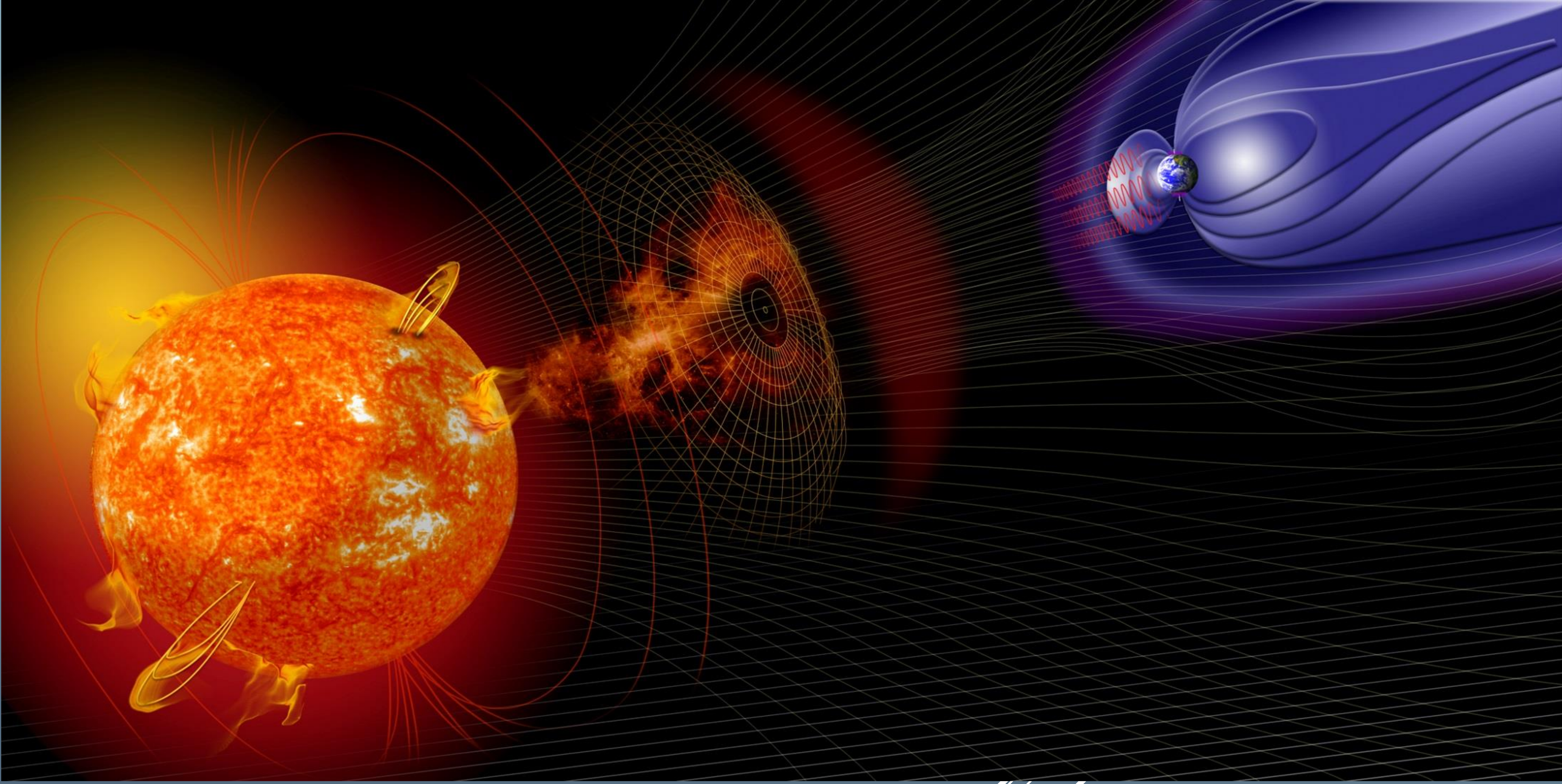

Surface Charging Overview

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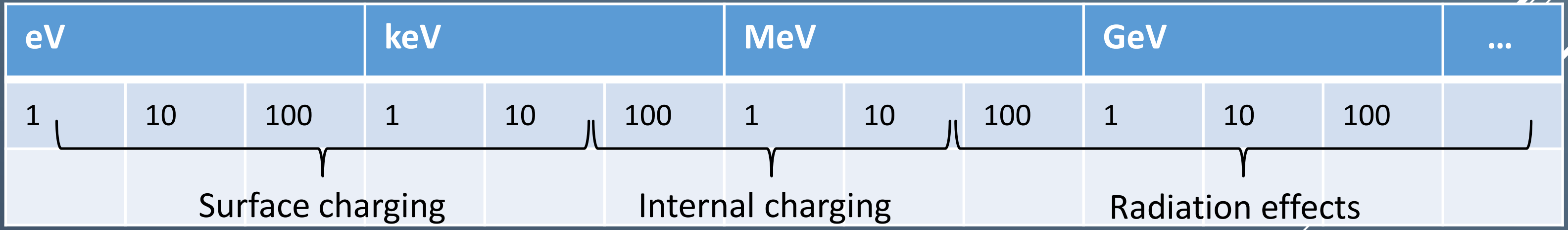
Deputy for Space Weather and Spacecraft Charging to NASA Space Environment Tech Fellow

Outline

- Definition
- Why we care
- Physics
  - Orbit limited theory
  - Space charge limited theory
  - Modeling as a circuit
- Orbit Characteristics and differences
- Summary

