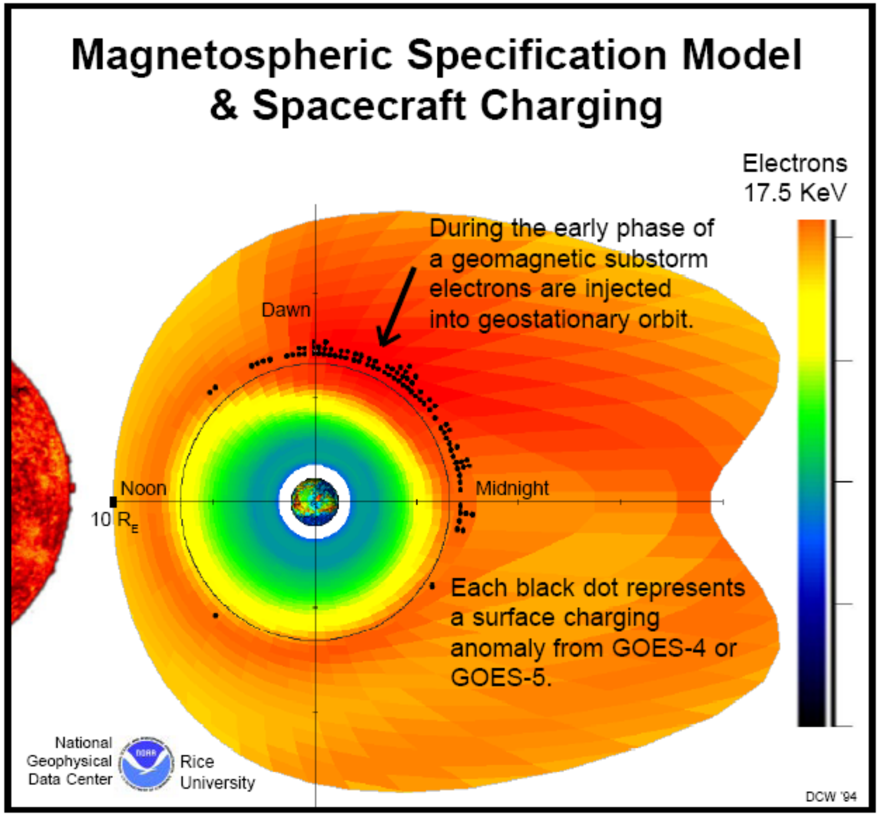


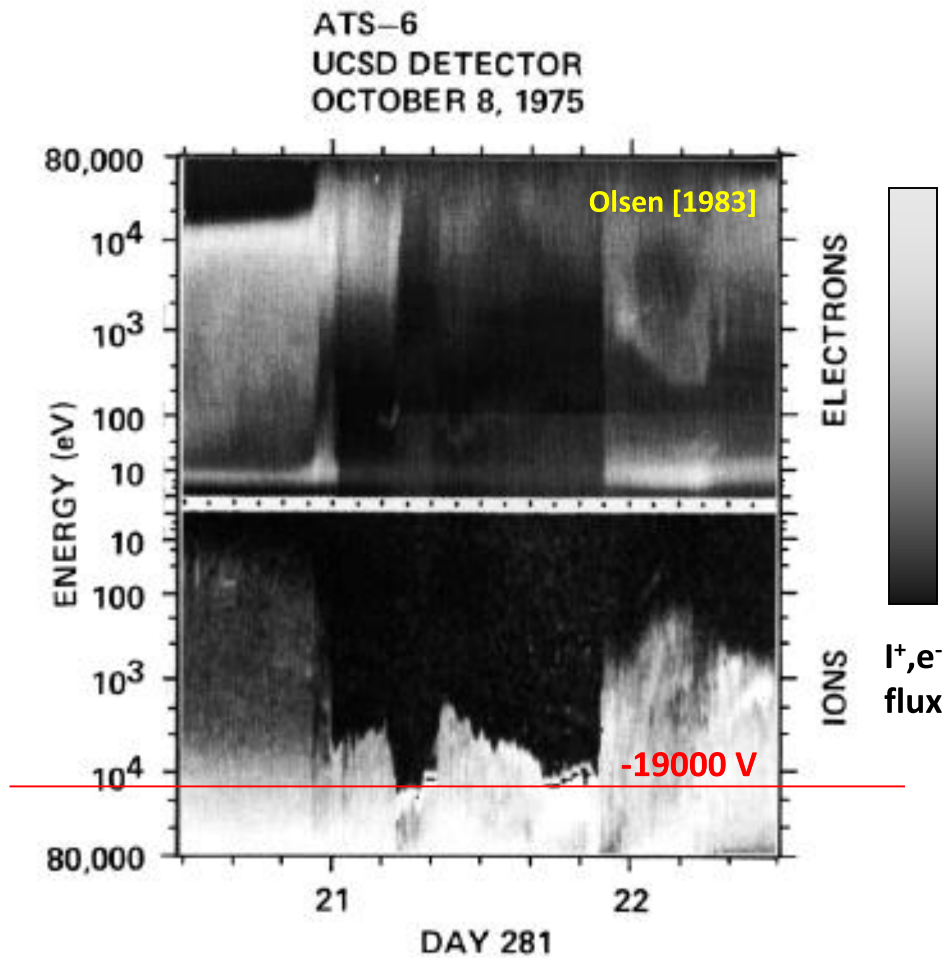
~ 8 kV in eclipse

~ 1 kV post midnight

During periods of significant hot plasma injection, spacecraft may become significantly charged relative to background plasma

GEO Surface Charging





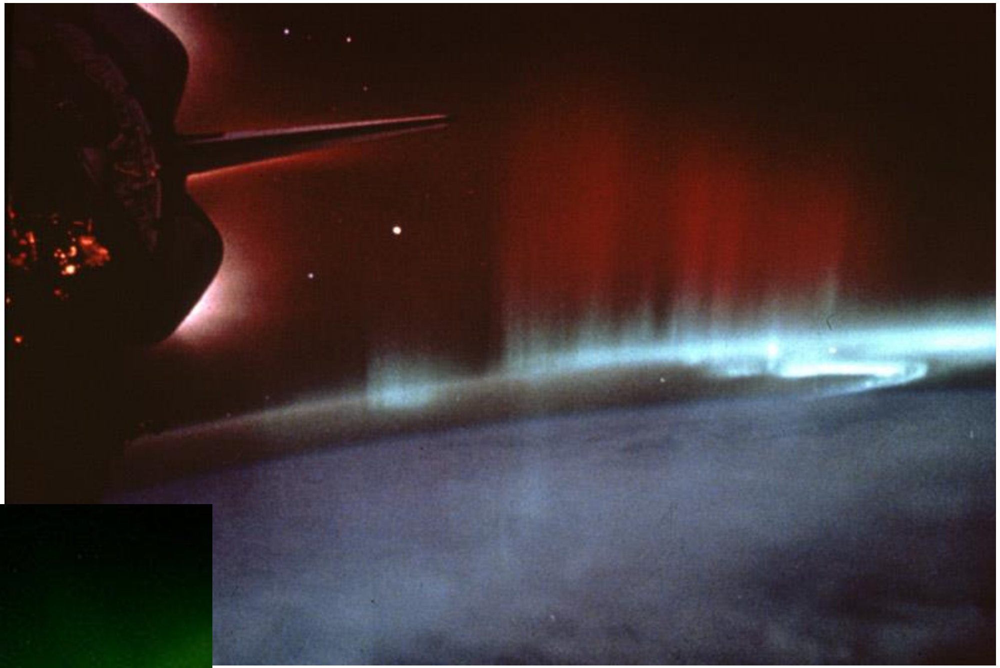
Surface charging anomalies typically occur in midnight to dawn local time sector where hot electrons are injected during geomagnetic substorms

Record ATS-6 charging event
Φ ~ -19 kV

Auroral Charging

Auroral charging is controlled by

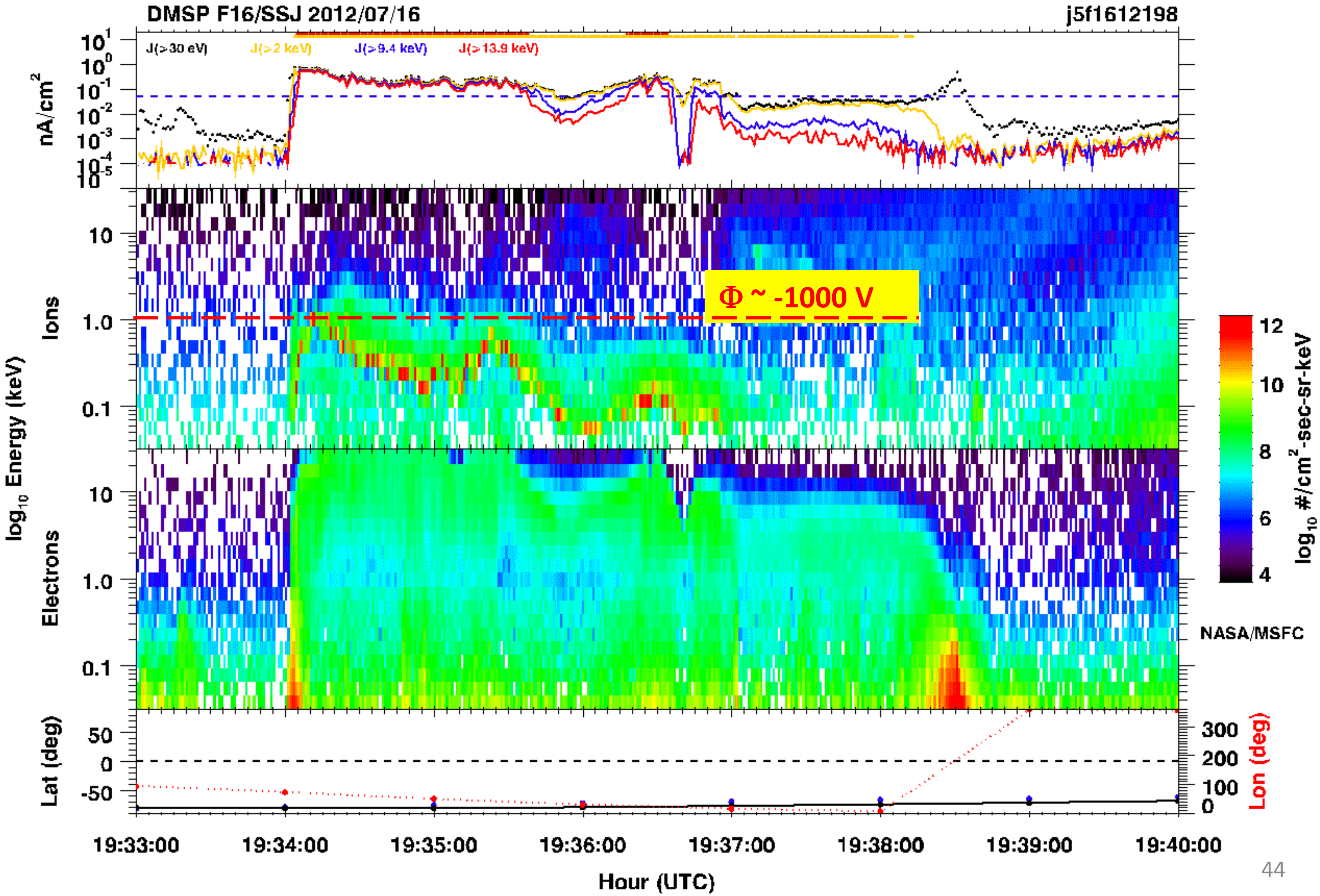
- Energy of primary electrons and secondary electron yields
- Density of ambient plasma (to balance auroral electron collection)

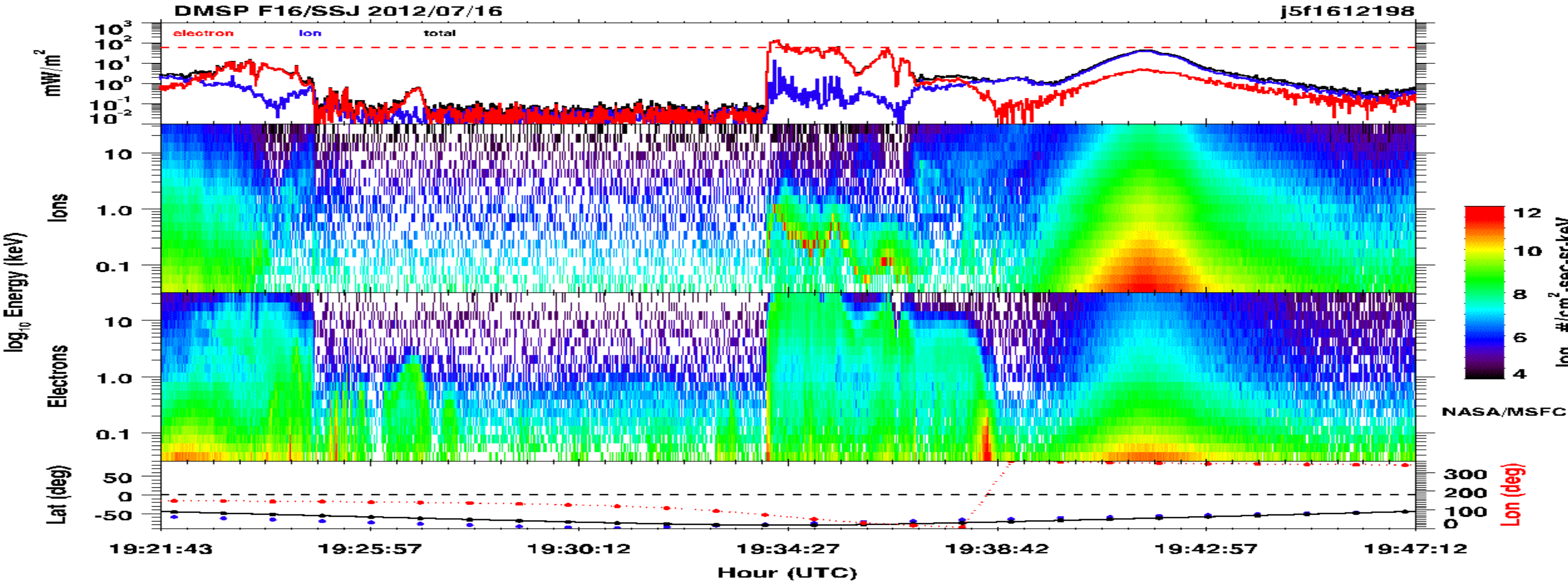


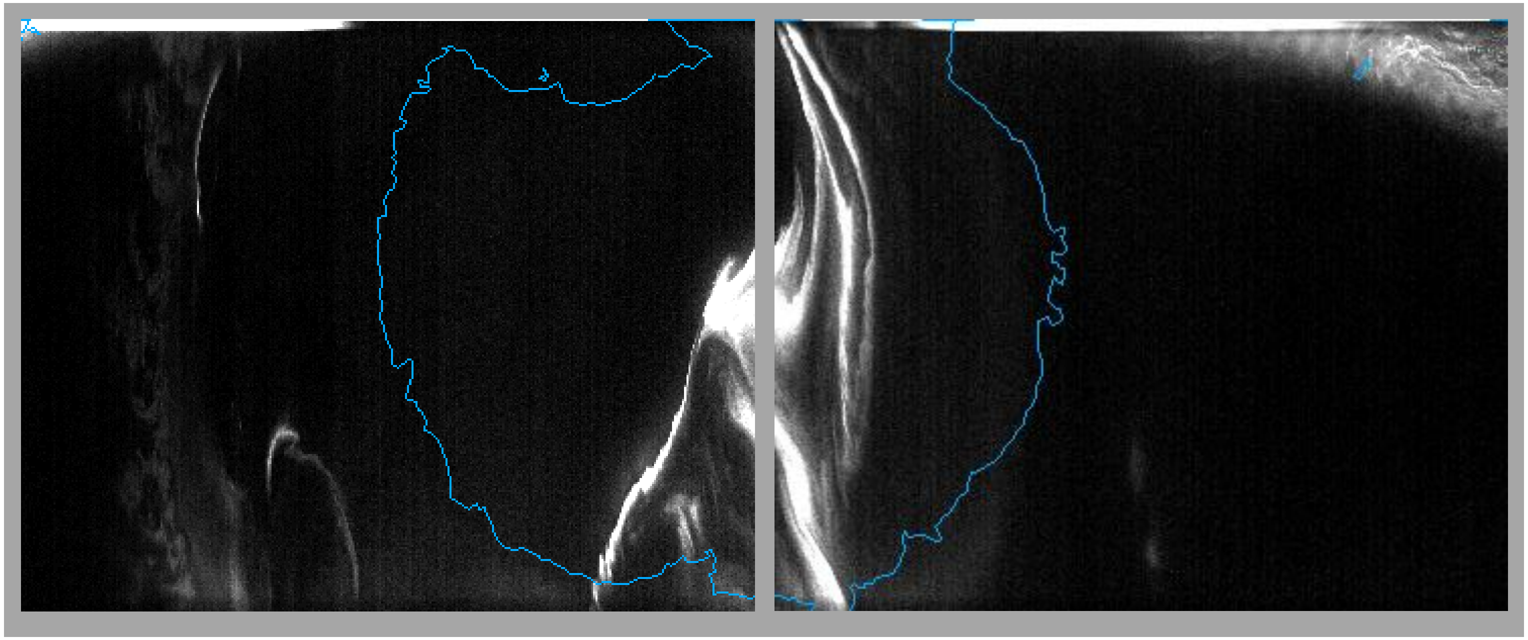
Examples of low Earth orbit charging in the auroral zone include

