SCIENCE & TECHNOLOGY OFFICE

A Tutorial on Spacecraft Charging

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SHEILDS CONFERENCE
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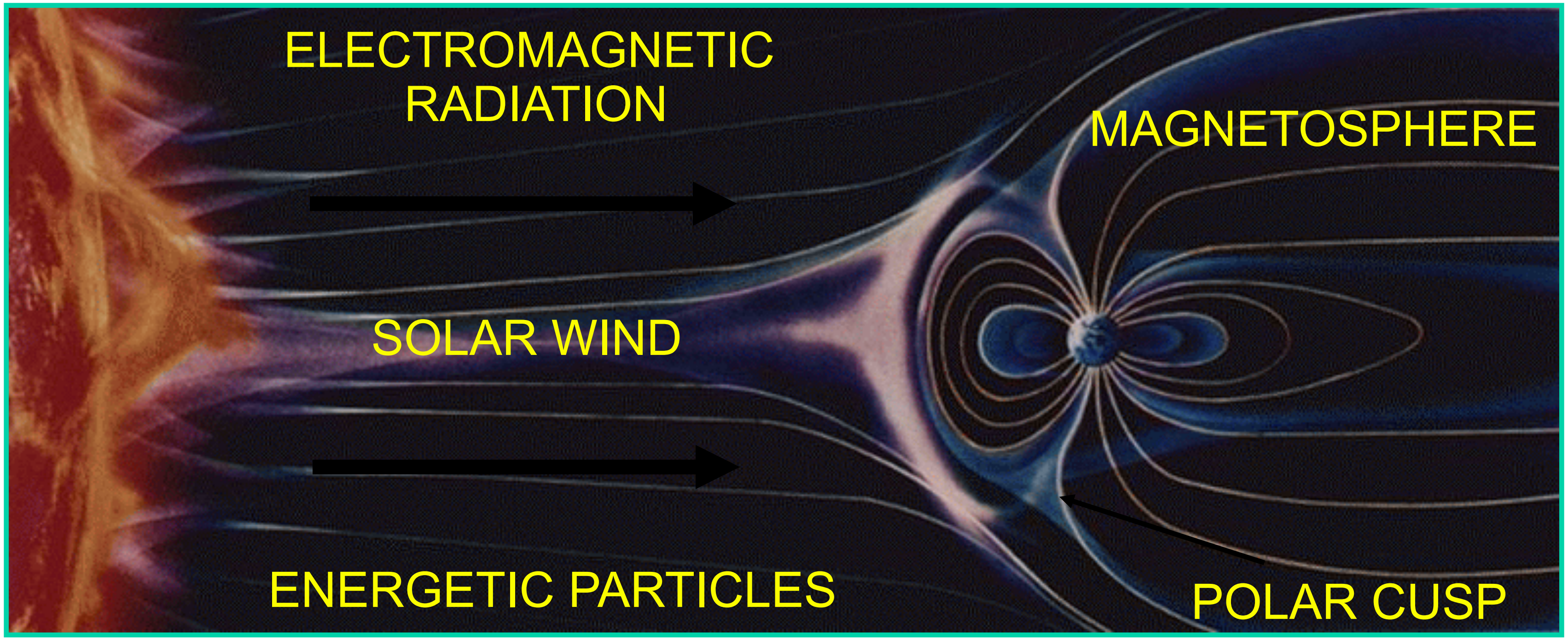
Motivation: Solar-Terrestrial Interactions