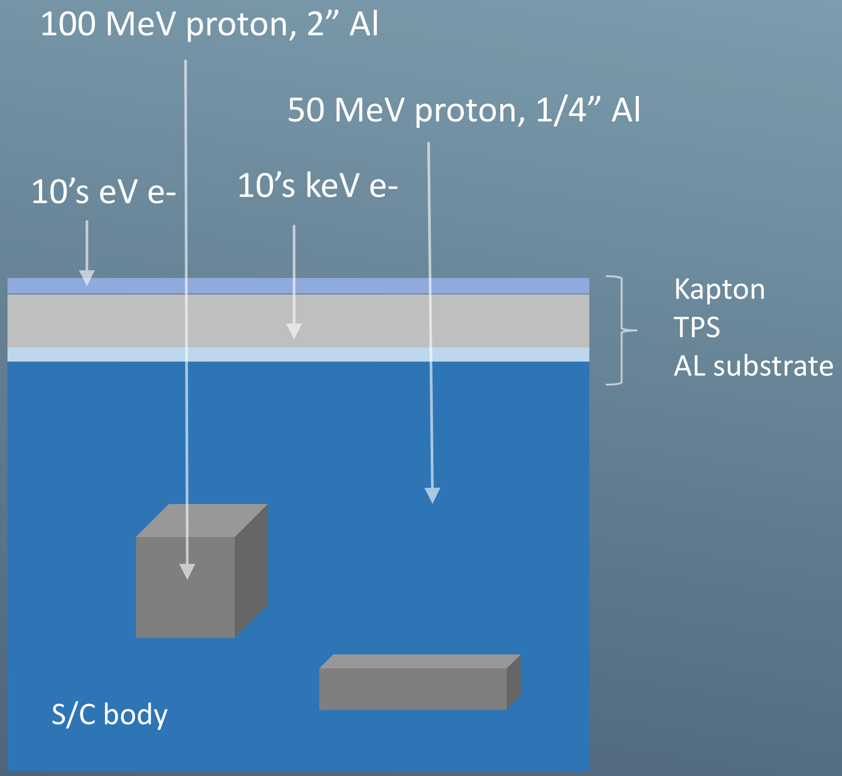
Satellite Charging

- Accumulation of charge (current) on or within the outer material of a spacecraft: surface and internal charging
- Factors of importance to surface charging
  - Spacecraft orbit: GEO, LEO, polar, interplanetary, etc.
  - Spacecraft geometry
  - Material properties (insulating materials increase the threat)
  - Environment parameters, including plasma, secondaries, sun intensity, ram/wake effect
- 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



eV			**keV**			**MeV**			**GeV**			**…**
1	10	100	1	10	100	1	10	100	1	10	100	
		Surface charging				Internal charging				Radiation effects		

Particle Penetration Depth



E < 50 keV, < 100 microns

300 MeV proton, 10” Al

1 GeV proton, 80” Al

- Geo – 10’s kV during substorms
- Polar - 1 kV during auroral precipitation events
- LEO – few volts unless large voltage solar arrays
- Solar wind – few volts positive

Note: positive currents generally result from emission of low energy secondary electrons and photoelectrons, the positive potentials that can be attained are relatively modest.

Impact of Charging on the Spacecraft

Cause	Effect	Impact
Electrostatic potentials due to net charge density on spacecraft surfaces or within insulating materials resulting from current collection to/from the space environment. Electrodynamic (inductive) potentials – motion of the spacecraft through the magnetic field, plasma environment is not required	Currents from electrostatic discharges (ESD)	• 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 noise levels in receiver band exceeding receiver sensitivity • Communications issues due to excess noise • Phantom commands, signals
	Power drains	• Parasitic currents and solar array power loss (LEO
	Physical damage from ESD	• 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
	Biasing of instrument readings	• Compromised science instrument, sensor function • Photoelectron contamination in electron spectrum • Modified “Ion line” charging signature in ion spectrum

Characterize charging environment and build spacecraft to withstand or avoid charging events

Anomalies and Failures Attributed to Charging

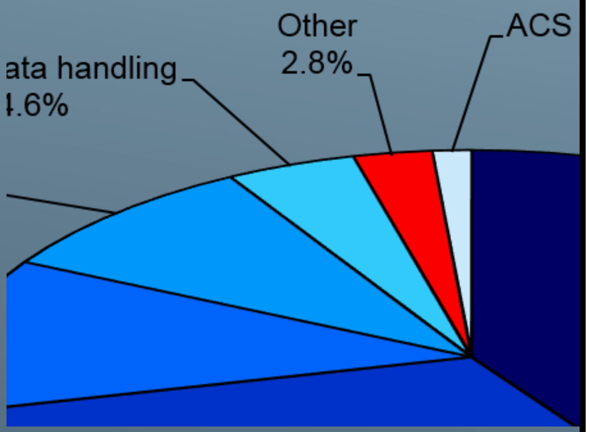
Spacecraft	Year(s)	Orbit	Cause	Impact*
DSCS II	1973	GEO	Surface ESD	LOM
Voyager 1	1979	Jupiter		Anom
SCATHA	1982	GEO		Anom
GOES 4	1982	GEO	Surface ESD	LOM
AUSSAT-A1, -A2, -A3	1986-1990	GEO		Anom
FLTSATCOM 6071	1987	GEO		Anom
GOES 7	1987-1989	GEO		Anom/SF
Feng Yun 1A	1988	LEO	ESD	Anom/LOM
MOP-1, -2	1989-1994	GEO		Anom
GMS-4	1991	GEO		Anom
BS-3A	1990	GEO		Anom
MARECS A	1991	GEO	Surface ESD	LOM
Anik E1	1991	GEO		Anom/LOM
Anik E2	1991	GEO	ESD?	Anom
Intelsat 511	1995	GEO		Anom
SAMPEX	1992-2001	LEO		Anom
MARECS A	1991	GEO	Surface ESD	LOM
Anik E1	1991	GEO		Anom/LOM
Anik E2	1991	GEO	ESD?	Anom
Intelsat 511	1995	GEO		Anom
SAMPEX	1992-2001	LEO		Anom

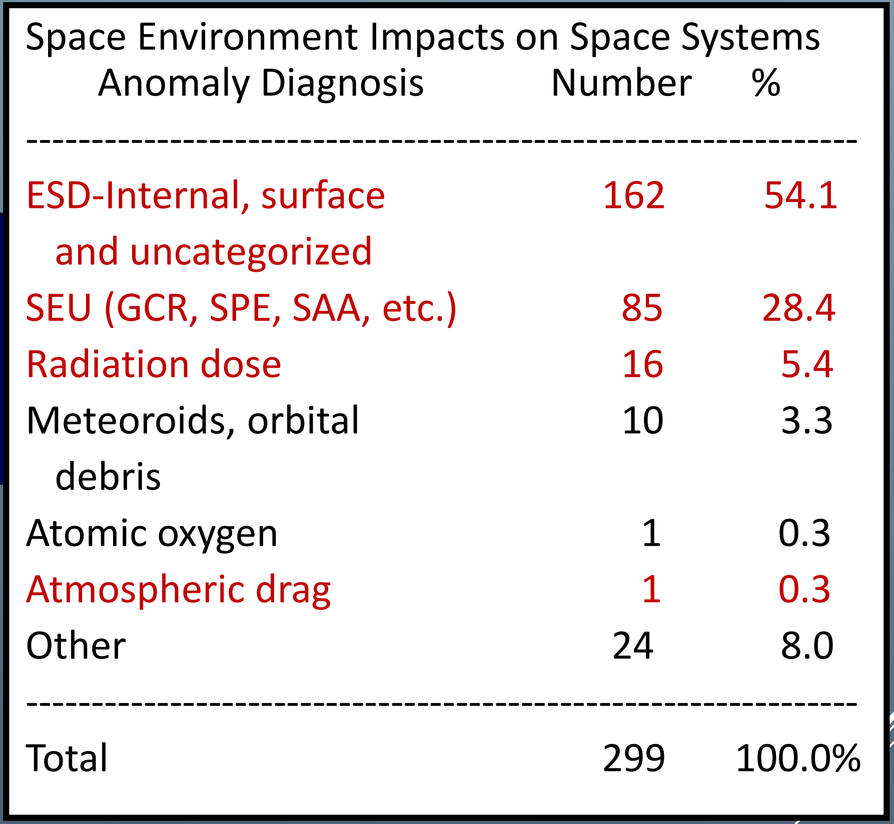
Spacecraft	Year(s)	Orbit	Cause	Impact*
Intelsat K	1994			Anom
DMSP F13	1995	LEO		Anom
Telstar 401	1994, 1997	GEO	ESD?	Anom/LOM
TSS-1R	1996	LEO		Failure
TDRS F-1	1986-1988	GEO		Anom
TDRS F-3,F-4	1998-1989	GEO		Anom
INSAT 2	1997	GEO	Surface ESD	Anom/LOM
Tempo-2	1997	GEO		LOM
PAS-6	1997	GEO		LOM
Feng Yun 1C	1999	LEO		Anom
Landsat 7	1999-2003	LEO		Anom
ADEOS-II	2003	LEO	ESD	LOM
TC-1,2	2004	~2GTO, GTO		Anom
Galaxy 15	2010	GEO	ESD	Anom
Echostar 129	2011	GEO		24 hr Pointing/ positioning loss
Suomi NPP	2011-2014	LEO		Anom
DMSP 15	2011	Polar		Computer upset
SkyTerra-1	3-7-12		SEU	Offline for 3 weeks
Venus Express, HughesNet-Spaceway 3	3-12			Anomolies