- DMSP ~830 km, 98 deg
  -10’s V > Φ > -1500 V
- Freja 590 km x 1763 km, 63 deg
  -10’s V > Φ > -3000 V

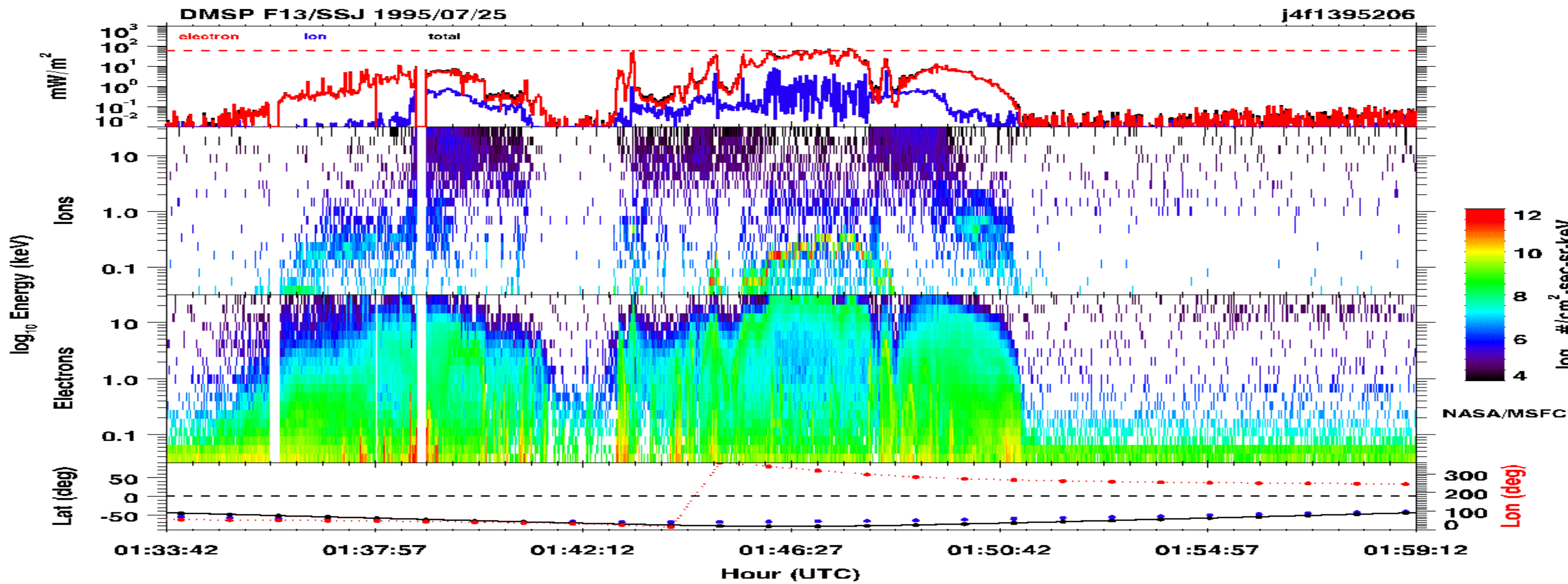
DMSP F16: -1000 V Charging Event

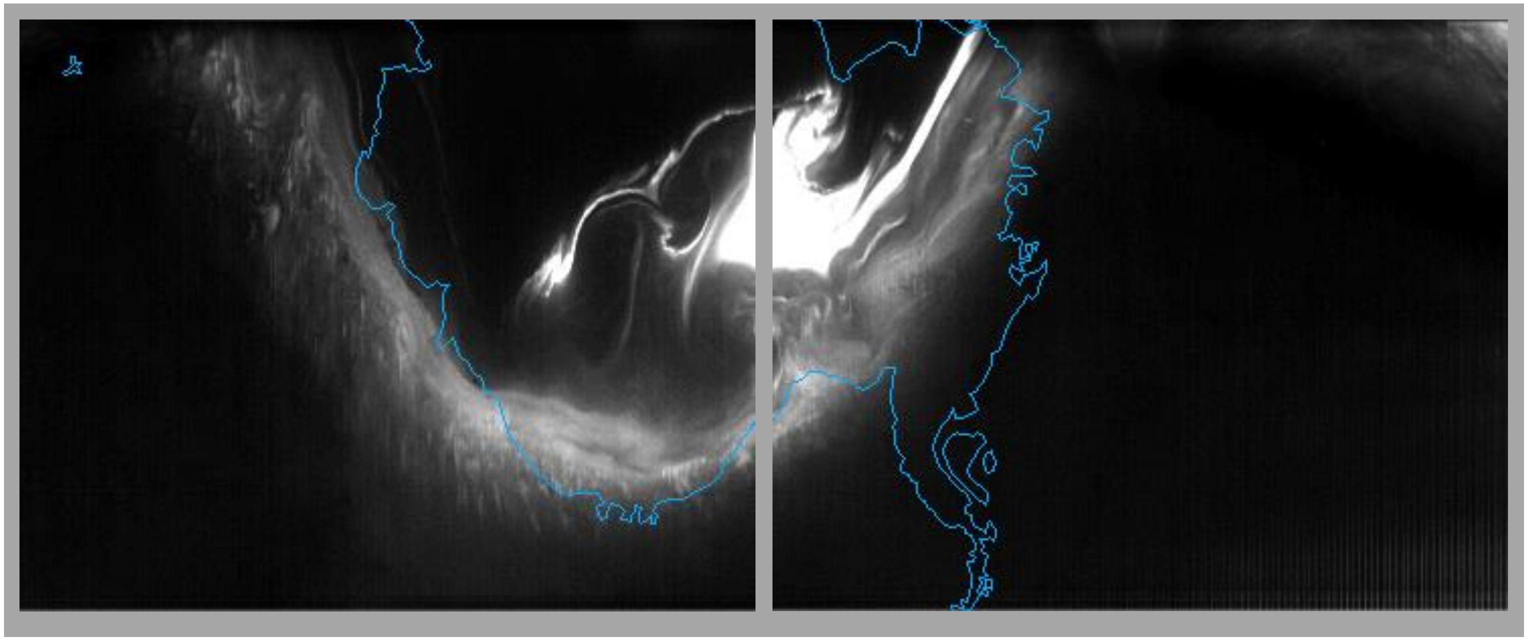






2012-07-16 19:21:43.0 2012-07-16 19:34:27.0 2012-07-16 19:47:12.0





1995-07-25 01:33:42.0 1995-07-25 01:46:27.0 1995-07-25 01:59:12.0

Fontheim Distribution

Ambient background

n=1.0e10	1/m3
Te=0.2	eV

Maxwellian

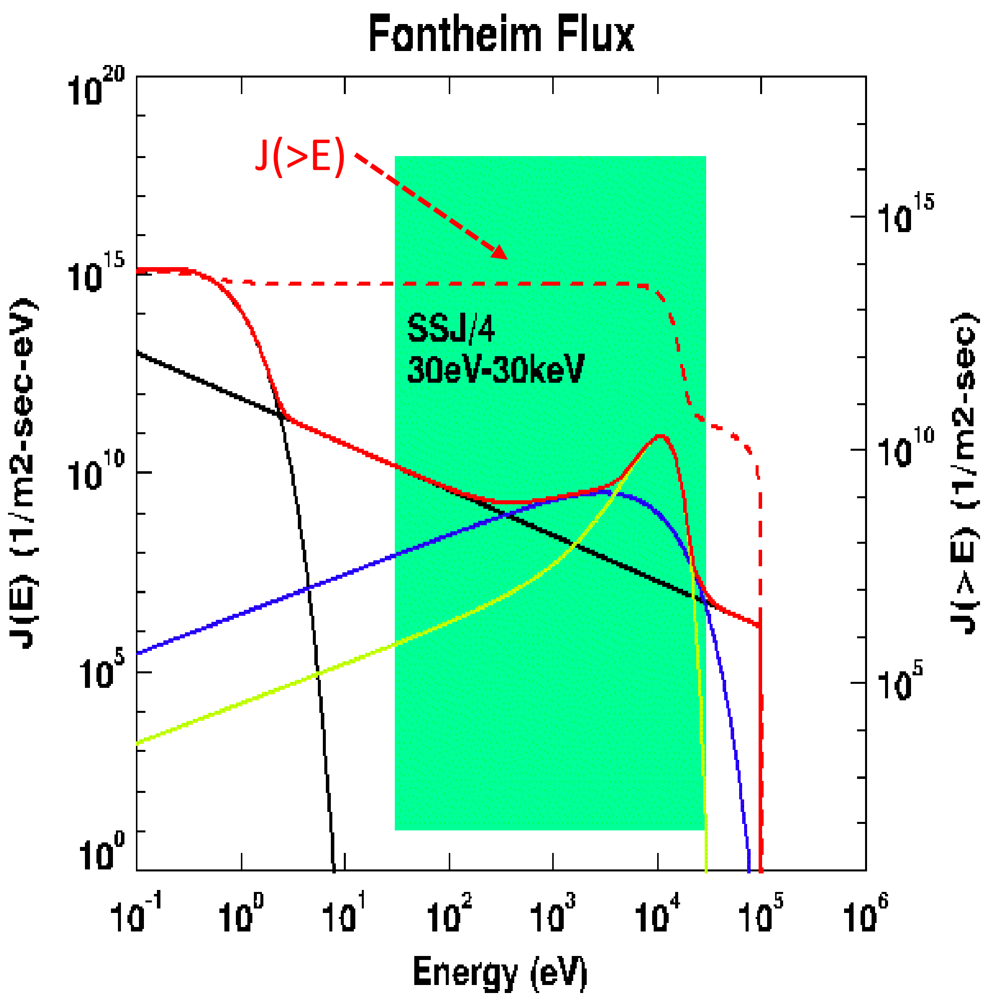
Jmax = 4.0e-6	A/m²
Te = 3.0e3	eV

Gaussian (beam)

Jgau =0.9e-4	A/m²	
Egau = 10.0e3	eV	beam energy
dgau = 4.0e3	eV	beam width

Power Law

Jpwr = 3.0e-7	A/m²
alpha = 1.15	exponent
E1=50.0	eV, first energy
E2=1.0e5	eV, second energy



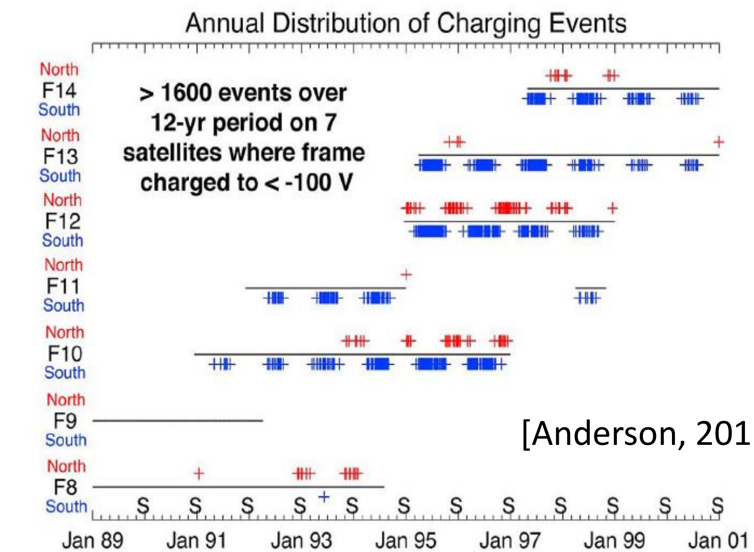
$$\mathrm{Flux}(E) = \sqrt{\frac{e}{2\pi\theta m_e}}\frac{E}{\theta} n \exp\left(-\frac{E}{\theta}\right) + \pi\zeta_{max} E \exp\left(-\frac{E}{\theta_{max}}\right) + \pi\zeta_{gauss} E \exp\left(-\left(\frac{E_{gauss}-E}{\Delta}\right)^2\right) + \pi\zeta_{power} E^{-\alpha}$$

[Davis et al., 2011]

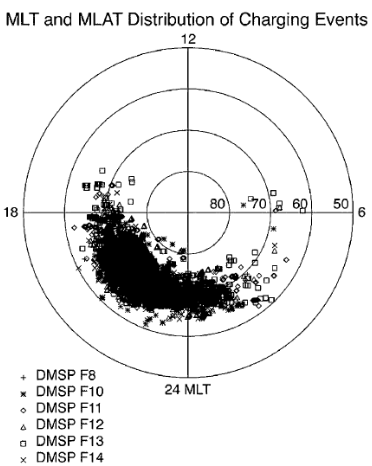
Auroral Charging Conditions

Necessary conditions for high-level (≥100 V) auroral charging*

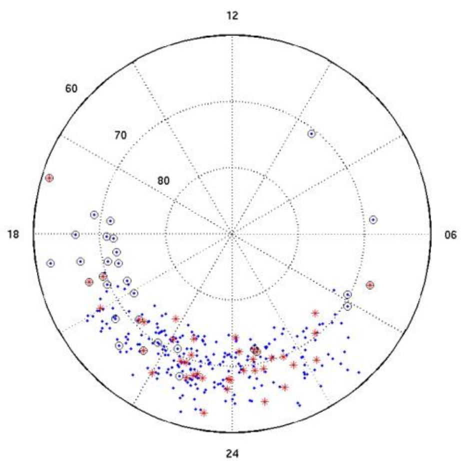
- No sunlight (or ionosphere below spacecraft in darkness)
- Intense electron flux $>10^8$ e/cm^2-s-sr at energies of 10's keV
- Low ambient plasma density ($<10^4$ #/cm^3)



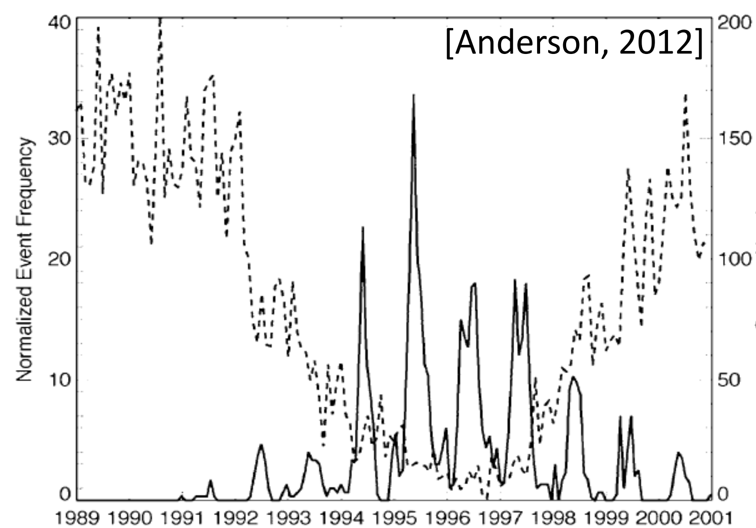
[Anderson, 2012]



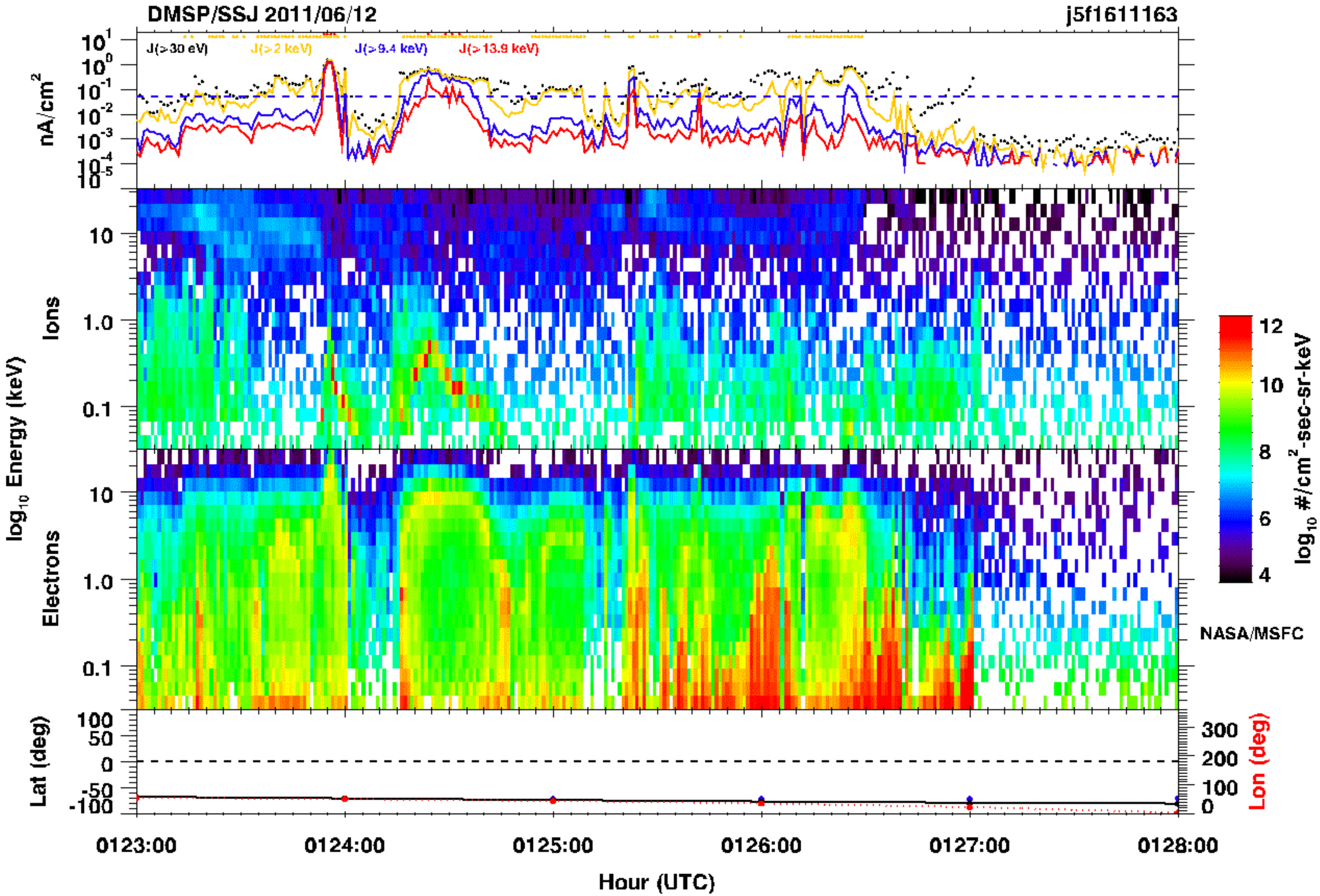
[Anderson, 2012]