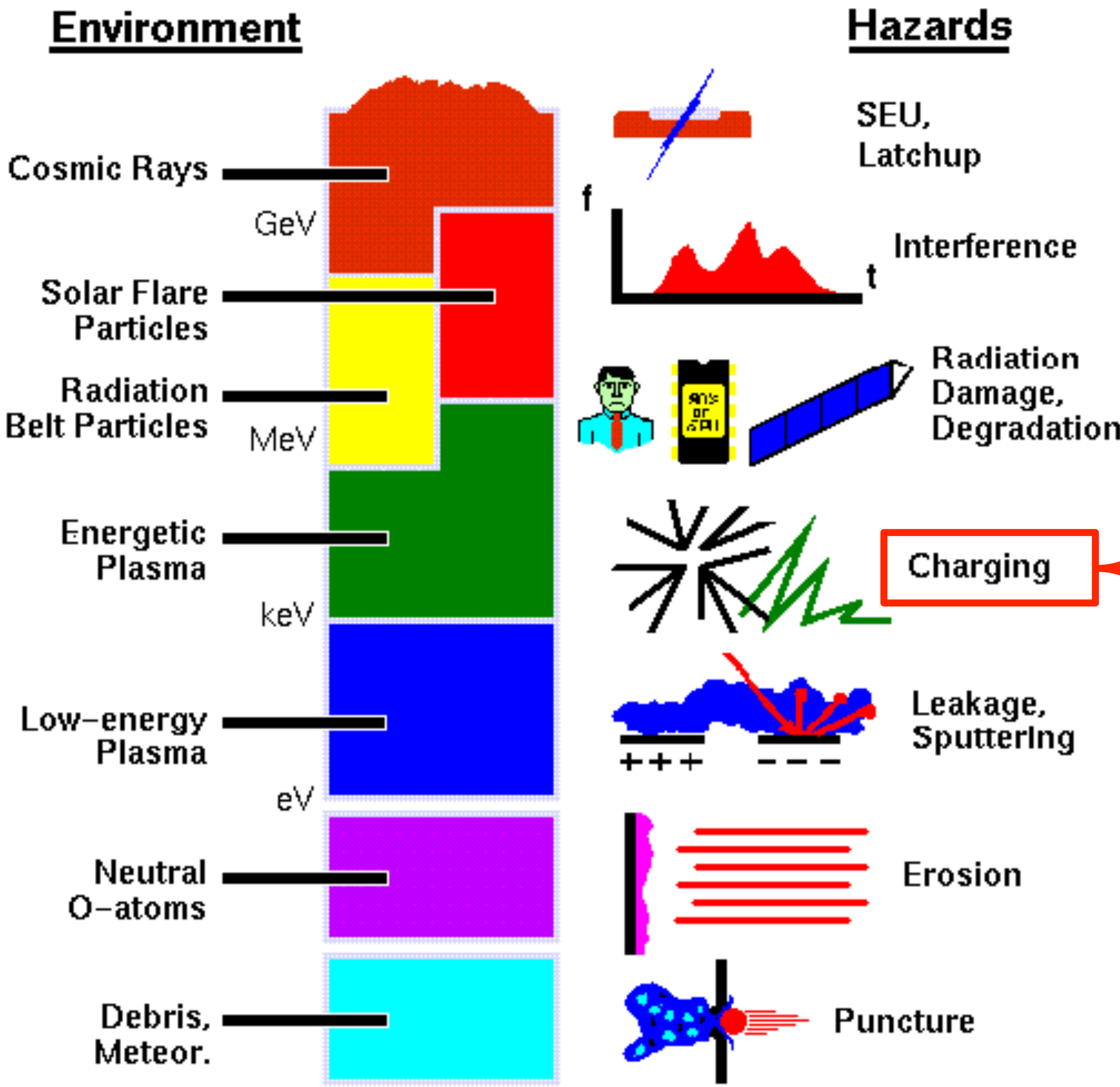


SPACE CLIMATE: Statistical Description of the Solar-Terrestrial Environment parameterized by solar and geomagnetic activity type and intensity

SPACE WEATHER: Processes associated with the temporal and spatial variability in the Solar-Terrestrial Environment

SPACE ENVIRONMENTAL EFFECTS: Effects of the space environment on man-made systems (e.g., impulsive disruptions, long-term degradation, etc.)

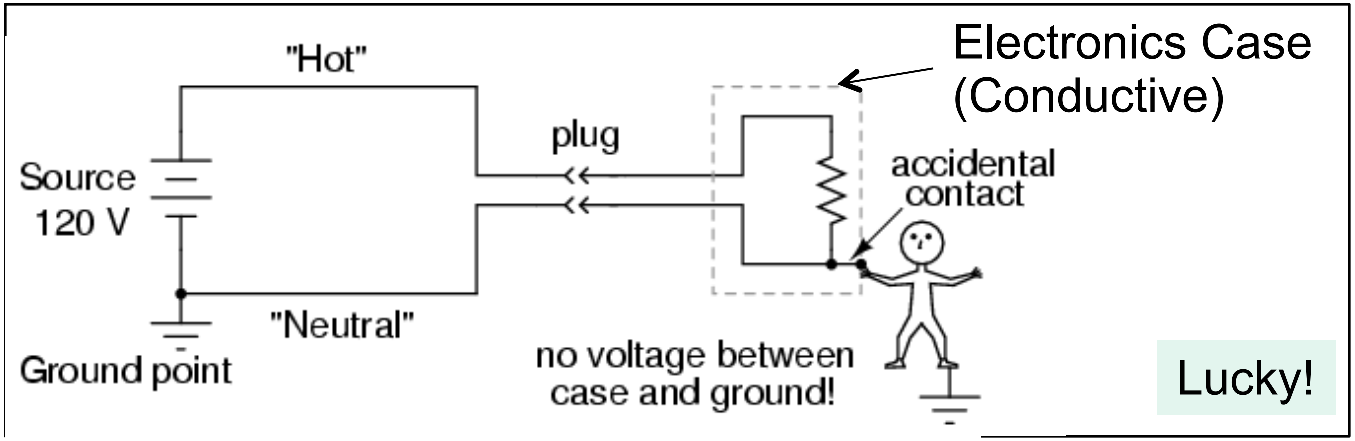
Motivation: Radiation Effects on Space Systems