Koons et al., 2000
Ferguson, 2015

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

Space Weather Risk to Satellites

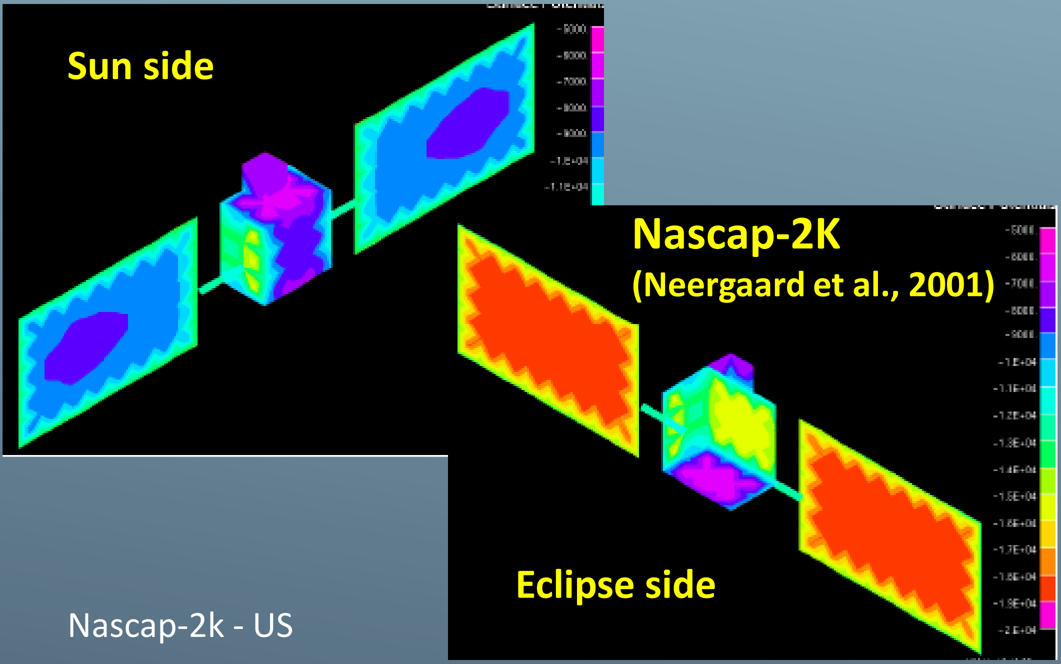



Space Environment Impacts on Space Systems

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%

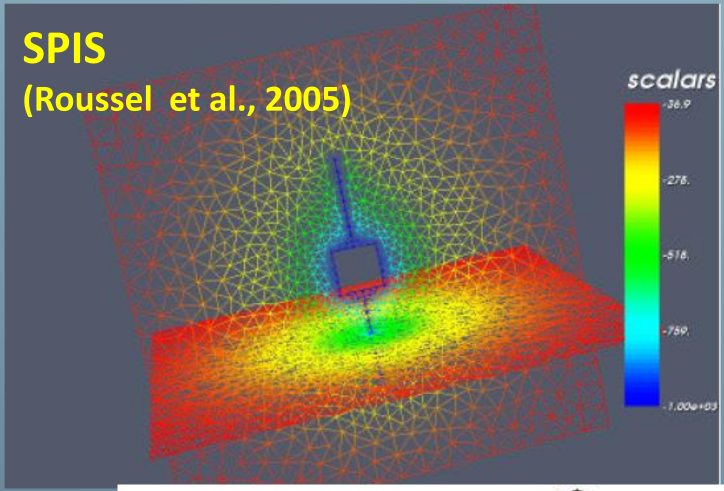
[Koons et al., 2000]

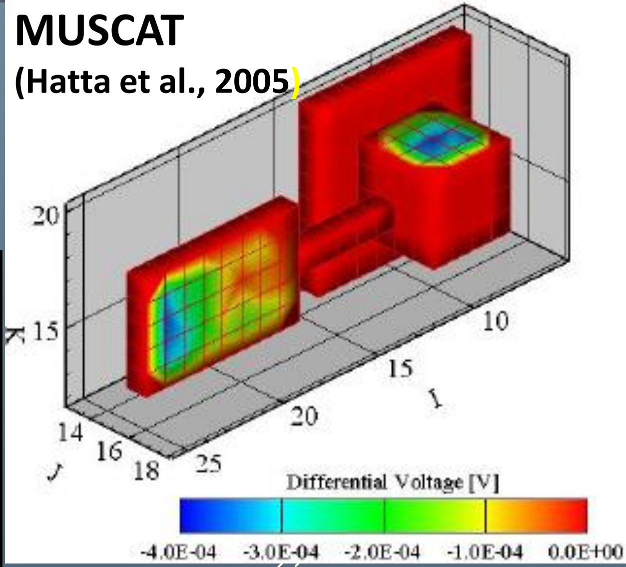
Surface Charging Codes


Sun side

Nascap-2K
(Neergaard et al., 2001)

Eclipse side


SPIS
(Roussel et al., 2005)


MUSCAT
(Hatta et al., 2005)