[Eriksson and Wahlund, 2006]

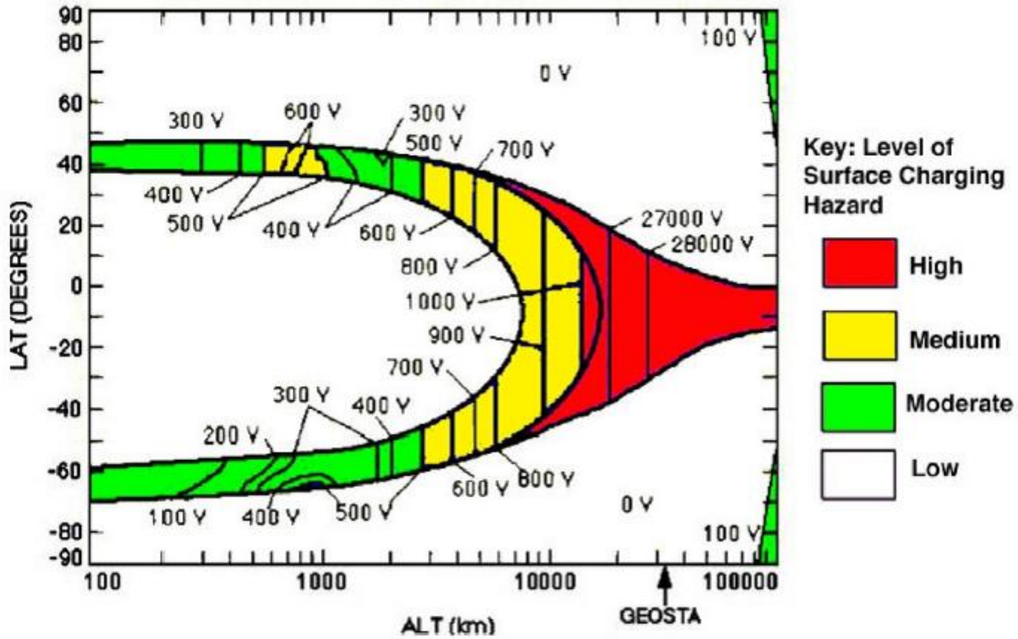


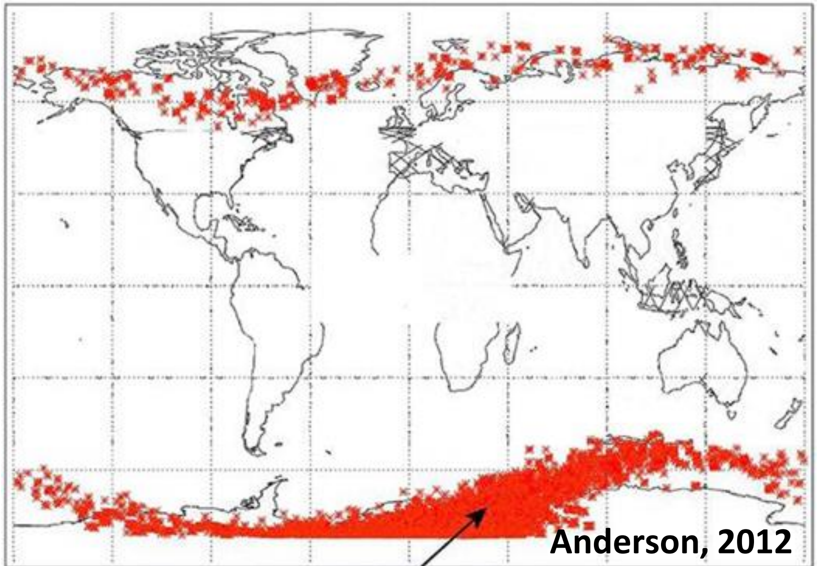
Inverted V, Broadband Aurora



Launch Vehicle Surface Charging

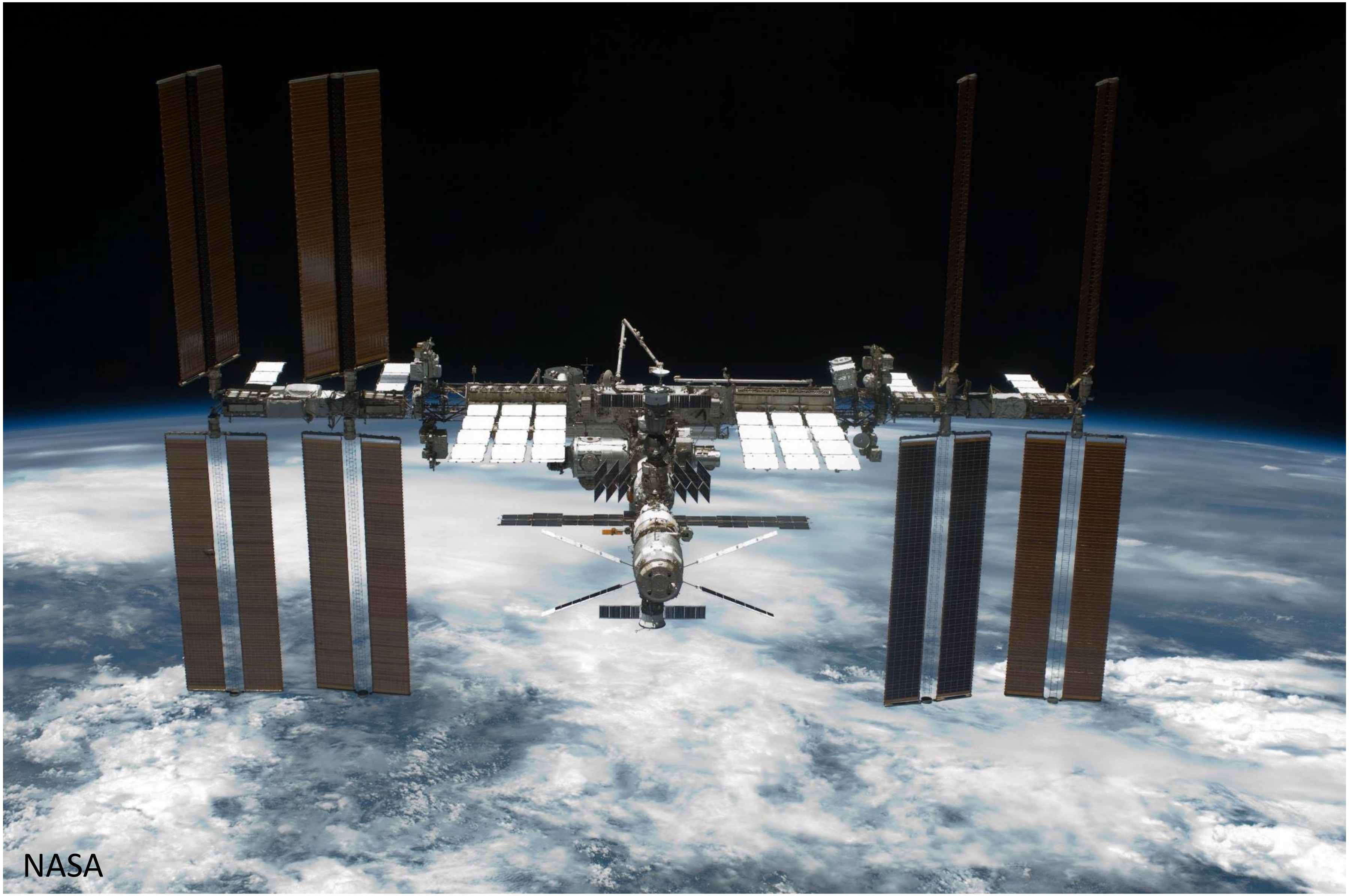
- Charging time scales of ~seconds
- Insulating materials on spacecraft surface increases threat of differential charging
- Are sensitive electronics located near the insulation materials?
- Will RF noise interfere with critical upcomm/downcomm transmissions?
- Will launch trajectory encounter regions of auroral charging threat?
- Will the encounter be in sunlight or darkness?





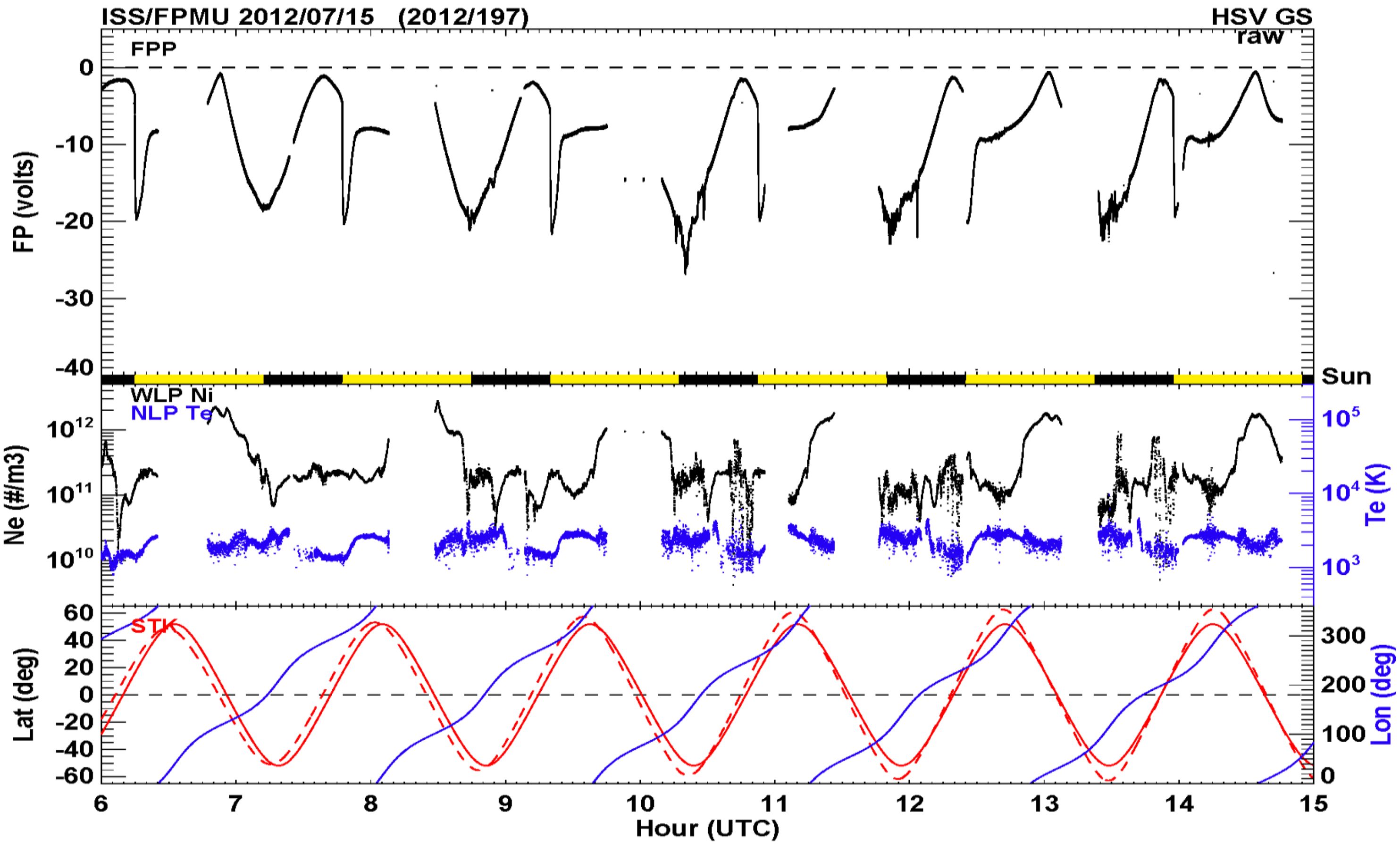
DMSP Charging Events

ISS Charging



International Space Station: 15 July 2012

Potential variations due to (a) vxB.L (b) eclipse exit solar array (c) auroral charging



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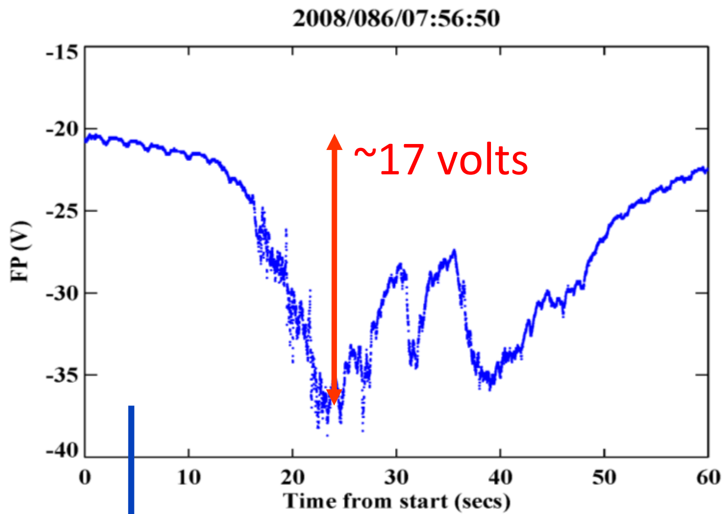
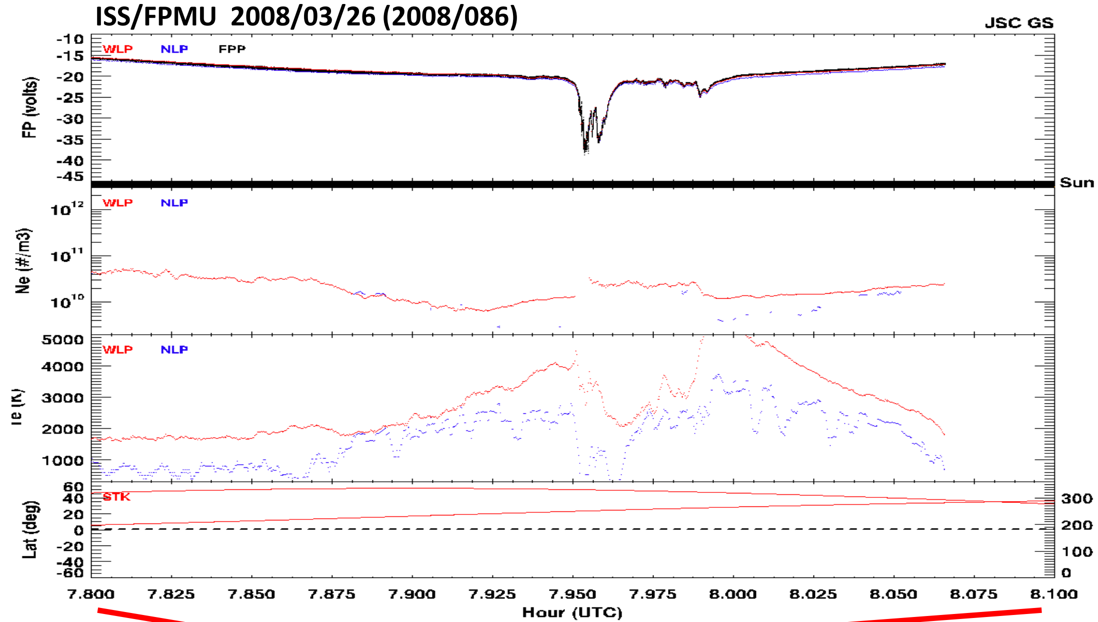
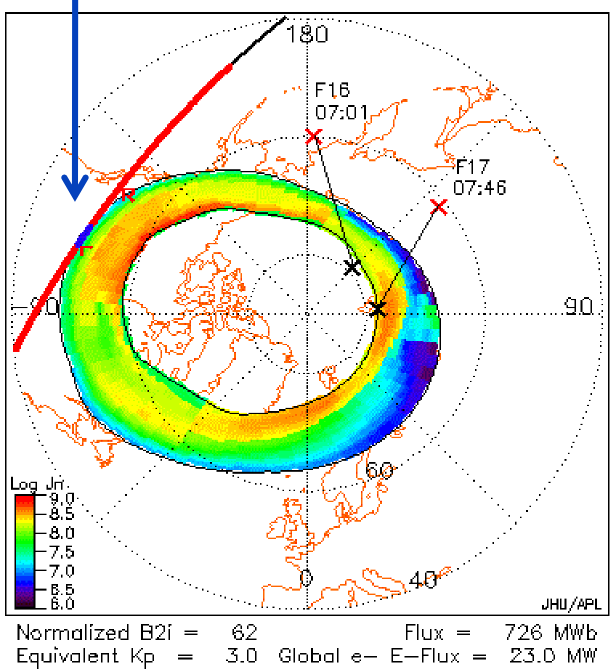
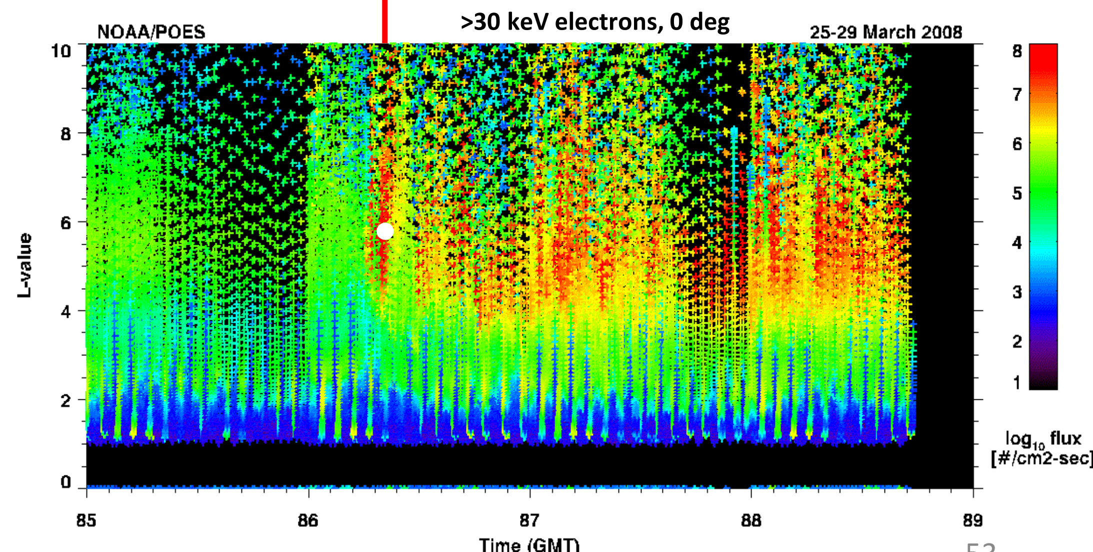
26 March 2008 -- Auroral Charging