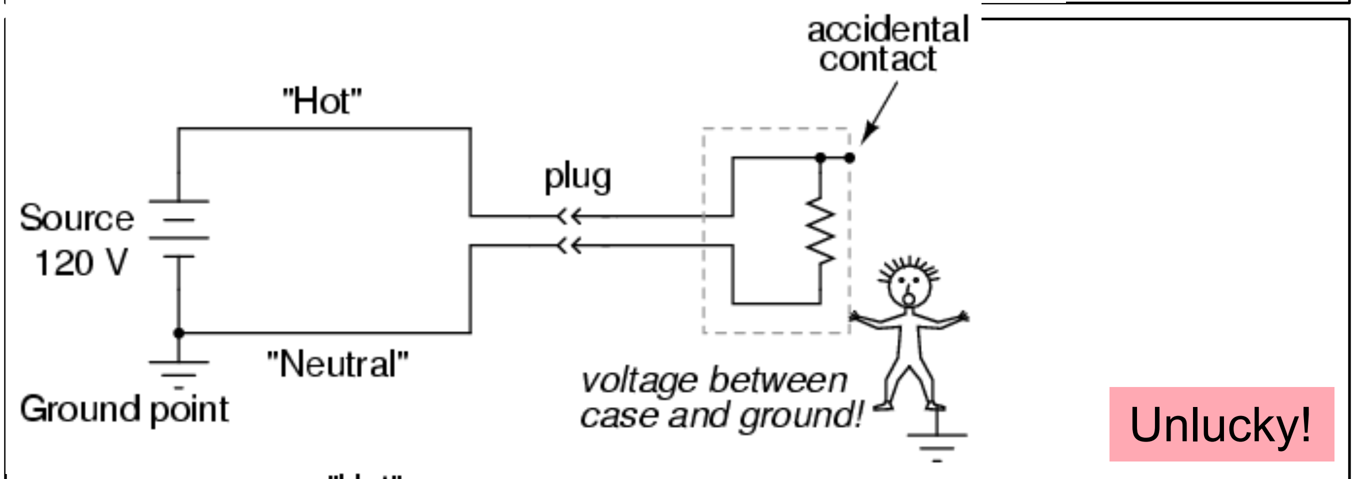
Spacecraft (S/C) Charging Effects:

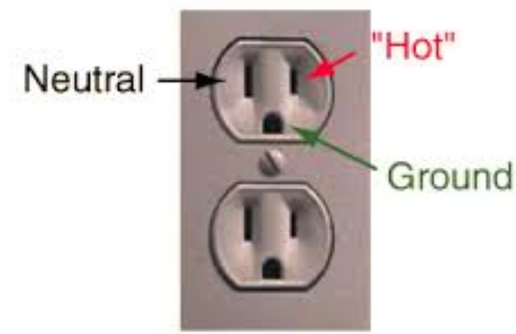
- Electrostatic Discharge (ESD)
- Circuit Damage
- Reduce Solar Panel Efficiency
- Material degradation
- Contamination of sensitive optics
- Interference with scientific measurements

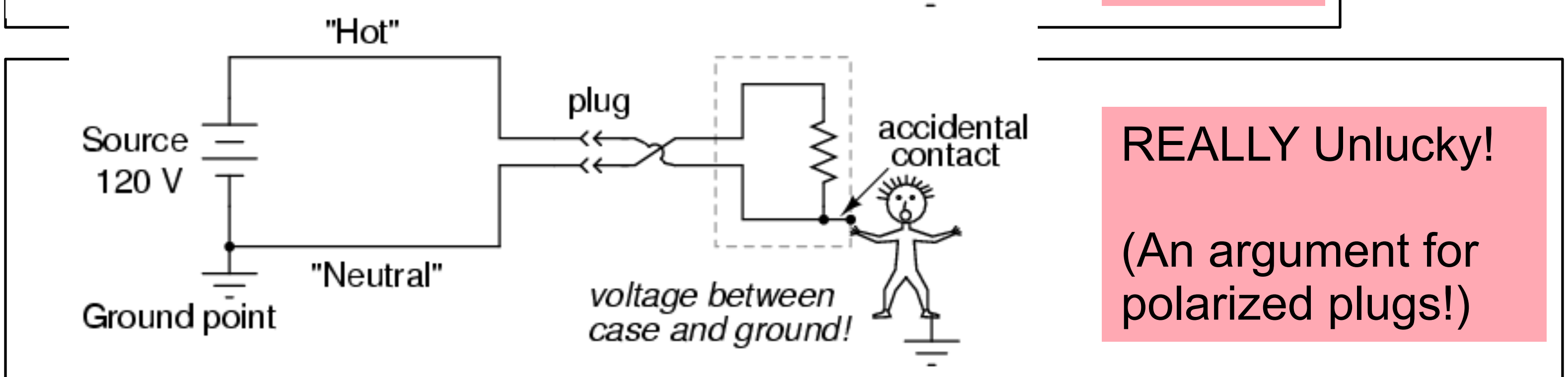
Intro: The Concept of "Ground"