Nascap-2k - US

Space Plasma Interaction System (SPIS) – ESA

SPacecRaft Charging Software (SPARCS) - Alcatel Space

Space Hazards Induced Near Earth by Large Dynamic Storms (SHIELDS) - LANL

Multi-Use Spacecraft Charging Analysis Tool (MUSCAT) - JAXA

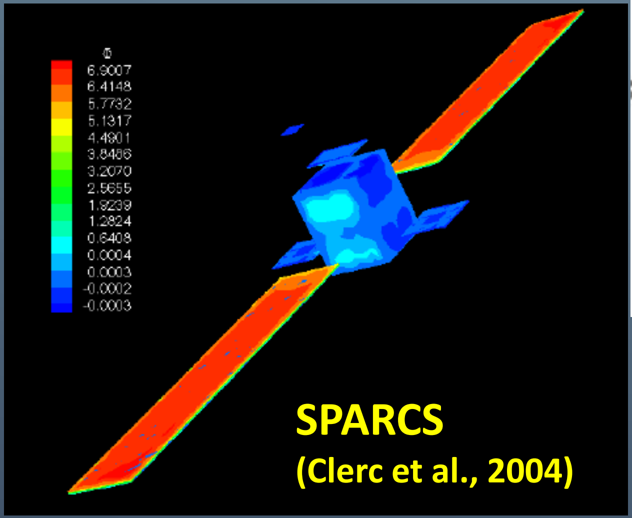
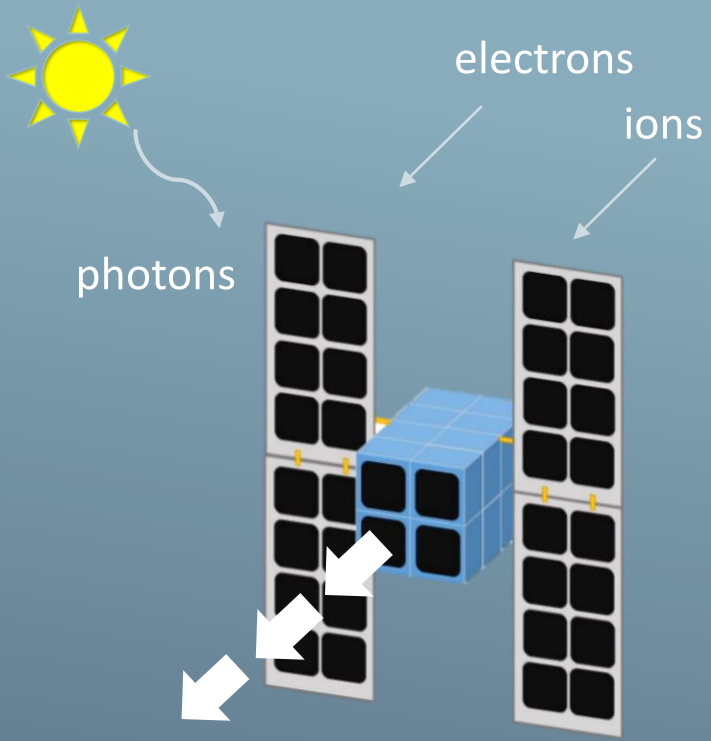

SPARCS
(Clerc et al., 2004)

Chart modified from Minow and Krause Spacecraft Charging Tutorial, 2011

Surface Charging



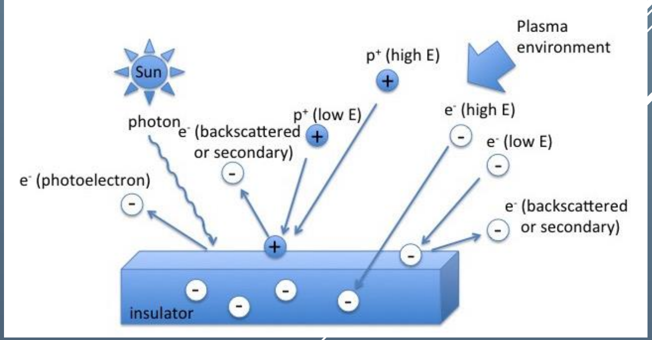
- The net charge is due to the sum of the incident currents.

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

- However, not just spacecraft current balance. Current balance is to each material
  - Flux asymmetries due to magnetic field, electric field, ram/wake effect
  - Sun/eclipse conditions
  - Material properties
  - High power solar arrays (LEO)
- Debye Length is the characteristic distance over which the plasma “shields” the electric field

$$\lambda_D = \sqrt{\frac{kT}{4\pi q^2 n_o}}$$

- $N_i \neq N_e$ because $v_e > v_i$
- Charging time scales ~seconds.



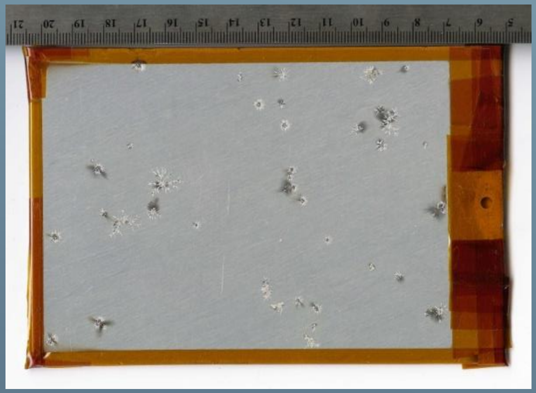
Parker et al., 2016

Charging Anomaly and Failure Mechanisms

- An electrostatic discharge (ESD) results when electric fields associated with potential differences (**E** = -∇Φ) exceed the dielectric breakdown strength of materials allowing charge to flow in an arc
- Damage depends on energy available to arc

$$C = \varepsilon \frac{A}{d} \qquad E = \frac{1}{2} C V^2$$

- 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)

Chart from Minow presentation

Current Collection

- Plasma particles charge the spacecraft to approximately a few volts of the electron energy
- At some potential, the spacecraft will attract an equal number of ions and electrons.
- Currents:
  - Incident ions (I_i)
  - Incident electrons (I_e)
  - Photoelectron ($I_{ph,e}$)
  - Backscattered electrons ($I_{bs,e}$)
  - Conduction currents (I_c)
  - Secondary electrons (I_{se}, I_{si}) due to I_e and I_i
  - Active current sources (beams, thrusters, etc: I_b)
- Orbit limited approximation (GEO, polar, interplanetary)
- Space Charge limited approximation (LEO)

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

Orbit Limited Approximation (Thick Sheath)

- Geosynchronous, polar, and interplanetary orbits where the Debye length is large compared with the spacecraft size
- Applies if any charged particle far from the spacecraft can reach the surface
- Low density, high energy – electron current exceeds the ion current so the spacecraft charges negative
- Derivation is based on the conservation of momentum
- Repelled species is energy-limited

$$J_e = J_{e,o}\, e^{q\phi/kT_e}$$

- Attracted species is angular momentum-limited

$$J_i = J_{i,o}\left(1 - \frac{q\phi}{kT_i}\right)$$

- So then,

$$\phi \sim -\frac{kT_e}{q}\, ln\left(\frac{J_{e,o}}{J_{i,o}}\right) \sim -\frac{1}{2} kT_e\, ln\left(\frac{m_i}{m_e}\right) \sim \text{few times the plasma temperature}$$

- Since the electron current decreases exponentially and the ion current increases linearly – the principle effect of the spacecraft potential is to decrease the electron current.