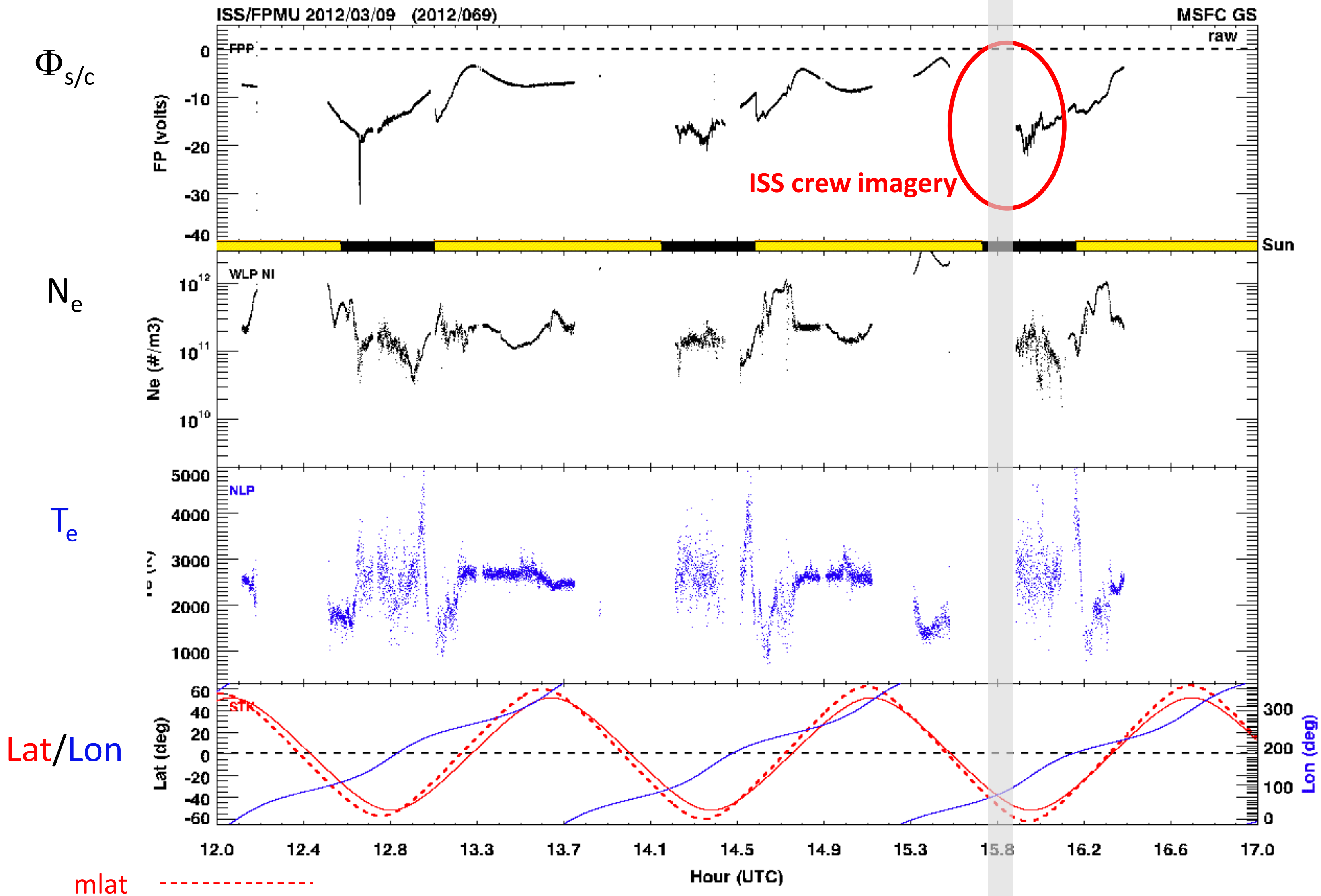
26 Mar 2008 07:30 – 08:00 UT





[adapted from *Craven et al.*, 2009]

9 March 2012


ISS/FPMU 2012/03/09 (2012/069)
MSFC GS
raw
$\Phi_{s/c}$
FPP
FP (volts)
ISS crew imagery
Sun
N_e
WLP NI
Ne (#/m3)
T_e
NLP
Lat/Lon
STK
Lat (deg)
Lon (deg)
Hour (UTC)
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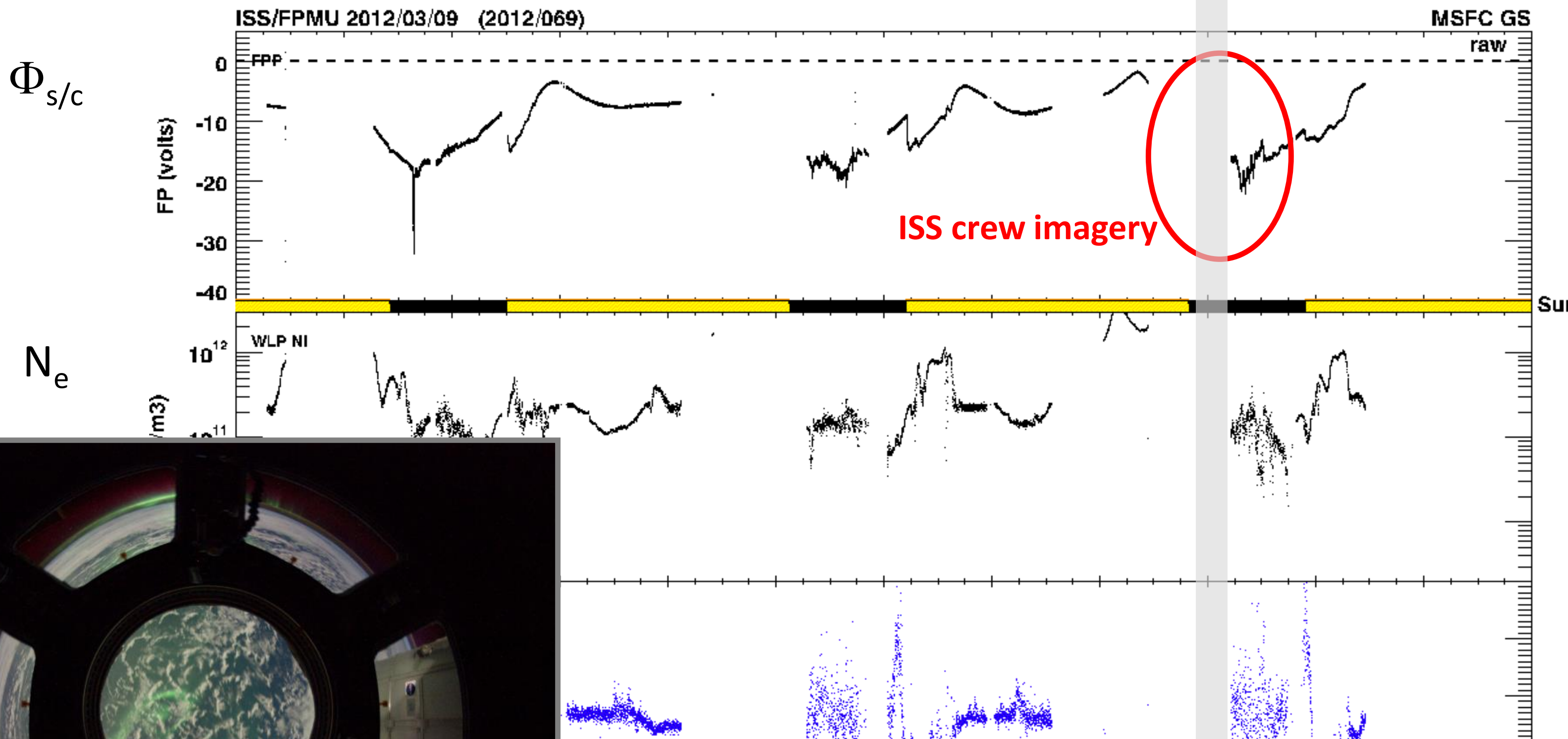
9 March 2012

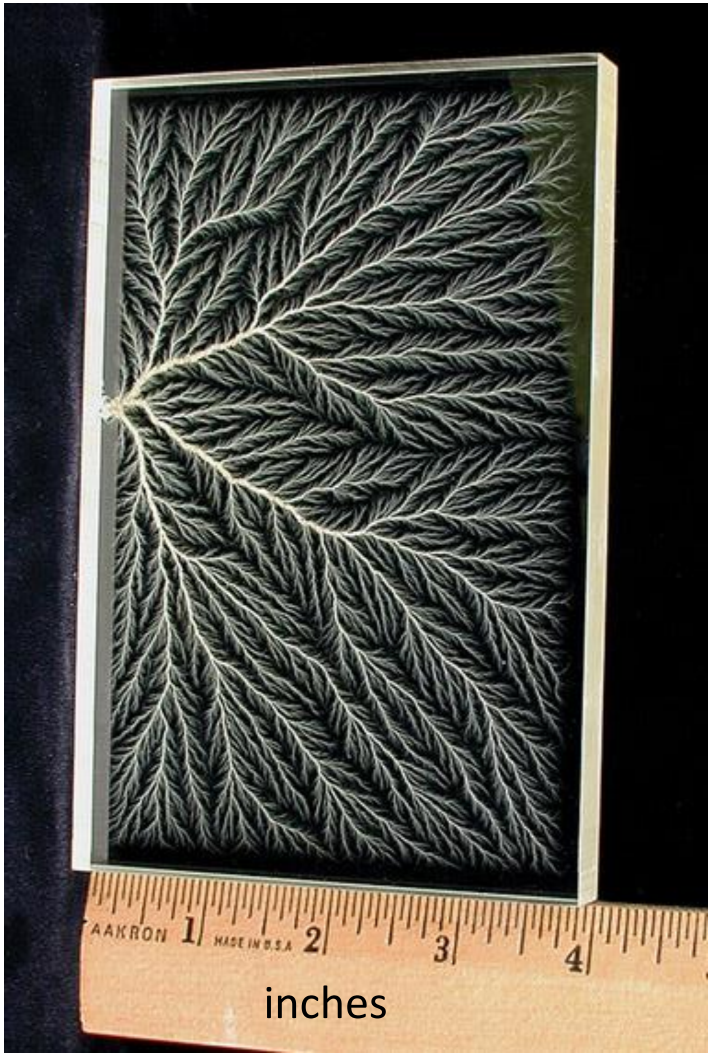


$\Phi_{s/c}$
N_e
ISS/FPMU 2012/03/09 (2012/069)
MSFC GS
raw
FPP
FP (volts)
0
-10
-20
-30
-40
Sun
ISS crew imagery
WLP NI
10^{12}
10^{11}
-60
12.0
12.4
12.
mlat

ISS030e131739
2012/03/09 15:52:06

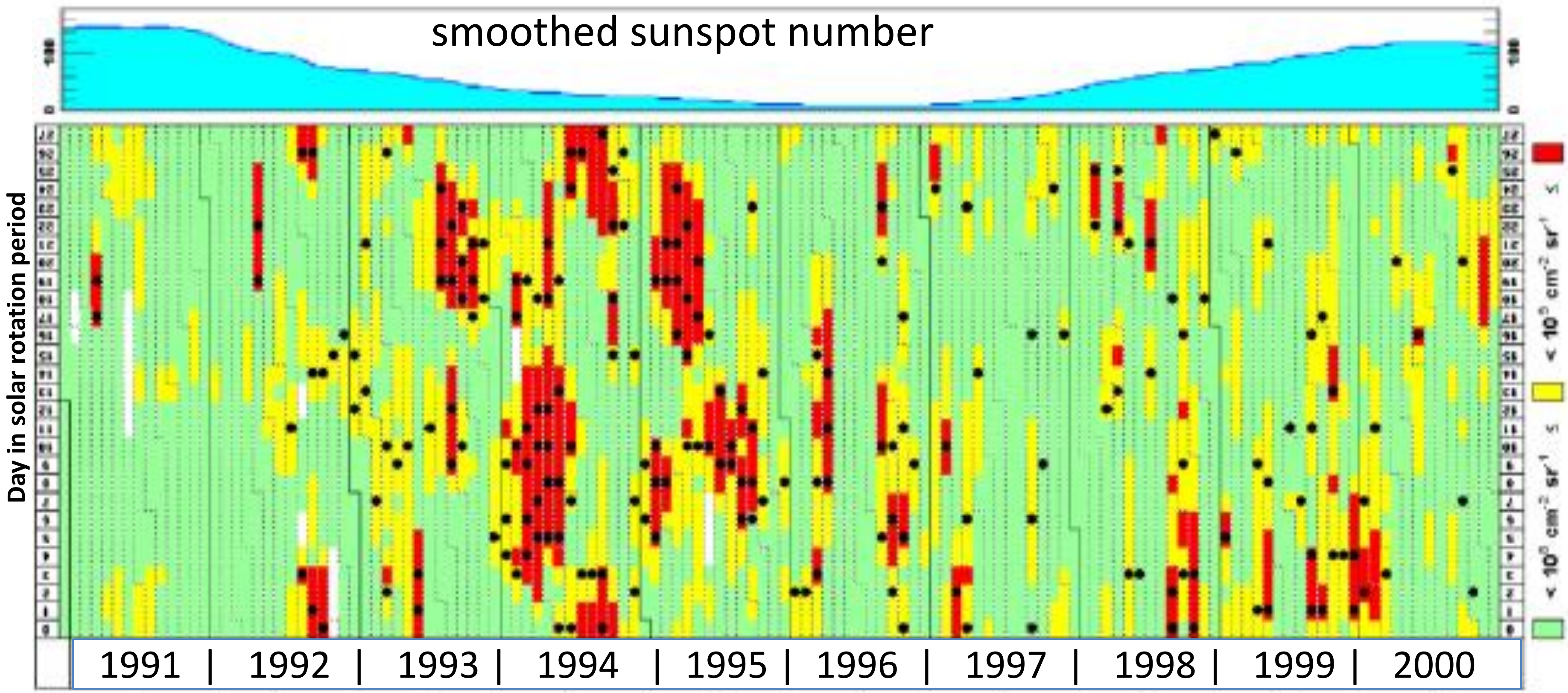
Internal (Deep Dielectric) Charging

- High energy (>100 keV) electrons penetrate spacecraft walls and accumulate in dielectrics or isolated conductors
- Threat environment is energetic electrons with sufficient flux to charge circuit boards, cable insulation, and ungrounded metal faster than charge can dissipate
- Accumulating charge density generates electric fields in excess of breakdown strength resulting in electrostatic discharge
- System impact is material damage, discharge currents inside of spacecraft Faraday cage on or near critical circuitry, and RF noise



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

GOES Solar Cycle 21 Internal Charging Anomalies (GEO)



Black: GOES phantom commands

[adapted from *Wrenn et al.* 2002]

2-day fluence (F2) > 2 MeV electrons

Red: F2 $\geq 10^9$ e^-/cm^2-sr

Amber: 10^9 > F2 $\geq 10^8$ e^-/cm^2-sr

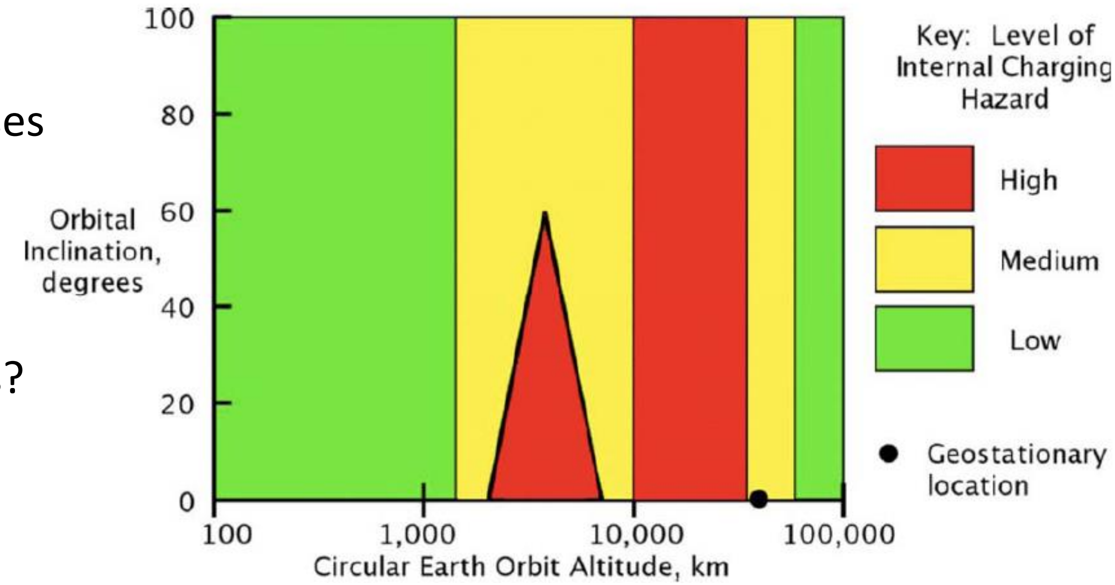
Green: F2 < 10^8 e^-/cm^2-sr

White: no data

Launch Vehicle Internal Charging

- Charging time scales of ~hours to days (or even months), typically low threat for launch vehicles
- Multiple GTO phasing orbits or complete radiation belt transits should be evaluated as special cases
- Insulation on exposed or lightly shielded signal and power cables?
- Cryotank insulation, paints, decals?
- Are sensitive electronics located near the insulation materials?
- Will RF noise interfere with critical upcomm/downcomm transmissions?