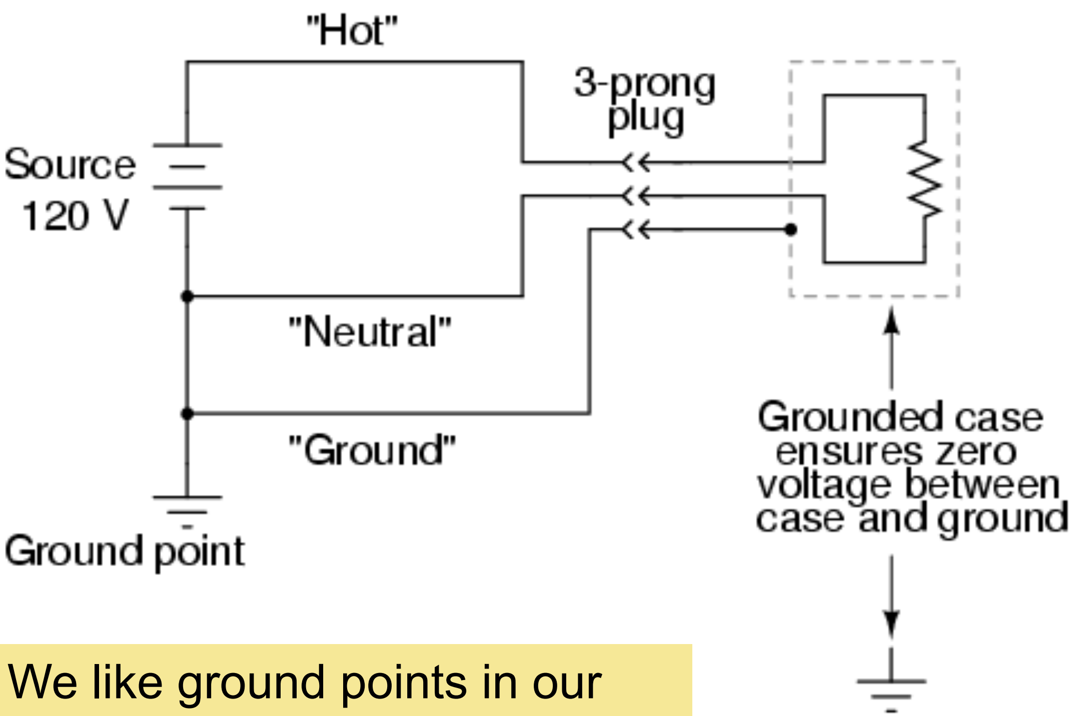
"Ground" on Earth: An arbitrary (but consistent) designation of an electric potential = 0





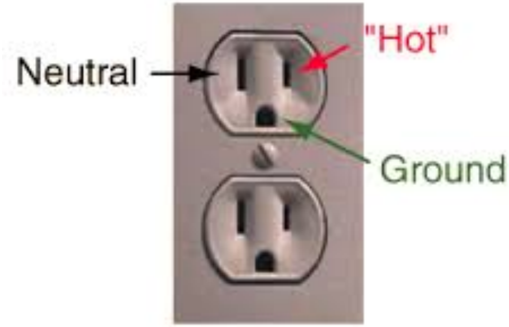


Intro: The Concept of "Ground"



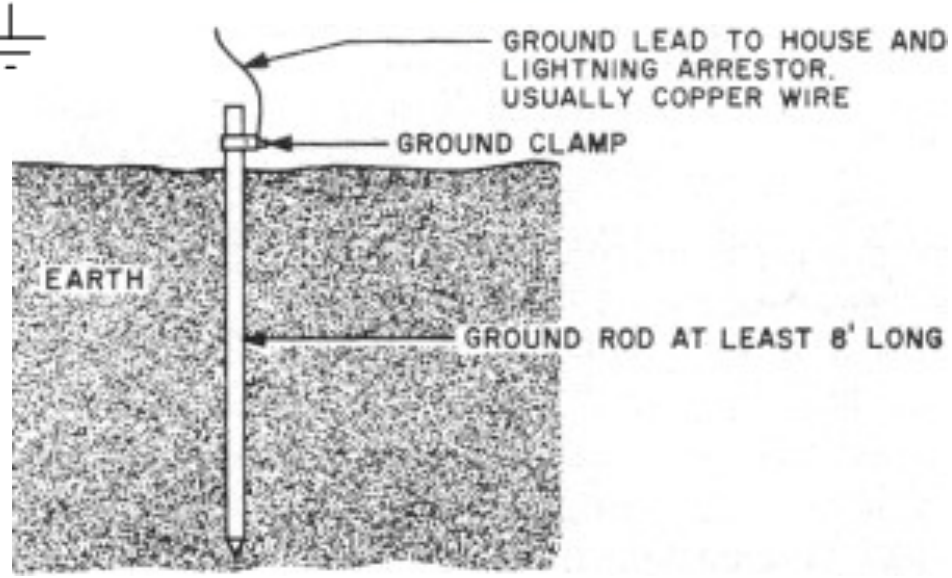
Hard-wired grounding of electrical case: **Safe!!**

"Ground" on Earth: Don't take that third prong for granted!