Space Charge Limiting Approximation (Thin Sheath)

- Dense, cold plasma (e.g. LEO) where the Debye length is equal to or smaller than the spacecraft
- Plasma density is such that the space charge of the attracted particles shields the attracting potential and thus limits the range of potentials
- As the spacecraft charges negative, the additional ions collected shield and thus limit the range of the potential
- Repelled species is energy-limited

$$I_e = I_{e,o} e^{\phi/\theta}$$

- Attracted species is space-charge limited

$$I_i = I_{e,o} \left(\frac{f}{a}\right)^2$$

- So then, at equilibrium

$$\phi \sim \theta \ ln \left[\left(\frac{f}{a}\right)^2\right]$$

where f is a function describing the space charge from the spacecraft to infinity

Circuit Model for Surface Charging

Electrical charging of the spacecraft can be modeled as a circuit where the plasma acts as a current source with a capacitance between the plasma and the spacecraft.

Capacitance to ground

(differential charging)

$$C_{Pl} = \varepsilon \frac{A}{d} \sim Ax10^{-6}\ Farad$$

Capacitance to space

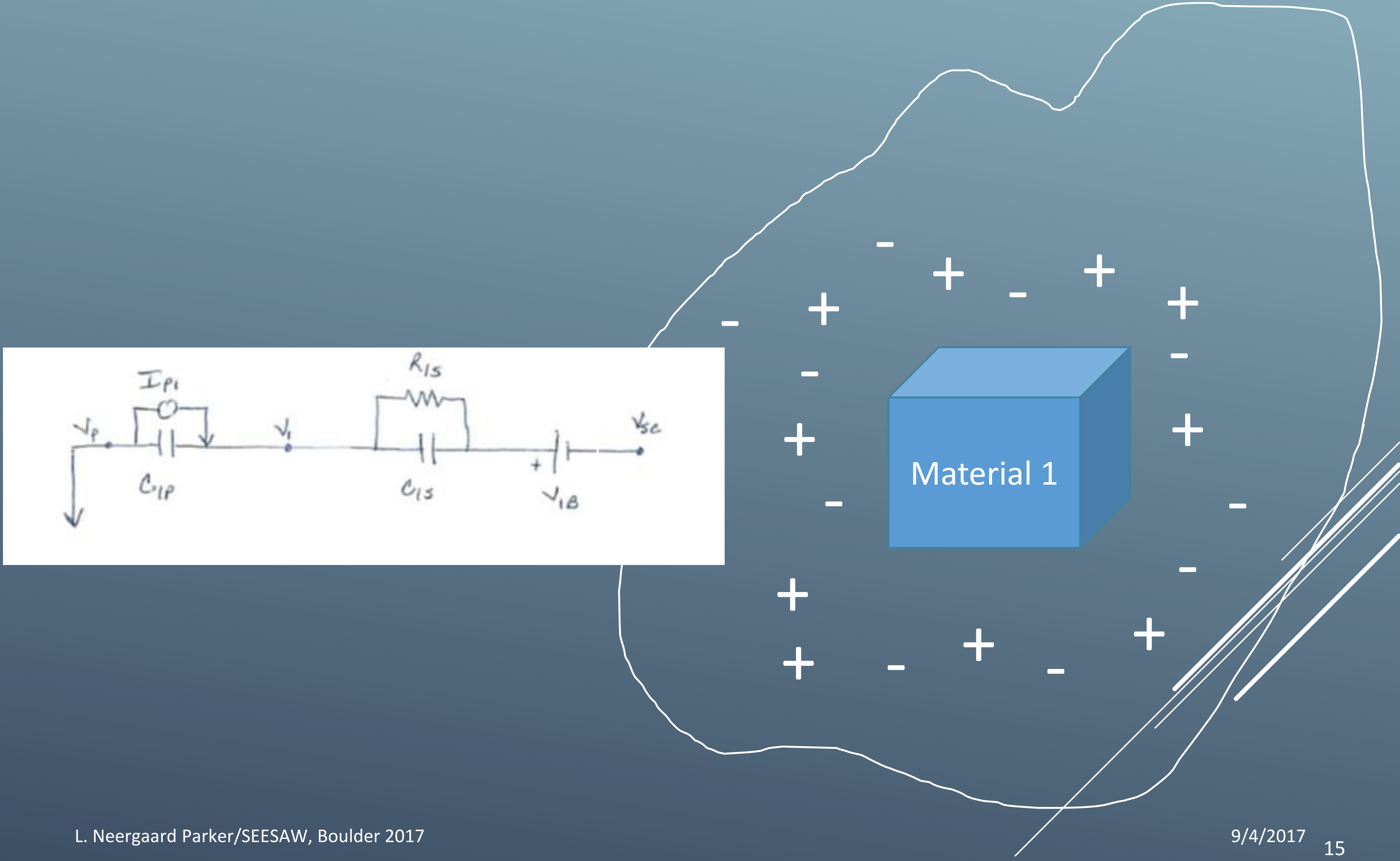
(absolute charging)

$$C_{SC} \sim 4\pi\varepsilon_o R\left(\frac{A}{4\pi R^2}\right) \sim \frac{A}{R} x10^{-11}\ Farad$$