[NASA-HDBK-4002a]



ESD Threat Threshold "Rule-of-Thumb"

10-hr fluence: 2×10^{9} e/cm^2 2×10^{10} e/cm^2

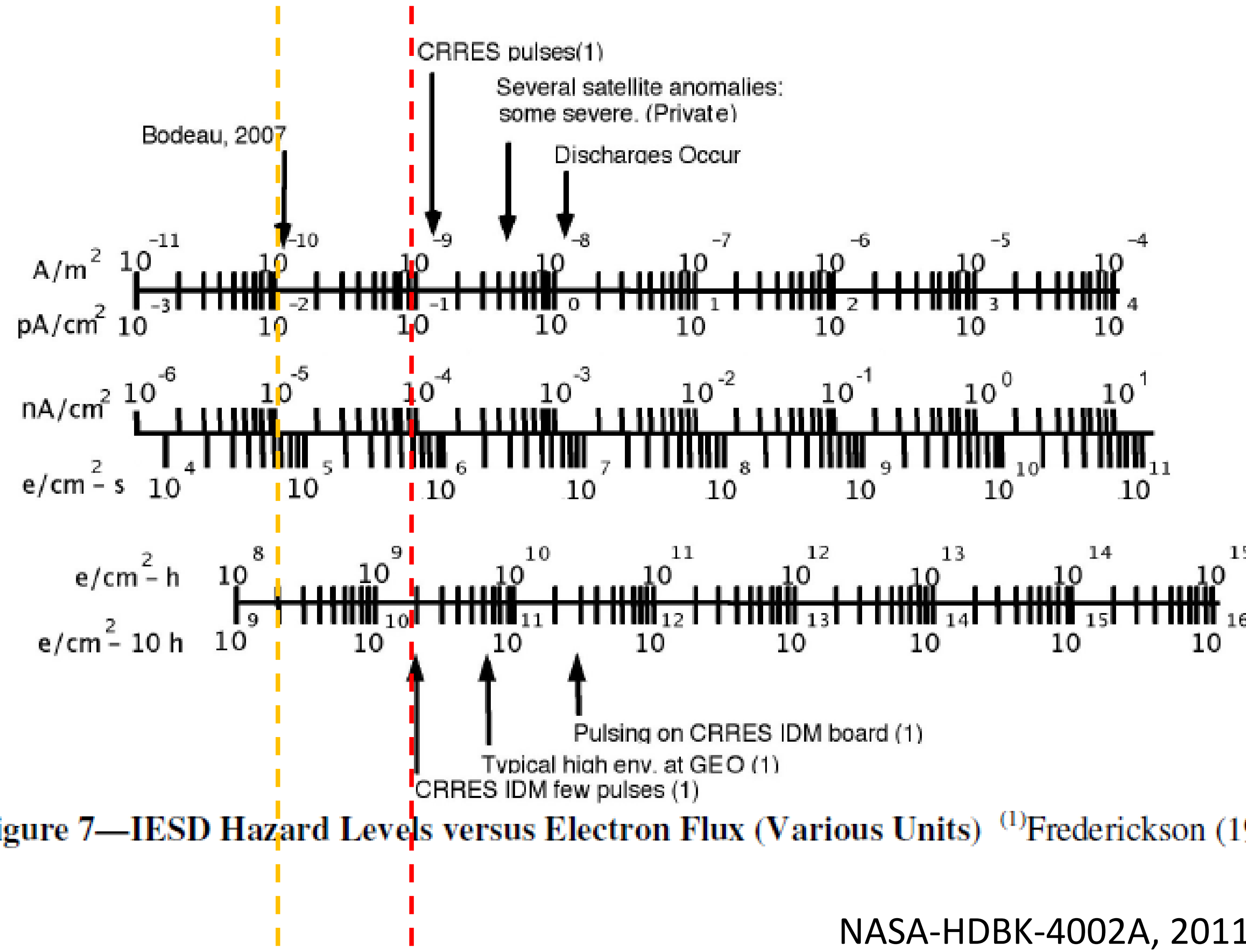


Figure 7—IESD Hazard Levels versus Electron Flux (Various Units) (1)Frederickson (1992)

NASA-HDBK-4002A, 2011

Bulk (Internal) Charging Environments

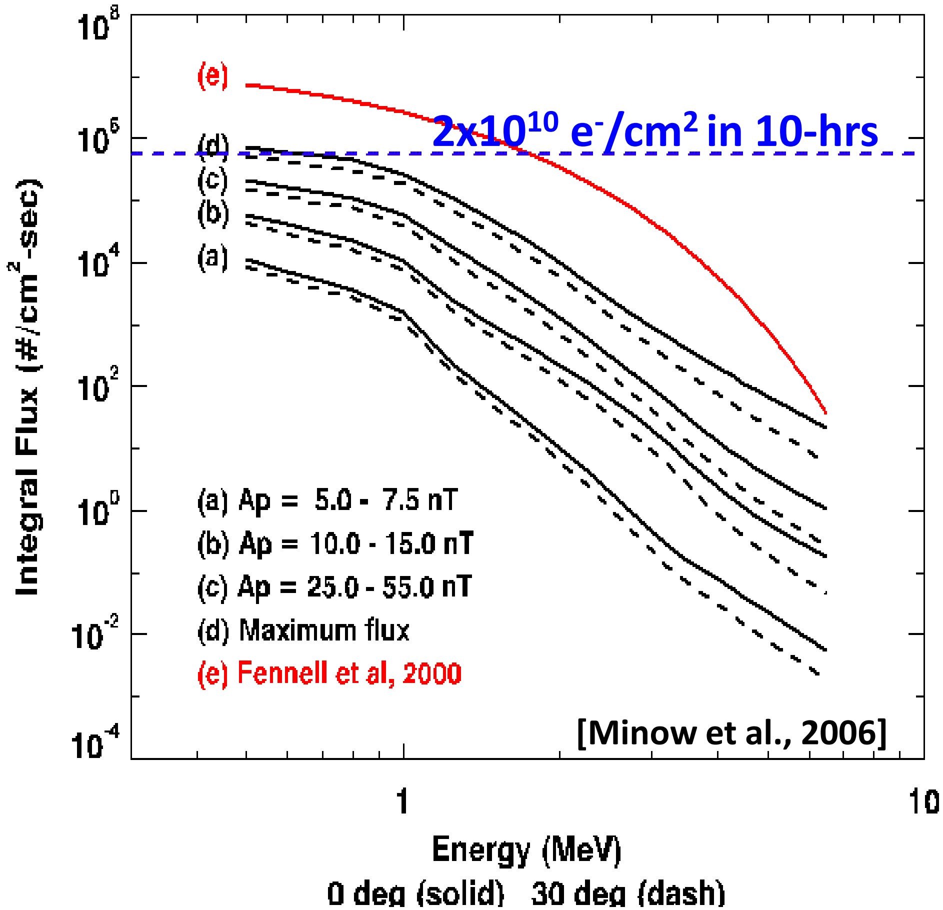
Trans-lunar and trans-Earth injection trajectories transit the radiation belts

TLI/TEI orbits are similar to the geostationary transfer orbit environments encountered by CRRES

- CRRES T~10 hours
  10 hours in radiation belt
- TLI/TEI T~8 days
  ≤4 hours in radiation belt

Basis of Fennell et al. [2000] preliminary lunar phasing orbit bulk charging environment specification

Orbit Average Electron Flux



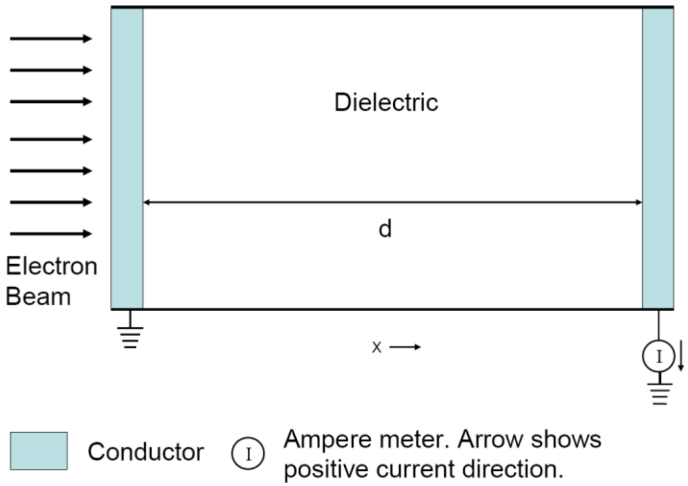
- CRRESELE Ap dependent (a-c), worst case (d) orbit averaged environments
- Fennell et al. 2000 (e) lunar transfer orbit charging environment derived from directly from CRRES data analysis

Example: Orion Radiation Belt Transit

- NASA-HDBK-4002A recommended thresholds evaluated for flight periods of 2, 4, and 8 hours
- SLS/Orion Design Specification for Natural Environments (DSNE) internal charging spec is an orbit averaged flux, needs to be multiplied by exposure period to evaluate internal charging threat
- DSNE specifies no less than 4 hours
- Design environment exceeds Internal charging threshold for energies less than a few MeV
- Credible threat for internal charging requires additional analysis, testing

Energy	Integral Flux	2-hr Integral Fluence	4-hr Integral Fluence	8-hr Integral Fluence
MeV	$1/cm^2$-sec	$1/cm^2$	$1/cm^2$	$1/cm^2$
0.1	3.27E+07	2.35E+11	4.71E+11	9.42E+11
0.2	2.67E+07	1.92E+11	3.84E+11	7.69E+11
0.4	1.78E+07	1.28E+11	2.56E+11	5.13E+11
0.6	1.18E+07	8.50E+10	1.70E+11	3.40E+11
0.8	7.88E+06	5.67E+10	1.13E+11	2.27E+11
1	5.25E+06	3.78E+10	7.56E+10	1.51E+11
1.2	3.50E+06	2.52E+10	5.04E+10	1.01E+11
1.4	2.33E+06	1.68E+10	3.36E+10	6.71E+10
1.6	1.55E+06	1.12E+10	2.23E+10	4.46E+10
1.8	1.04E+06	7.49E+09	1.50E+10	3.00E+10
2	6.90E+05	4.97E+09	9.94E+09	1.99E+10
2.2	4.60E+05	3.31E+09	6.62E+09	1.32E+10
2.4	3.06E+05	2.20E+09	4.41E+09	8.81E+09
2.6	2.04E+05	1.47E+09	2.94E+09	5.88E+09
2.8	1.36E+05	9.79E+08	1.96E+09	3.92E+09
3	9.06E+04	6.52E+08	1.30E+09	2.61E+09
3.2	6.04E+04	4.35E+08	8.70E+08	1.74E+09
3.4	4.02E+04	2.89E+08	5.79E+08	1.16E+09
3.6	2.68E+04	1.93E+08	3.86E+08	7.72E+08
3.8	1.79E+04	1.29E+08	2.58E+08	5.16E+08
4	1.19E+04	8.57E+07	1.71E+08	3.43E+08
4.2	7.93E+03	5.71E+07	1.14E+08	2.28E+08
4.4	5.28E+03	3.80E+07	7.60E+07	1.52E+08
4.6	3.52E+03	2.53E+07	5.07E+07	1.01E+08
4.8	2.35E+03	1.69E+07	3.38E+07	6.77E+07
5	1.56E+03	1.12E+07	2.25E+07	4.49E+07
5.2	1.04E+03	7.49E+06	1.50E+07	3.00E+07
5.4	6.94E+02	5.00E+06	9.99E+06	2.00E+07
5.6	4.62E+02	3.33E+06	6.65E+06	1.33E+07
5.8	3.08E+02	2.22E+06	4.44E+06	8.87E+06
6	2.05E+02	1.48E+06	2.95E+06	5.90E+06

NUMIT ("numerical integration") 1D Geometry



[Jun et al. 2007]

$$\nabla \bullet D = \rho$$

$$D = \varepsilon E, \qquad \varepsilon = \kappa \varepsilon_0$$

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

$$J = J_R + J_C = J_R + \sigma E$$
$$= J_R + \left[\sigma_{dark} + \sigma_{radiation}\right]E$$

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

Dielectric Material Properties

Parameter	Material 1	2	3	4	5	6
Dark Conductivity (S/cm)	$1x10^{-15}$	$1x10^{-17}$	$1x10^{-19}$	$2.19x10^{-18}$	$1x10^{-15}$	$1x10^{-18}$
κ	3	3	3	4.48	3	3
k (S/m-rad-s^{-1})	$3x10^{-16}$	$3x10^{-16}$	$3x0^{-16}$	0	$1x10^{-19}$	$1x10^{-19}$
α	1.0	1.0	1.0	0	1.0	1.0
Molecular weight	38	38	38	38	38	38
Atomic number	19	19	19	19	19	19
Density (g/cm^3)	2.00	2.00	2.00	2.00	2.00	2.00
Thickness (cm)	1.00	1.00	1.00	1.00	1.00	1.00

Siemen (S) = $1/\Omega$

Lunar Transit Environments Summary

Orbit:

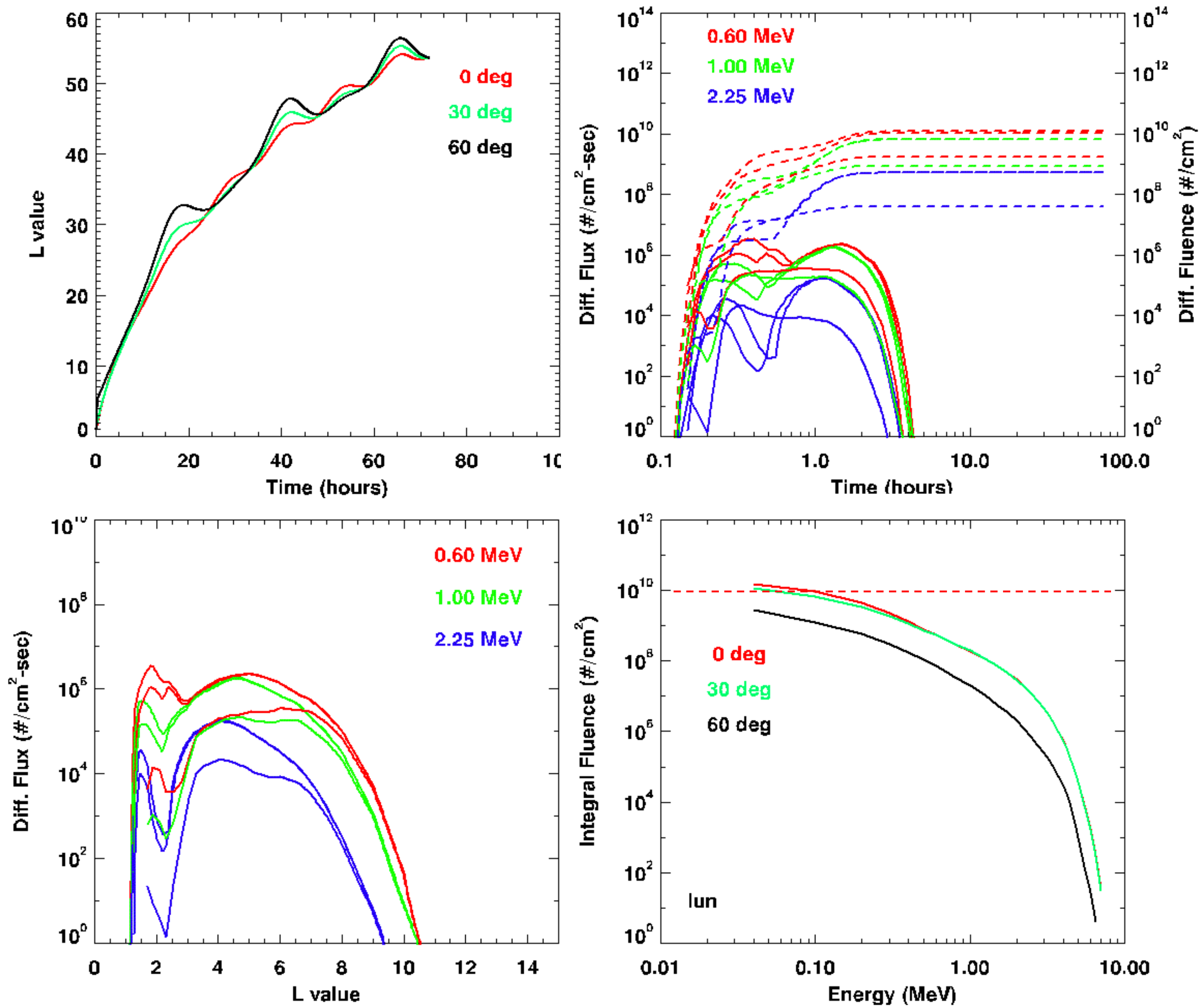
250 km x 379,867 km

n degree inclination

n = 0º, 30º, 60º

Environment:

AE-8 solar max



Lunar Transit (Extreme) Environments Summary

Orbit:

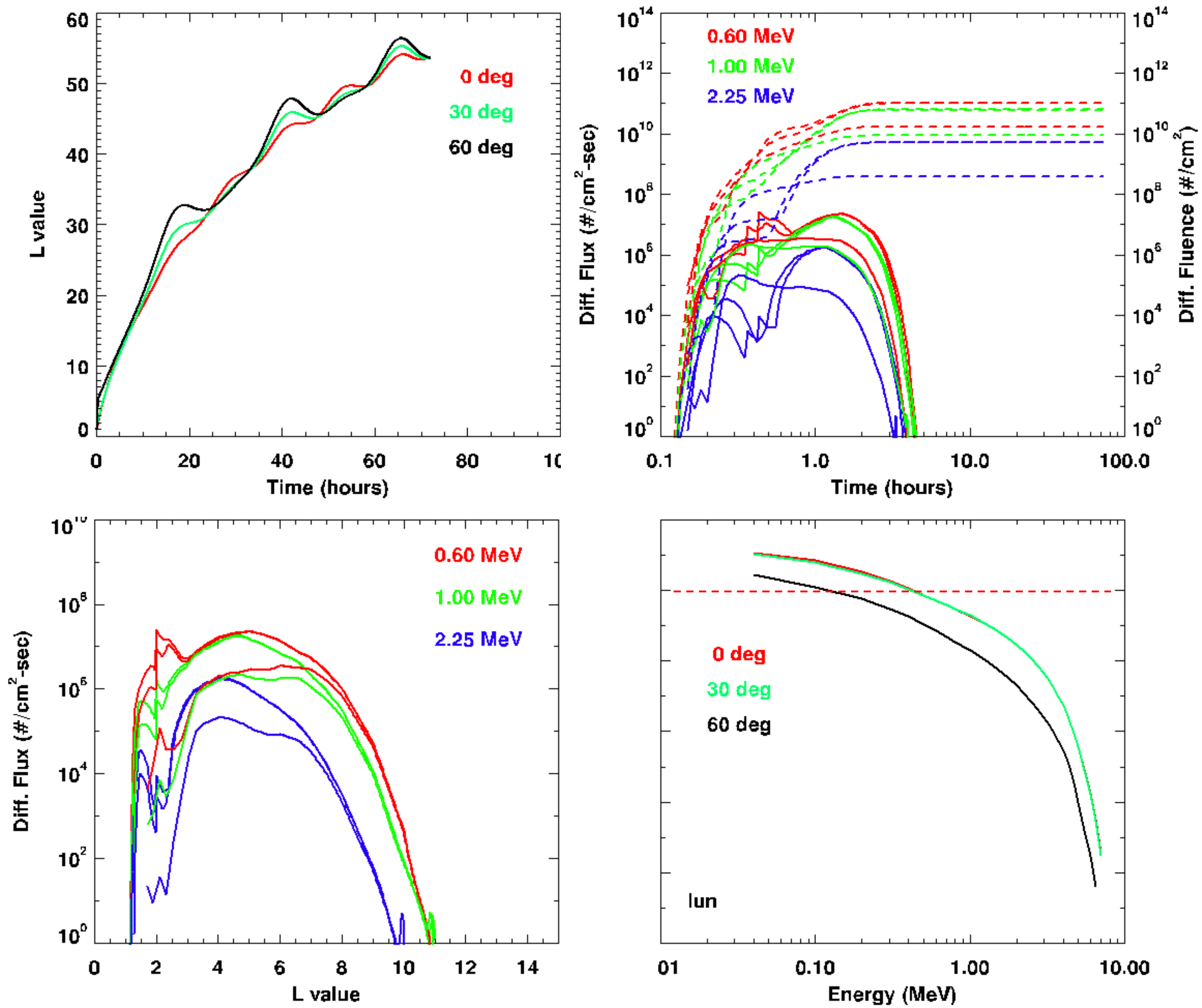
250 km x 379,867 km

n degree inclination

n = 0º, 30º, 60º

Environment:

10x AE-8 solar max



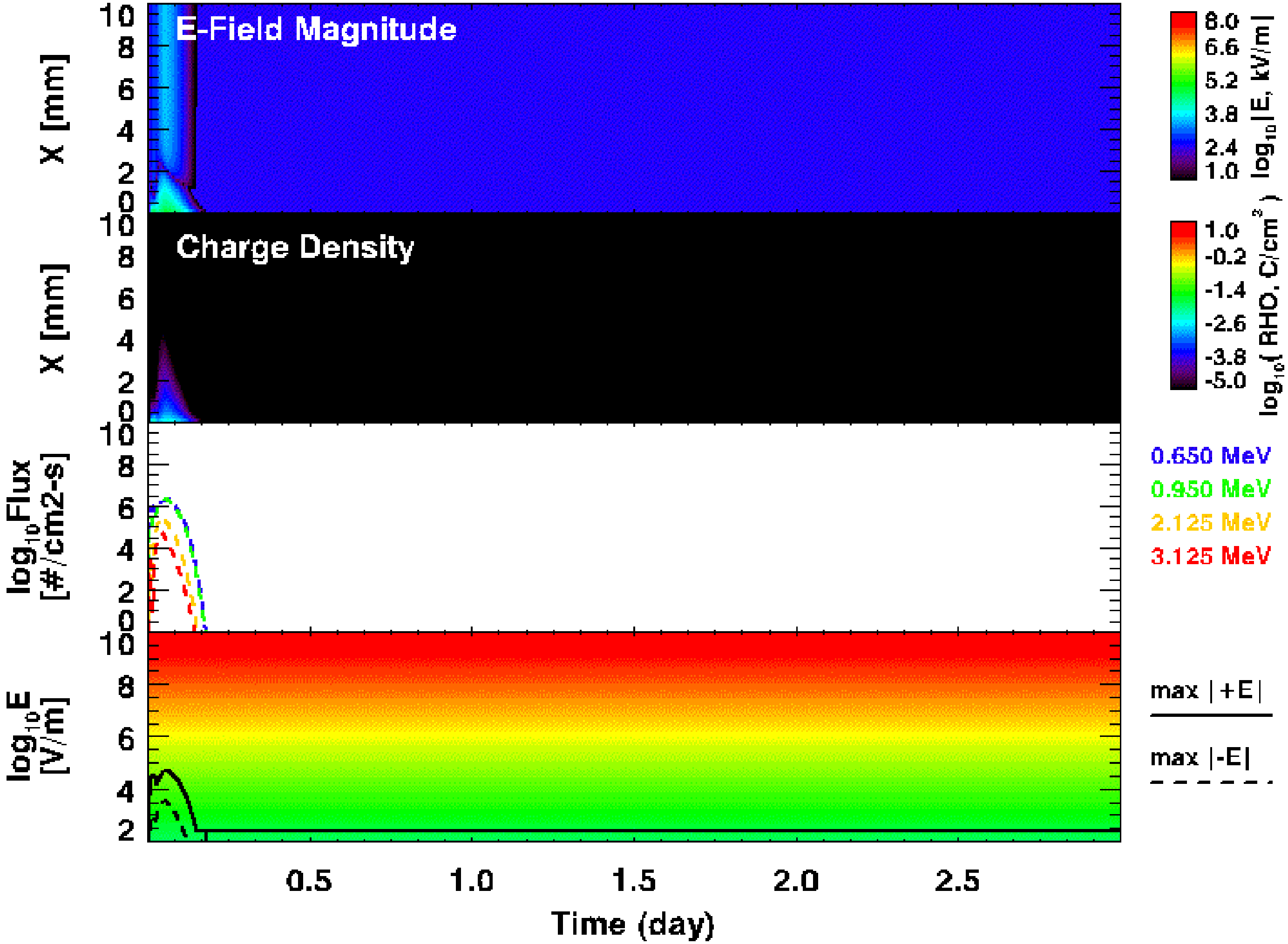
Lunar Transit

- **30 deg inc**
- **AE-8 max**
- **Material 1**

σ ~ 10^{-15} S/m

τ ~ 256 second

Materials at fixed inclination 30 deg



Siemen (S) = 1/Ω

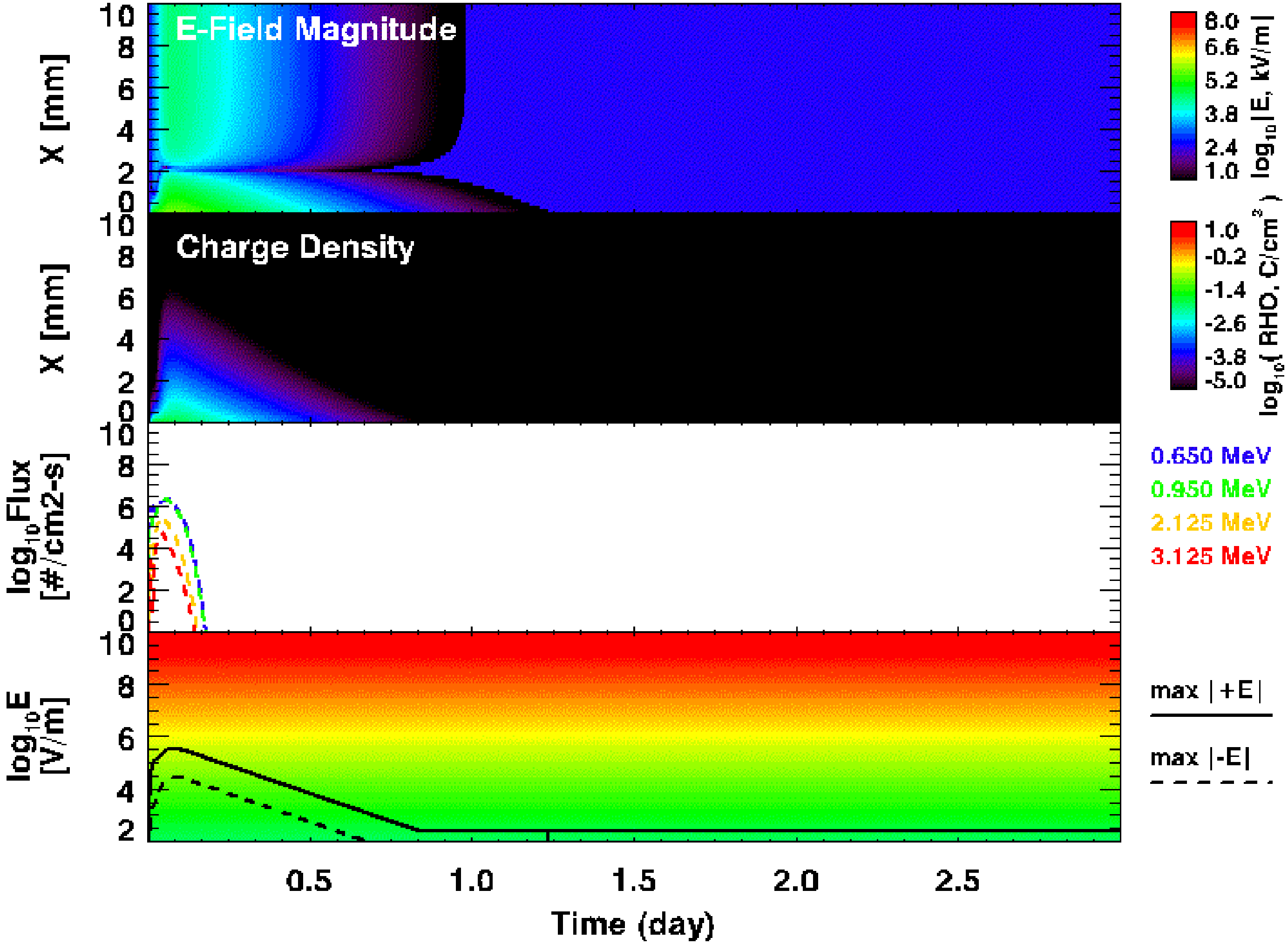
Lunar Transit

- 30 deg inc
- AE-8 max
- Material 2

  σ ~ 10^{-17} S/m

  τ ~ 2.5 hours

Materials at fixed inclination 30 deg



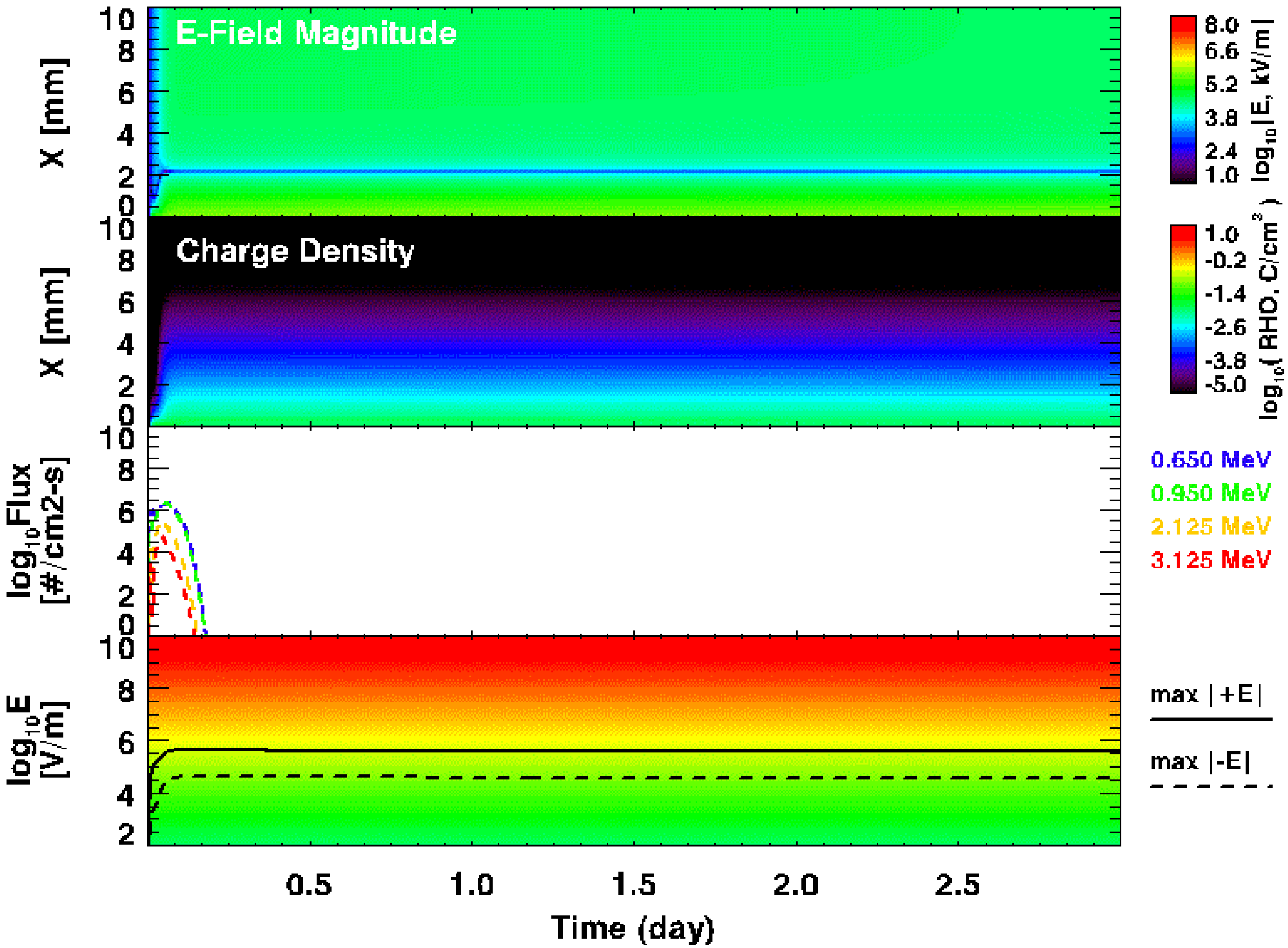
Lunar Transit

- 30 deg inc
- AE-8 max
- Material 3

  σ ~ 10^{-19} S/m

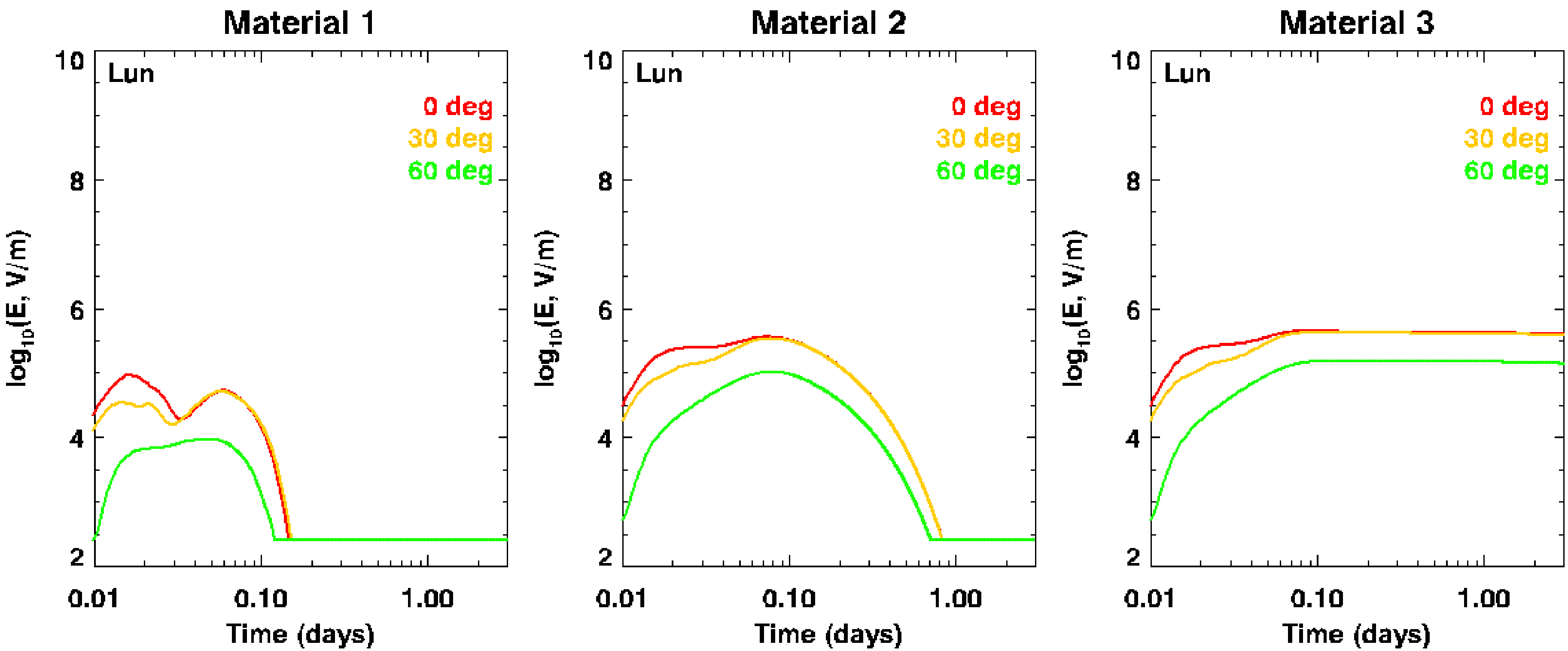
  τ ~ 31 days

Materials at fixed inclination 30 deg



Lunar Transit Summary

- **Maximum electric field magnitudes**



Lunar Transit

- 30 deg inc
- AE-8 max
- Material 4

  $\sigma \sim 10^{-18}$ S/m

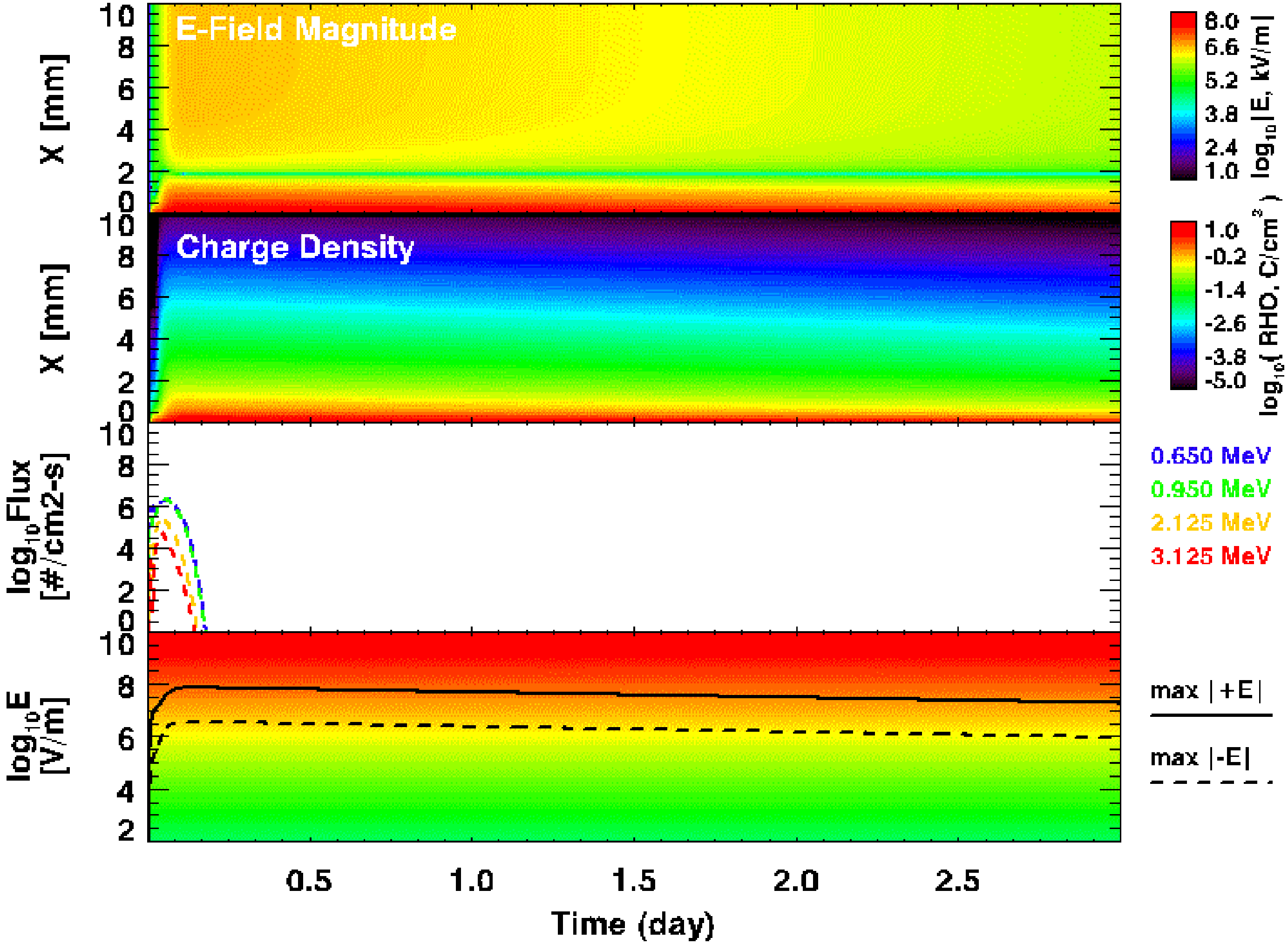
  τ ~ 50 hours

Materials at fixed inclination 30 deg

epoxy-fiberglass

$k_p \sim 0$

[*Rodgers et al.*, 2003]



Lunar Transit (Extreme Environments)

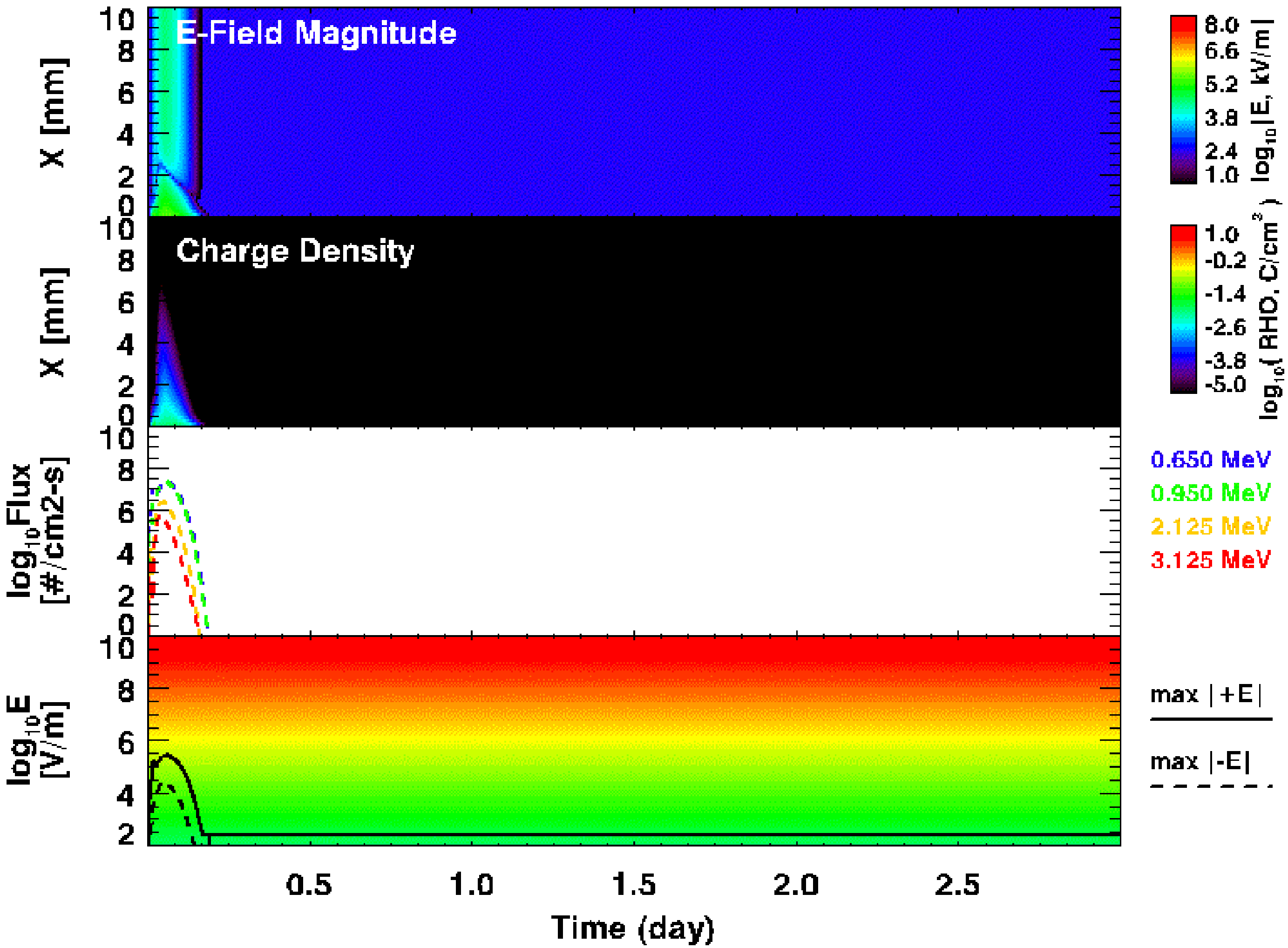
- 30 deg inc
- AE-8 max

  10x L ≥ 2
- Material 1

  $\sigma \sim 10^{-15}$ S/m

  $\tau \sim 256$ seconds

Materials at fixed inclination 30 deg



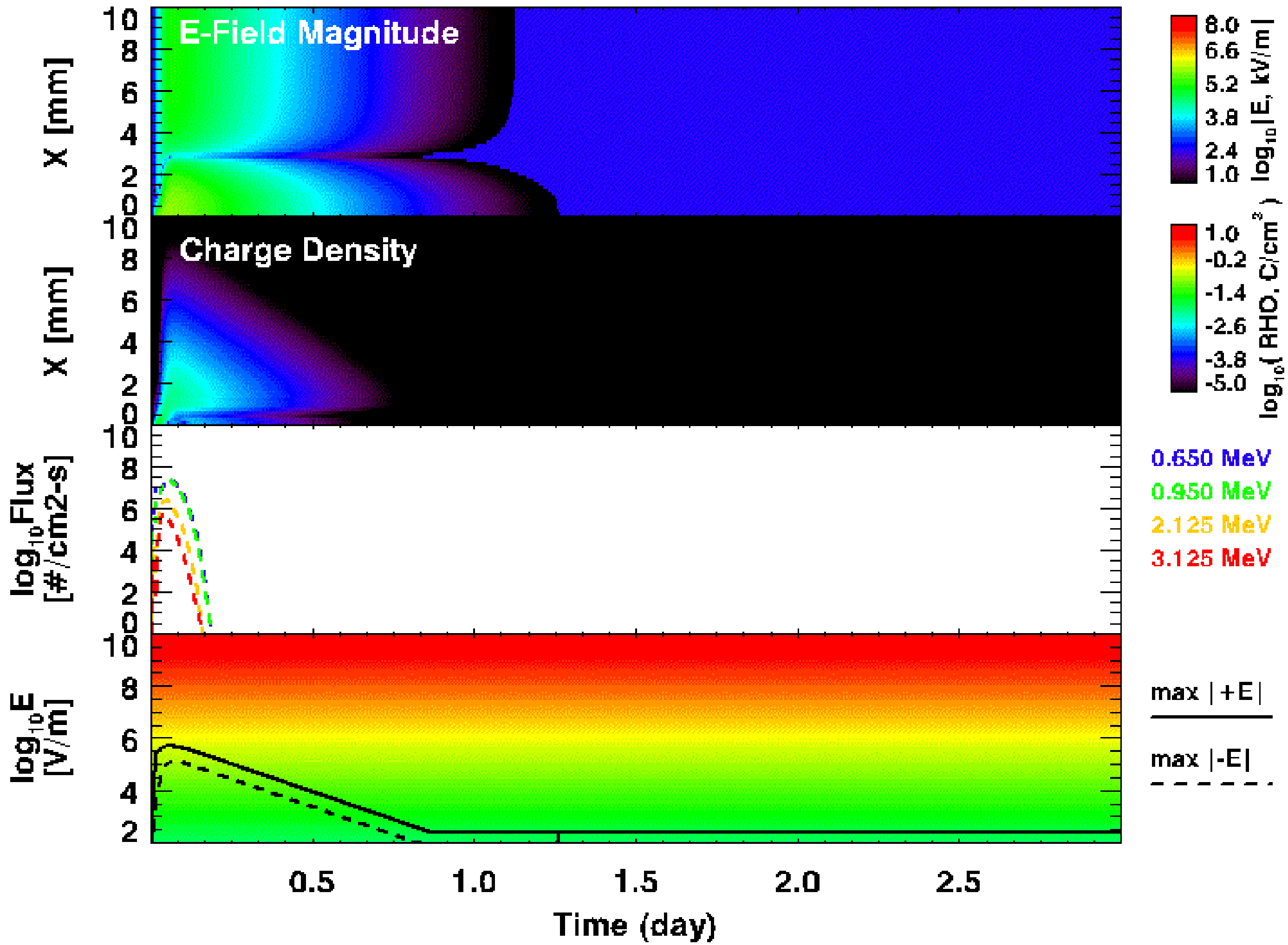
Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max

  10x L ≥ 2
- Material 2

  $\sigma \sim 10^{-17}$ S/m

  $\tau \sim 2.5$ days



Materials at fixed inclination 30 deg

Lunar Transit (Extreme Environments)