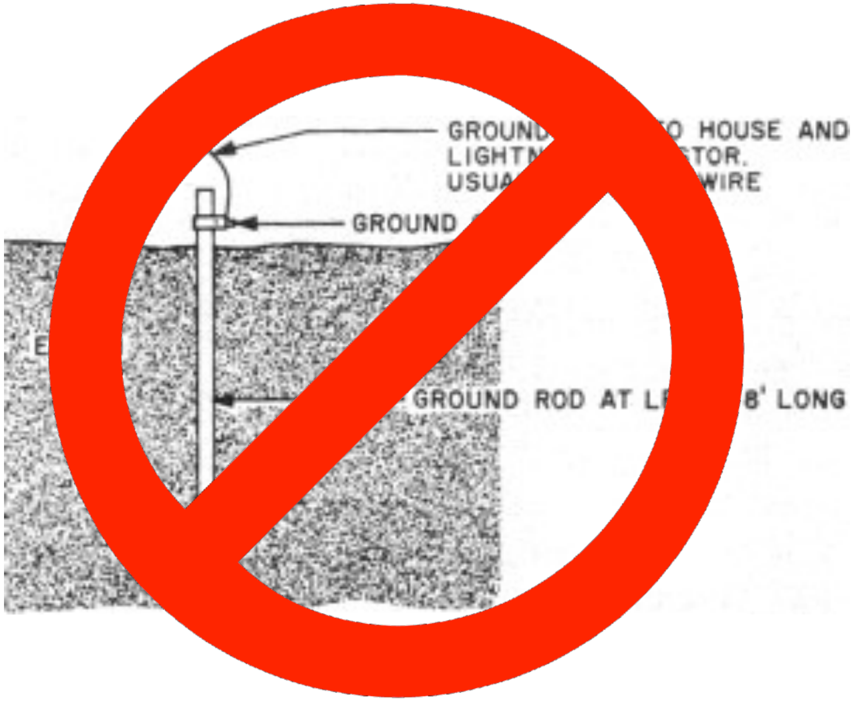
We like ground points in our circuit.

- Important for safety
- "Absolute" voltage reference for circuit components
- Can serve as a current sink
- Reminds us of best practices (e.g. avoiding ground loops)



Intro: There is no "ground" in space!

Conundrum: There is no "ground" in space! → **How do we characterize "Spacecraft Charging"?**



Definitions:

Charging is a voltage relative to some reference potential

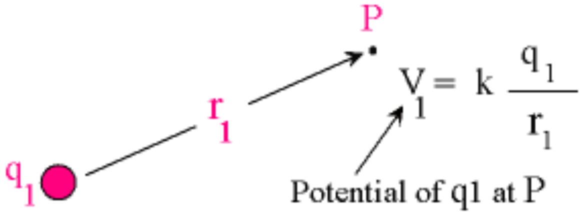
Spacecraft frame charging is commonly referenced to the ambient space plasma potential

Differential surface charging commonly describes the voltage between an electrically-insulated component and the s/c frame

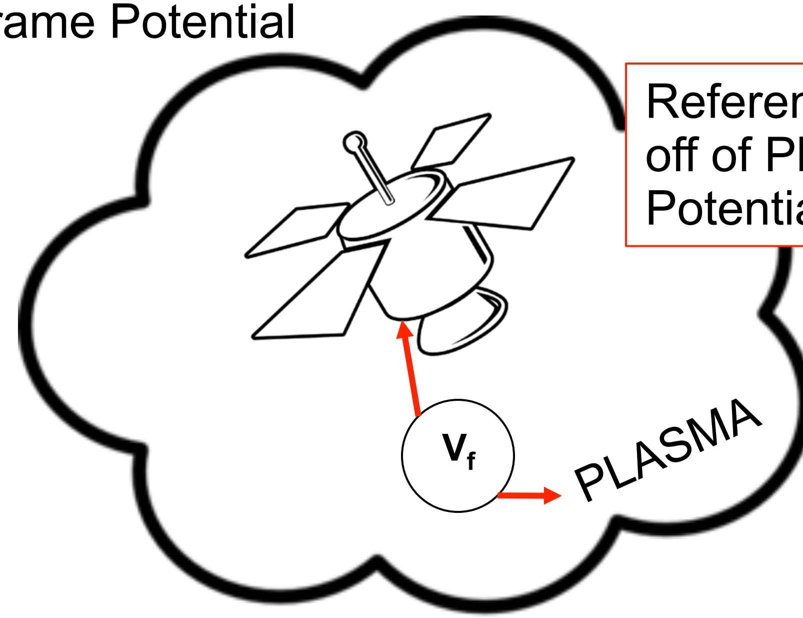
Fundamentals: Space, Plasma, and Frame Potentials