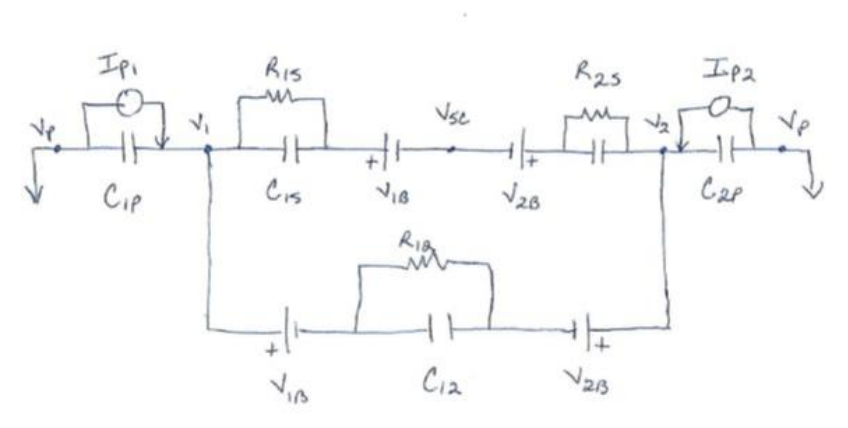
$I = C\frac{dV}{dt}$ ⇨ Charging time

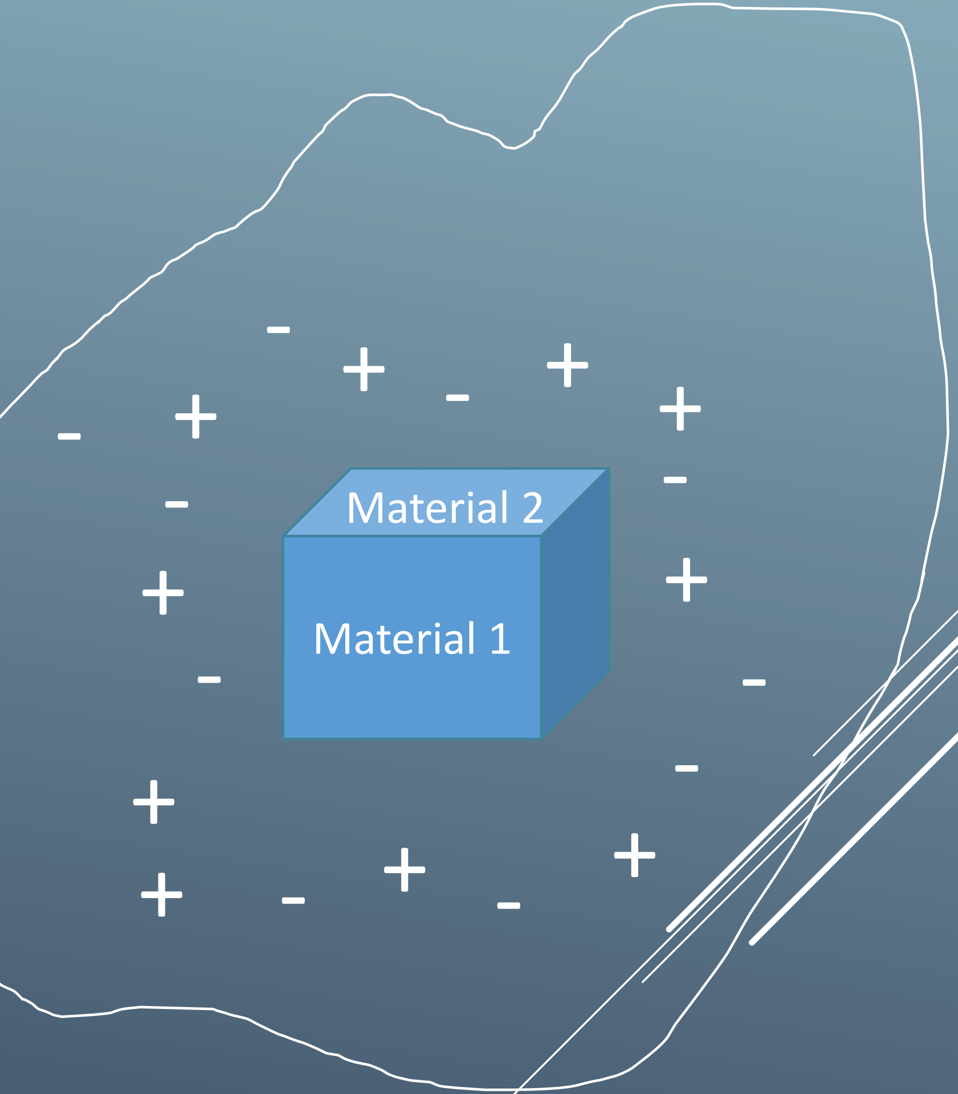
	Electron current density (A/m^2)	Debye length (m)	Capacitance to space (F)	Capacitance to ground (F)	Charging time to space (s)	Charging time to ground (s)
GEO (at 10kV)	3.3e-6	100's	1.0e-11	0.1e-6	0.03 s	300
LEO (at 50V)	8.5e-3	2.4e-3			~6e-8	~6e-4
Polar (at 1kV)	5e-6	7.4			0.002	20
Solar wind (at 50 V)	7.3e-7	10			~7e-4	~7

Circuit analysis - 1 Material



Circuit analysis - 2 Materials





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.

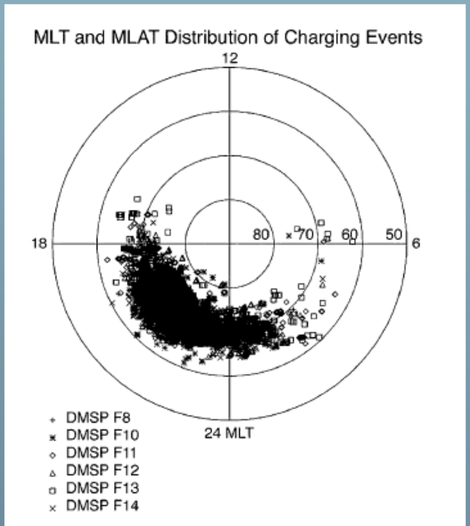
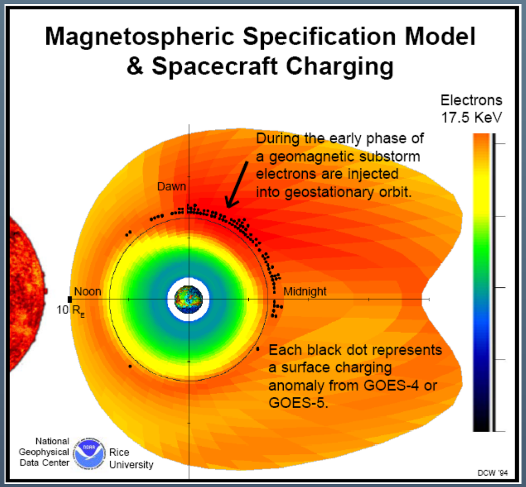
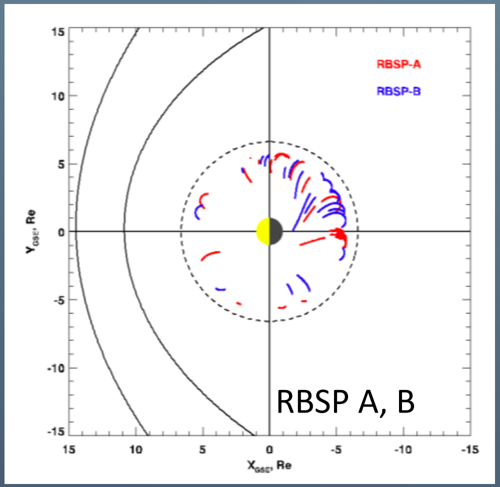


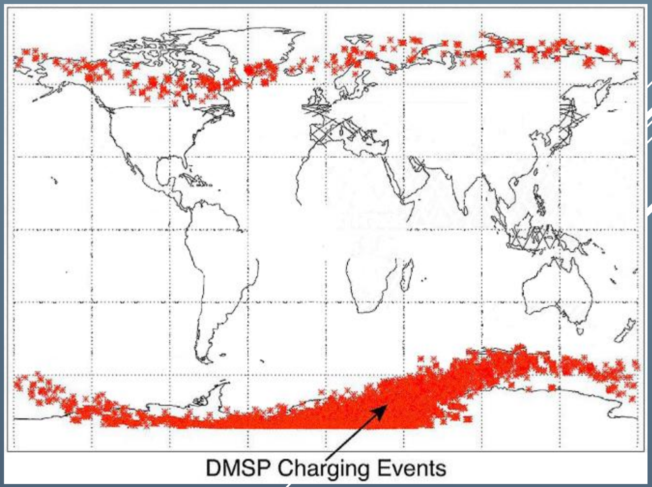
Figure 4. Distribution of all DMSP charging events in MLT and MLAT.