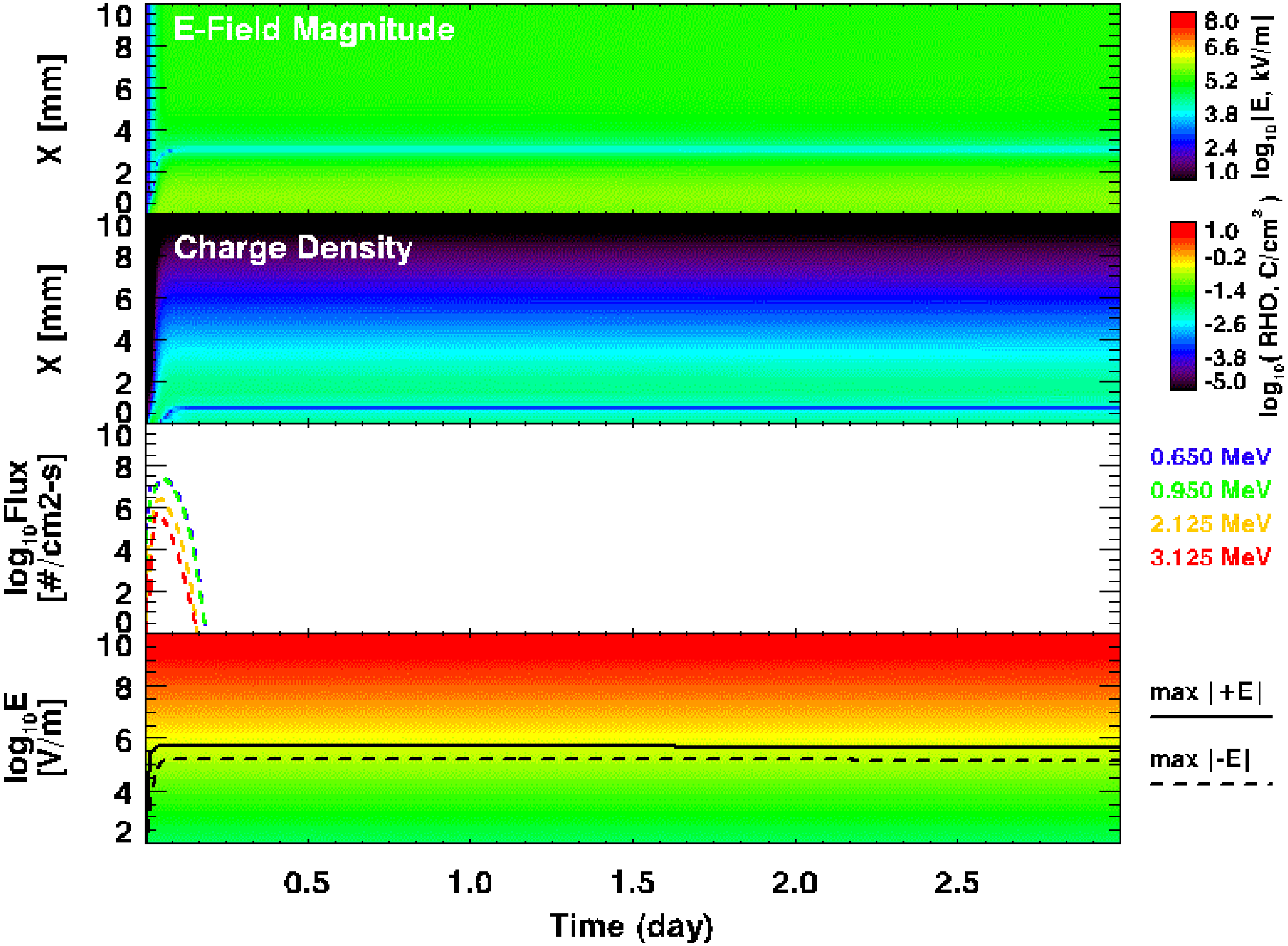
- 30 deg inc
- AE-8 max

  10x L ≥ 2
- Material 3

  $\sigma \sim 10^{-19}$ S/m

  $\tau \sim 31$ days

Materials at fixed inclination 30 deg



Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max

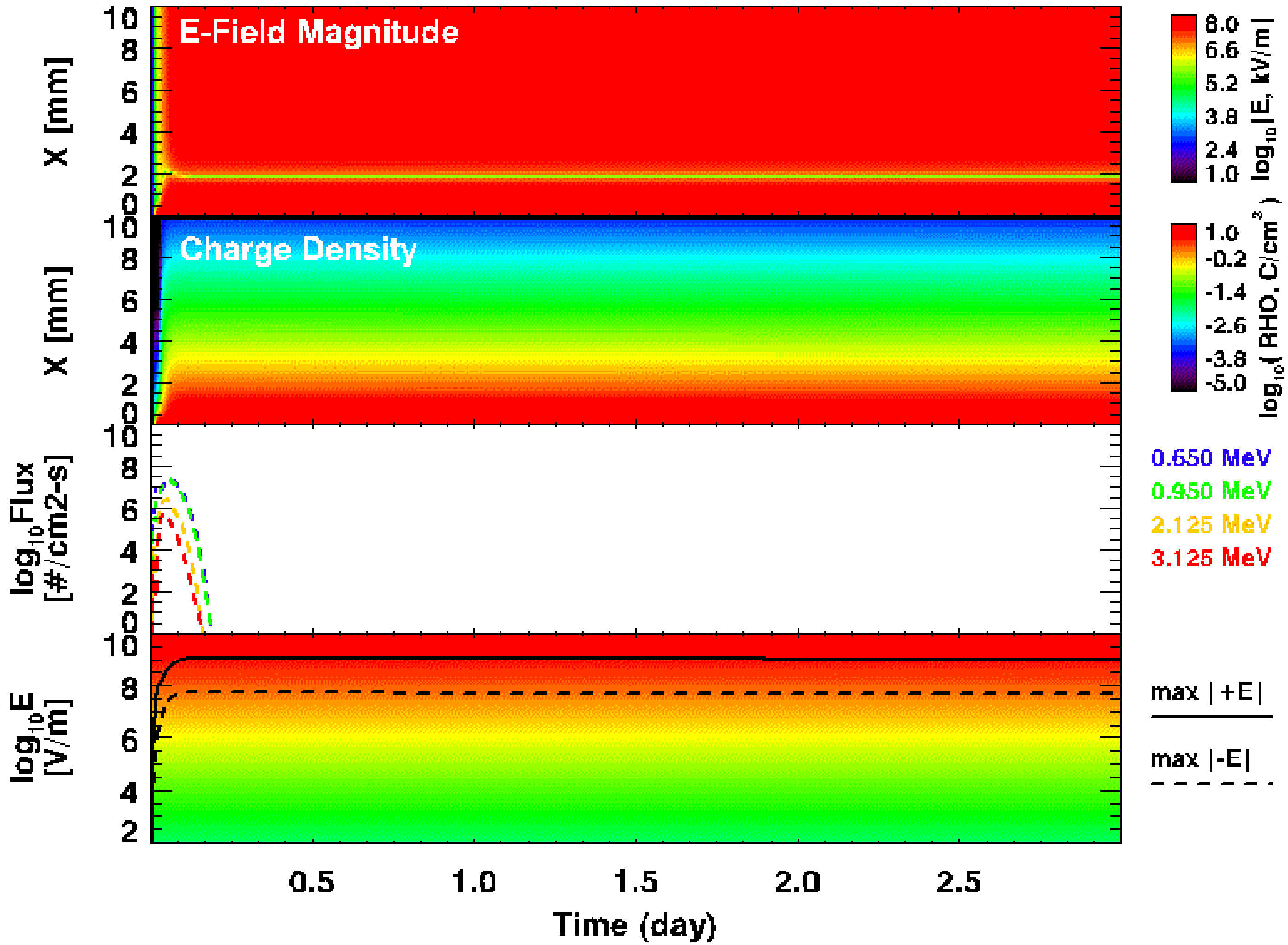
  10x L ≥ 2
- Material 4

  $\sigma \sim 10^{-18}$ S/m

  $\tau \sim 50$ hours

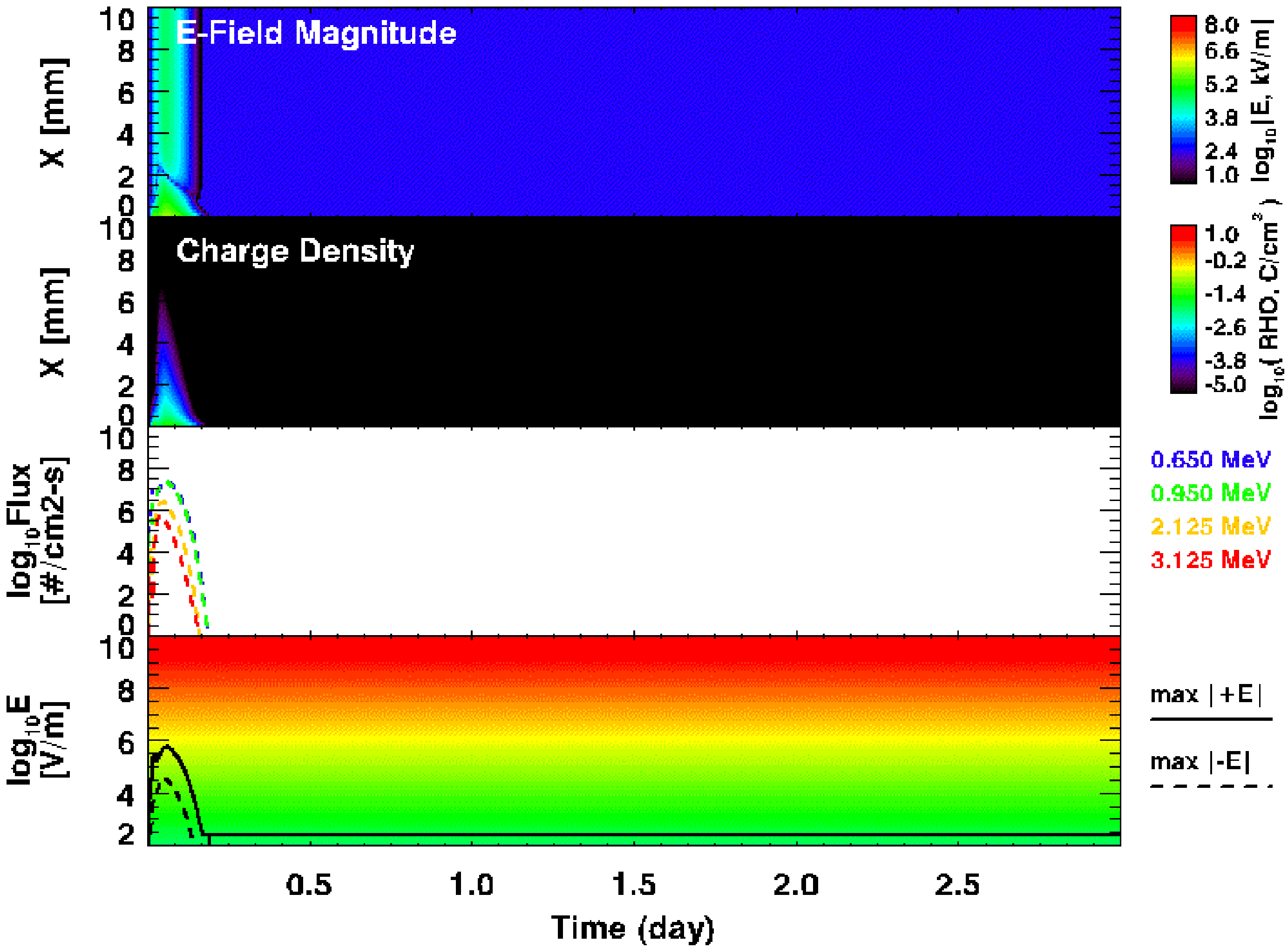
Materials at fixed inclination 30 deg

k = 0



Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max
  10x L ≥ 2
- Material 5
  σ ~ 10^{-15} S/m
  τ ~ 256 seconds



Materials at fixed inclination 30 deg

Ambient T ~ 300K

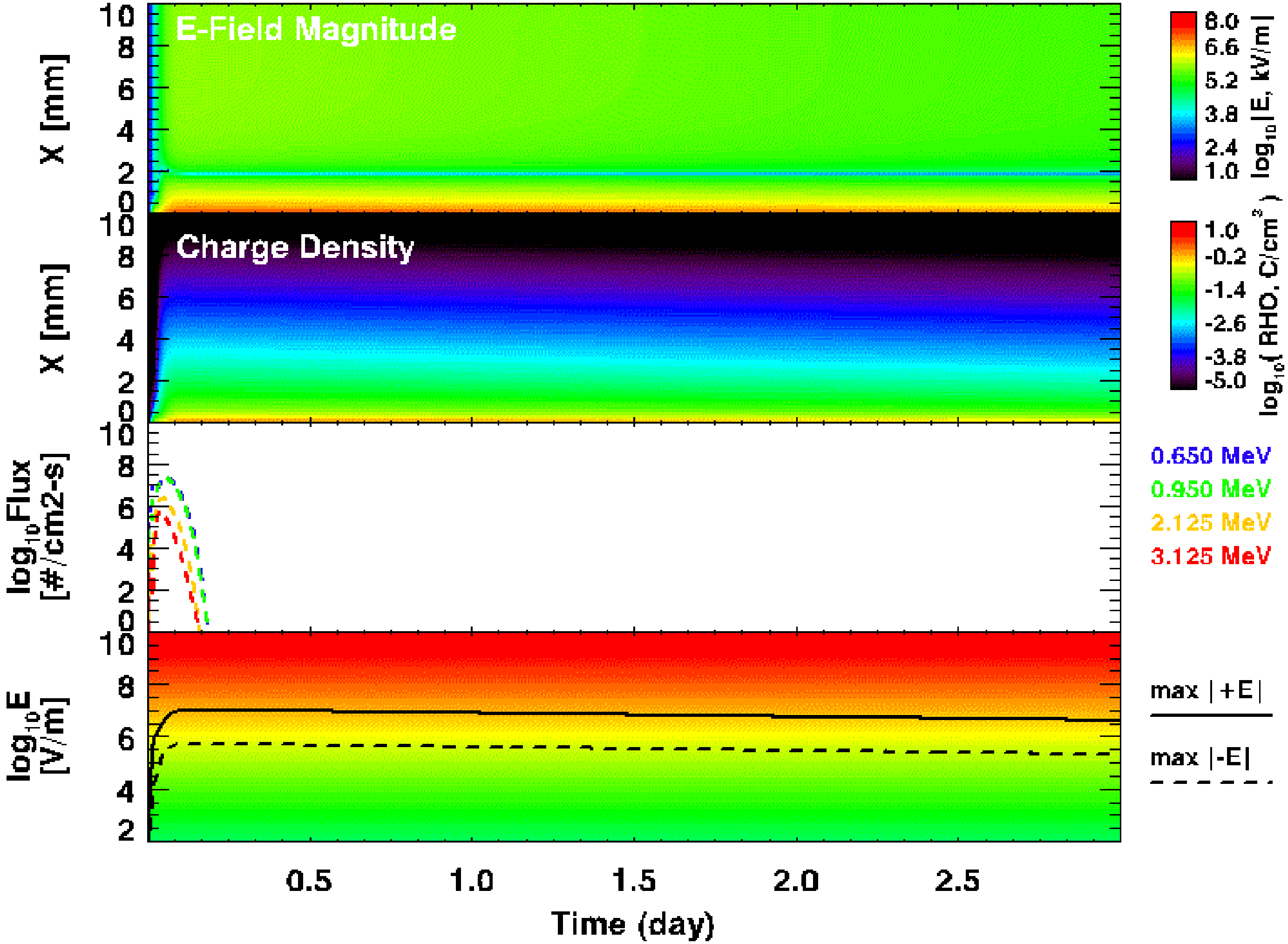
Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max

  10x L ≥ 2
- Material 6

  $\sigma \sim 10^{-18}$ S/m

  $\tau \sim 256$ seconds



Materials at fixed inclination 30 deg

Cryogenic
T ~ 100K

Outline

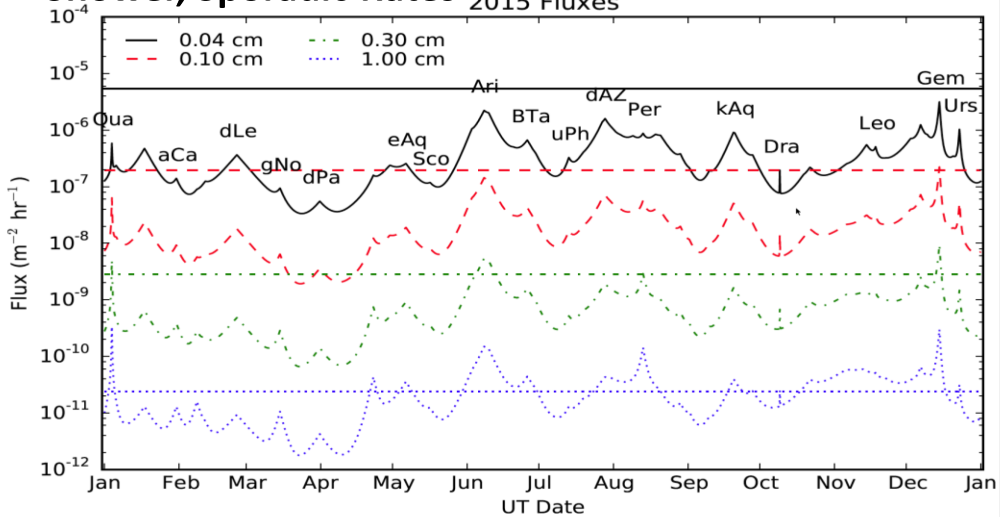
- Todays presentation will discuss the impact of space weather on satellites with additional emphasis on launch vehicles

- Outline
  - General notes on space environments and effects
  - Environments of importance to satellites, launch vehicles
  - Ionizing radiation effects
  - Spacecraft charging effects
  - **Meteors and orbital debris**

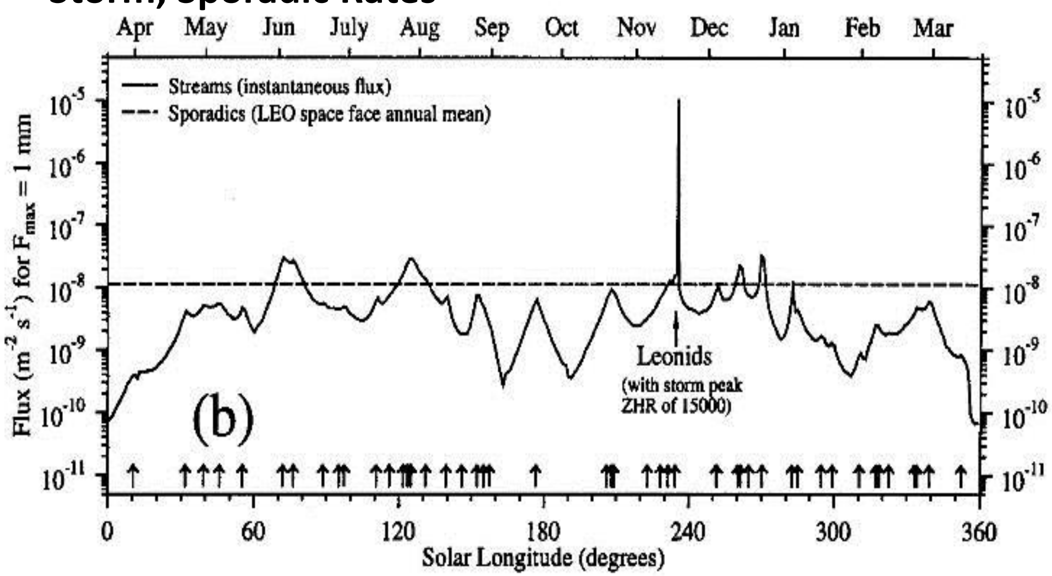
Meteors and Orbital Debris

- Meteor and orbital debris impact on spacecraft and launch vehicles represent a small but potentially catastrophic risk
- Other than large trackable debris items, the untrackable debris environment represents a "climatology" threat that is best mitigated by good design
- Primary meteor threat is sporadic background, mitigated by design
- Meteor showers and storms may exceed the sporadic rates and could be avoided by LV if necessary by scheduling launch to avoid high flux environment

Shower, Sporadic Rates



Storm, Sporadic Rates



[B. Cooke, NASA Meteoroid Environment Office]


Questions?
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