Vacuum Space Potential

$$V_1 = k\frac{q_1}{r_1}$$



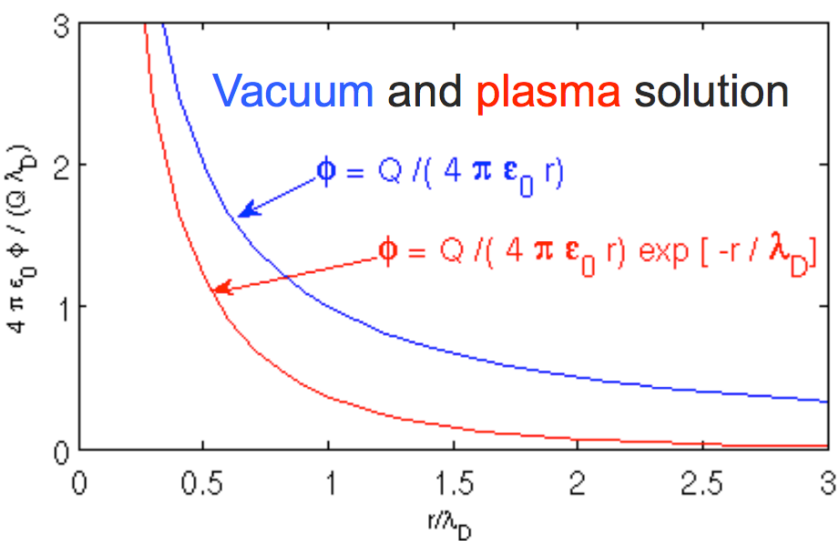
Frame Potential



Referenced off of Plasma Potential

Plasma Potential

Shielding due to the charge screening



Debye Length: a function of ambient plasma (electron) temperature and density

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e q_e^2}}$$

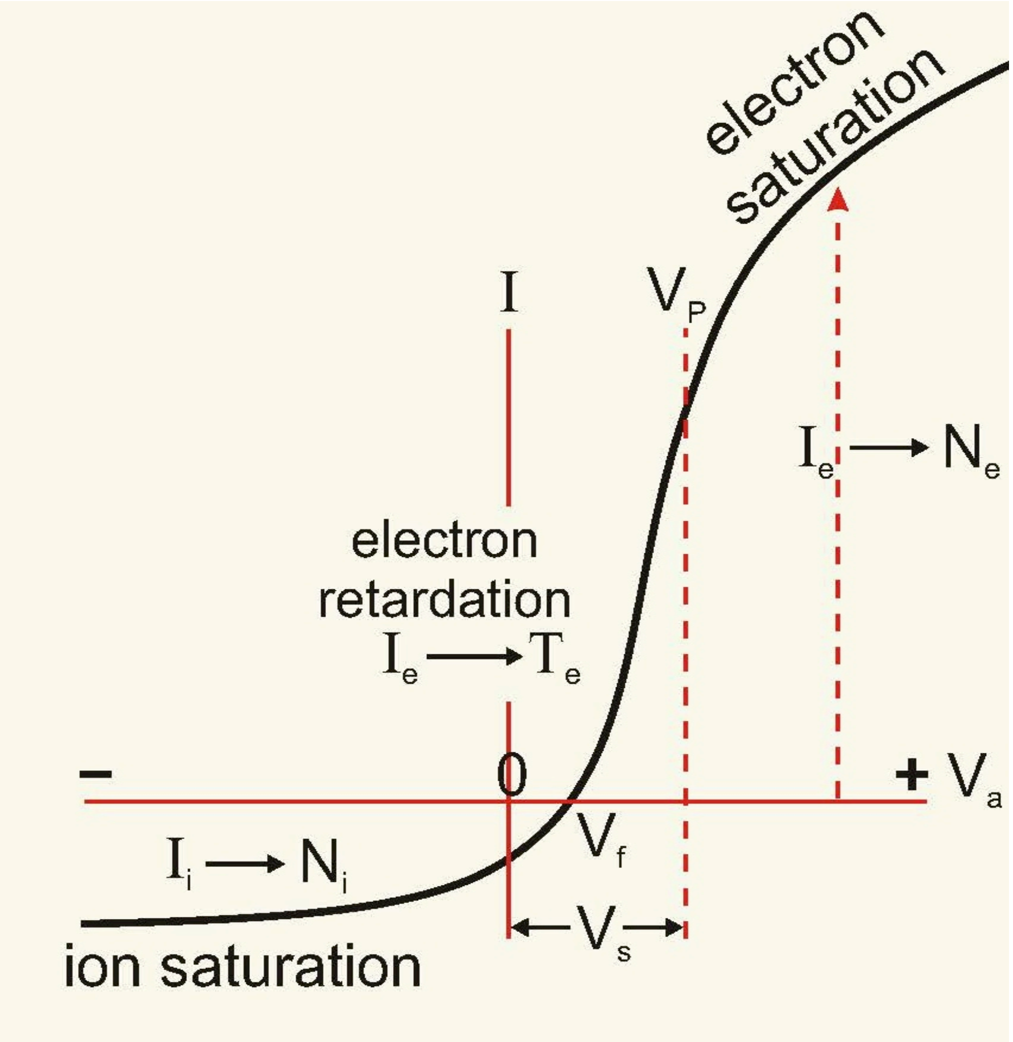
In Vacuum: Space Potential ➔ 0 as r ➔ ∞

In Plasma: Local Plasma Potential is referenced off of space potential as r ➔ ∞

Convention: Let Plasma Potential == 0

We commonly use “space” and “plasma” potentials interchangably

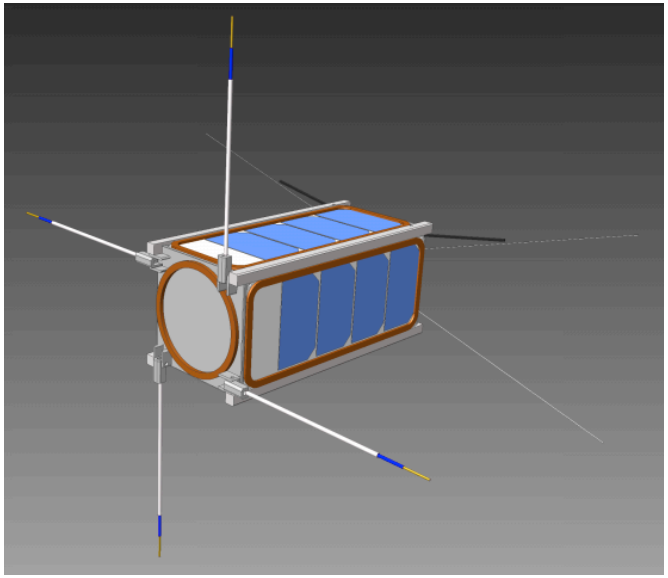
Example: Satellite with Langmuir Probe



Characteristic I-V Langmuir Probe Curve

Langmuir probes provide:

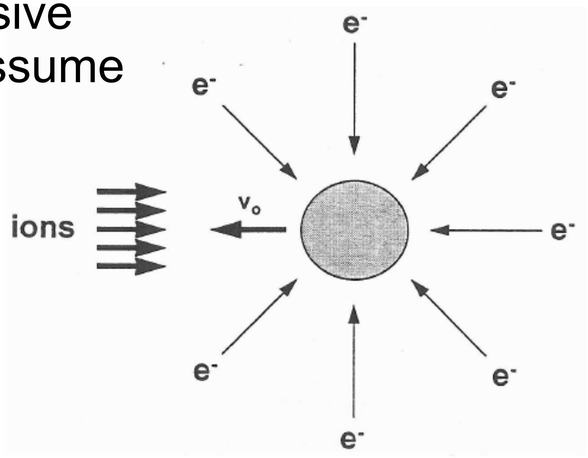
- Plasma electron and ion density and temp
- S/C potential
- Plasma Potential



CUBESTAR from U. of Oslo
http://cubestar.no/

THEORY: S/C Surface Charging Calculation

To derive the equation for the potential of a stationary, passive conducting object: balance the electron and ion fluxes & assume the election and ion temperatures are the same



- Mean speed of the particles in a plasma is given by
  - u = mean speed
  - α = species (electron or ion)
  - k = Boltzmann's constant
  - T = temperature

$$u_{o,\alpha} = \sqrt{\frac{8kT_\alpha}{\pi m_\alpha}}$$

- Flux (particles per unit area per unit time crossing a surface) is given by $\Gamma_\alpha = \frac{n_o u_{o,a}}{4}$
- The electron density is given by $n_e = n_o \exp\left(\frac{e\Phi}{kT_e}\right)$

(This represents the electron density at the surface of a conducting object charged to Φ. In a space plasma, Φ will be negative, so n_e will be less than the ambient plasma density $n_{o)}$

- Electron flux = ion flux $n_o \exp\left(\frac{e\Phi}{kT_e}\right)\sqrt{\frac{8kT_e}{\pi m_e}} = n_o \sqrt{\frac{8kT_i}{\pi m_i}}$
- Assume the electron & ion temperatures are the same $\exp\left(\frac{e\Phi}{kT}\right) = \sqrt{\frac{m_e}{m_i}}$