(*Anderson*, 2012)





Parker and Minow, AGU 2014

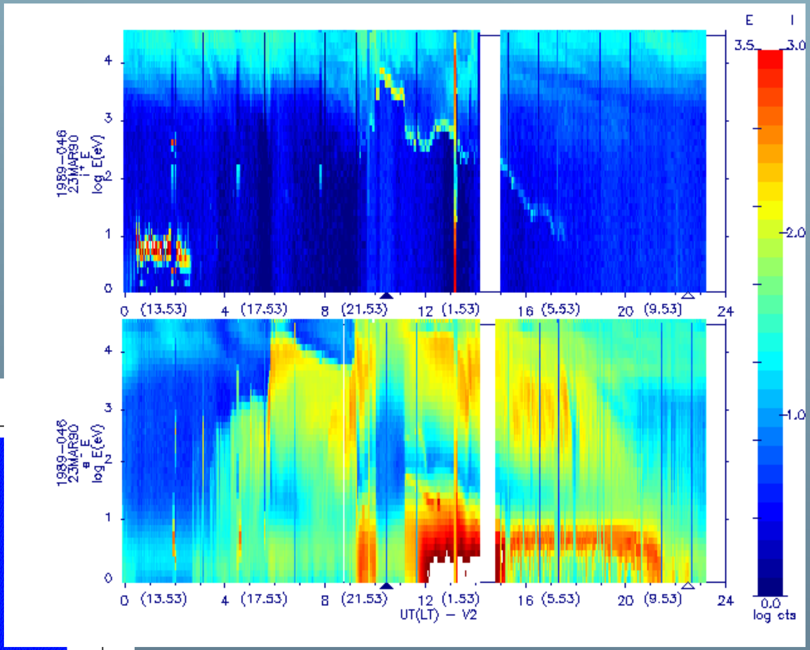


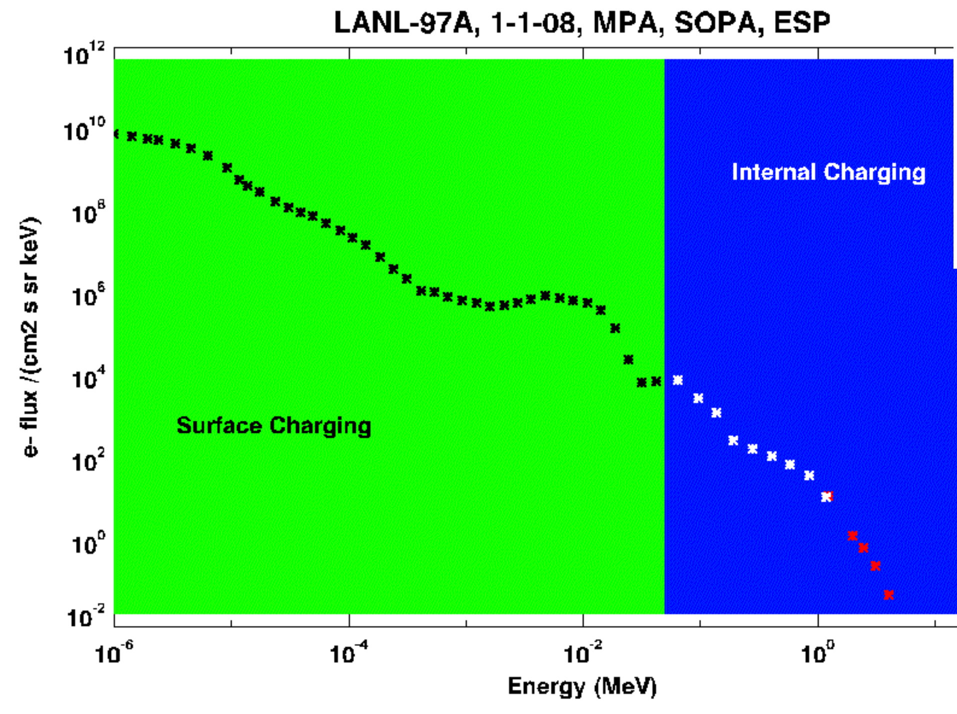
modified from *Anderson*, 2001

Geosynchronous

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

LANL 1989-046 23 March 1990



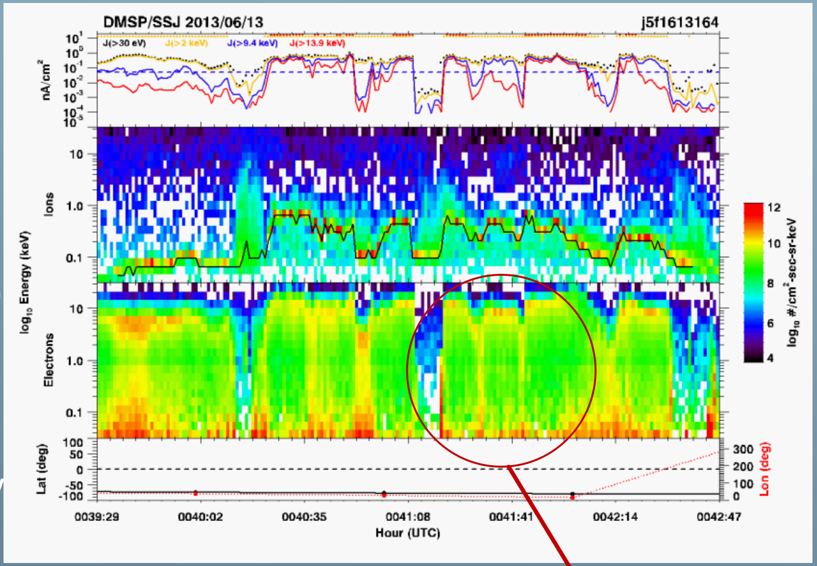


~ 10 kV in eclipse

~ 1 kV post midnight

Polar

- 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



Inverted V

- Fontheim distribution
  - Power law - 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.

Backscattered and secondary e- fluxes

Energetic spectrum

Monoenergetic high energy beam

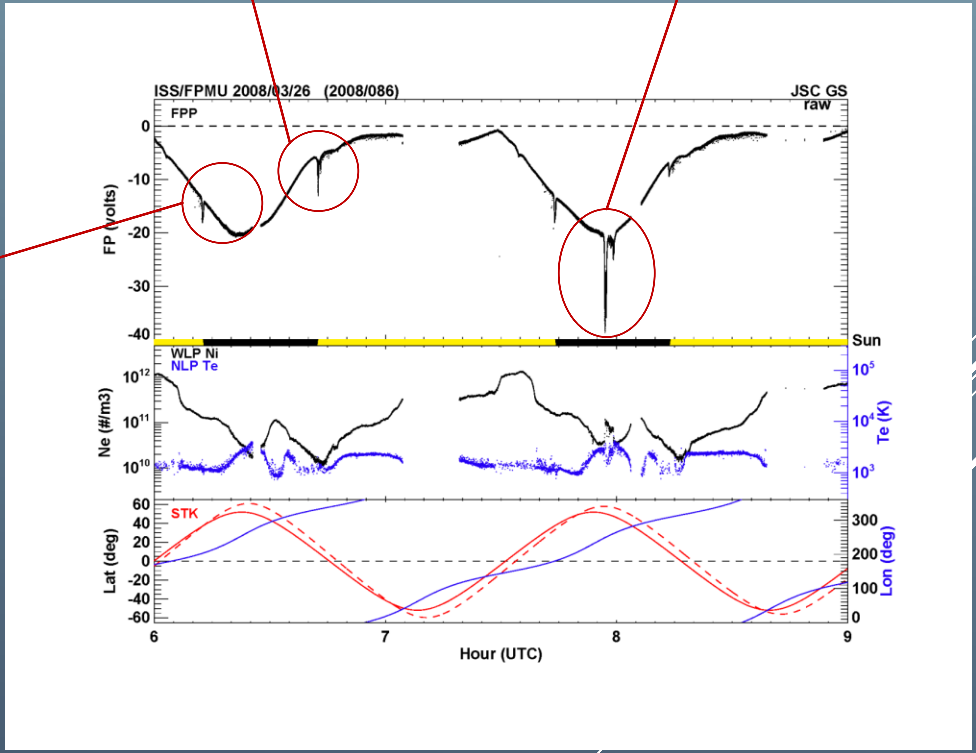
$$F(E) = \pi\zeta_{power}\, E^{-\alpha}\, H(E < E_U)H(E > E_L) + \pi\zeta_{max}\, E\, exp\left(\frac{-E}{kT}\right) + \pi\zeta_{gauss}\, E\, exp\left(-\left(\frac{E - E_o}{\Delta_{gauss}}\right)^2\right)$$

Low Earth Orbit, Low Latitudes

- Surface charging generally a concern only with high power solar arrays

- Inductive potential

$$\varphi = \oint (\bar{E} + \bar{v}x\bar{B}) \cdot d\bar{S}$$



Eclipse exit

Auroral event

Eclipse entry

Spacecraft Design Guidelines for Surface Charging

Questions to ask:

- Will launch trajectory encounter regions of auroral charging threat?
- Will the encounter be in sunlight or darkness?
- Are sensitive electronics located near the insulation materials?
- Will RF noise interfere with critical up/down communications?

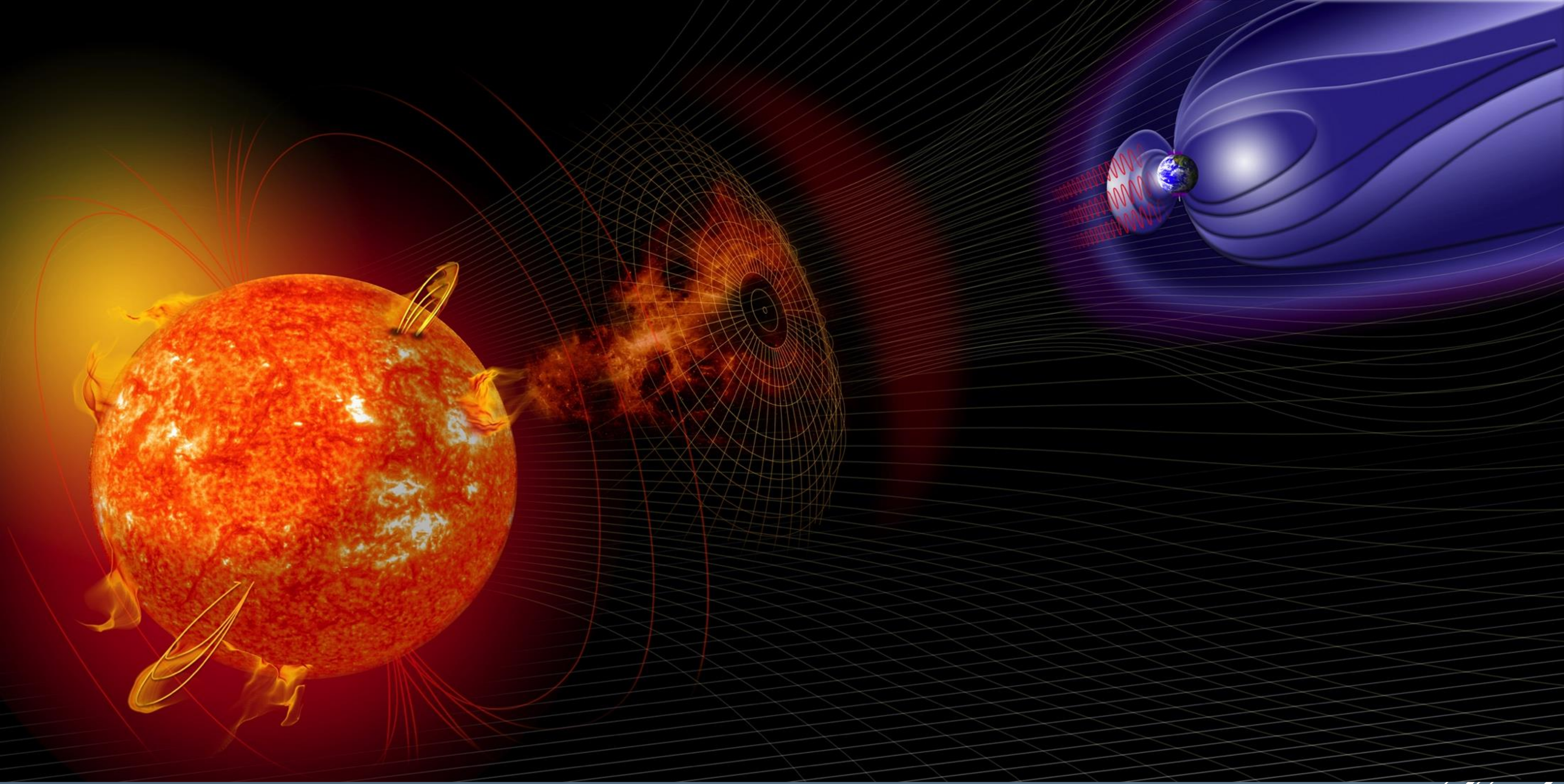
Excerpts from NASA-HDBK-4002A

- Determine whether missions passes through/stays in charging regimes.
- Determine if threat is applicable to their spacecraft
  - Modeling
  - Testing (materials, components, circuit boards, etc)
- Implement mitigation techniques
  - Shield electronics, cables
  - Bond all structural elements
  - Surfaces as conductive as possible

Summary

- Surface charging – 10's eV – 100 keV
- Spacecraft charging is a complicated process based on the sum of the incident currents, material properties, high voltage solar arrays, general orbit characteristics, etc.
- Orbit limited approximation
- Space charging limited approximation

- Build the spacecraft to withstand the charged particle environment.



QUESTIONS?