Satellite Surface Charging

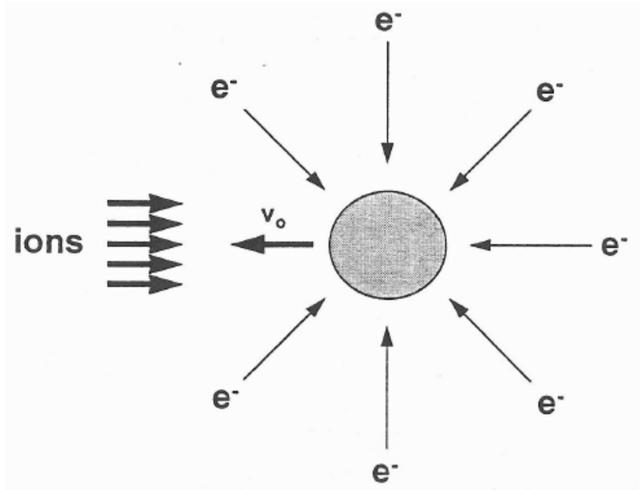
- Solve for potential, Φ

$$\Phi = \left(\frac{kT}{e}\right)\ln\left(\frac{m_e}{m_i}\right)$$

- In an oxygen plasma (near earth),

$$\Phi \approx -10\left(\frac{kT}{e}\right) \approx -1V$$

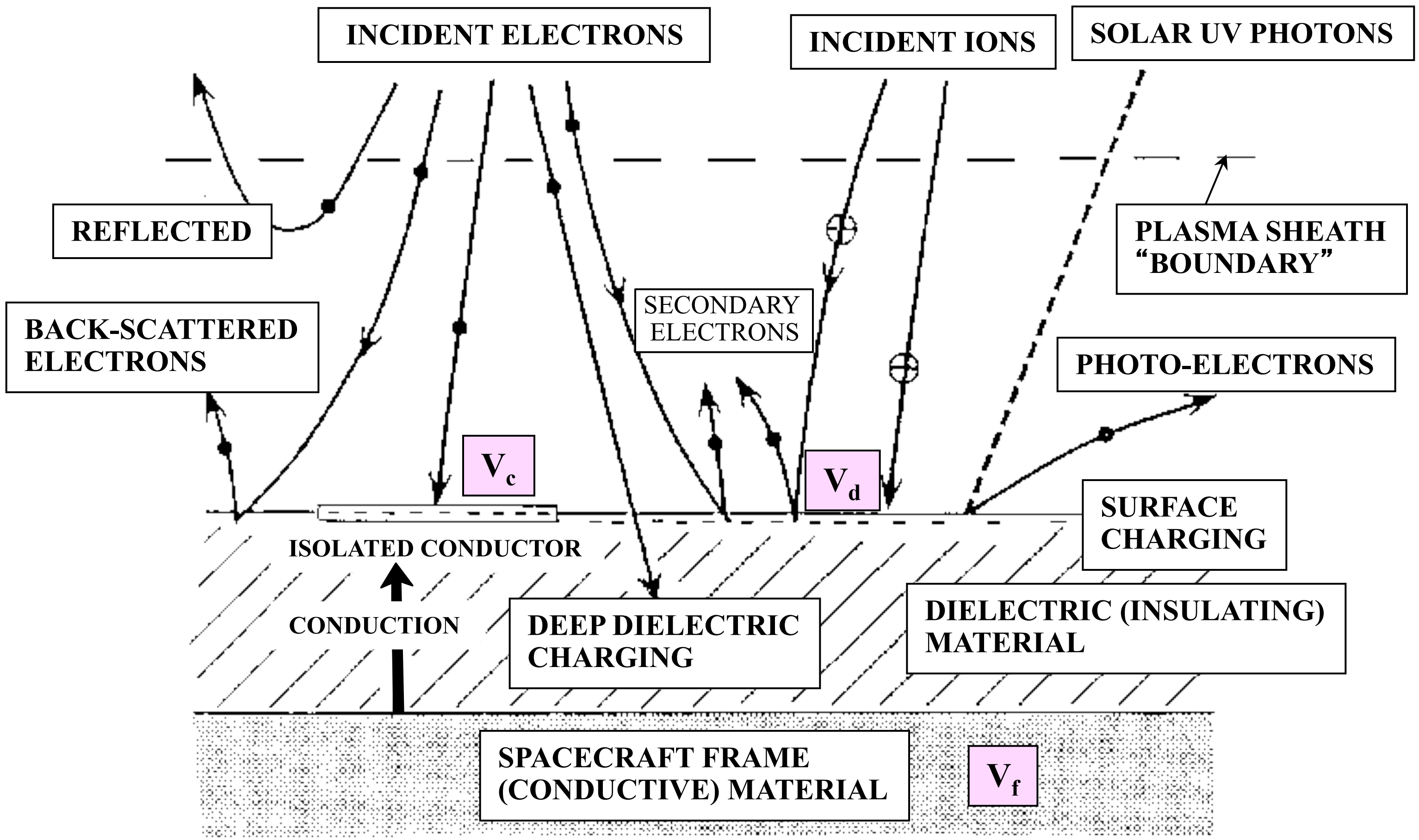
For thermal ionosphere plasma temp = 0.1 eV



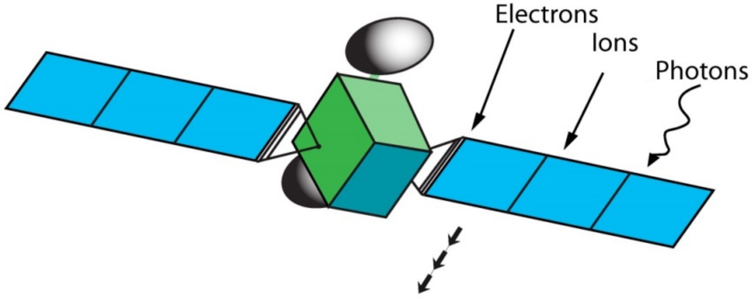
QUESTION: OK, in LEO the spacecraft might charge up to -1V, but… who cares about that?

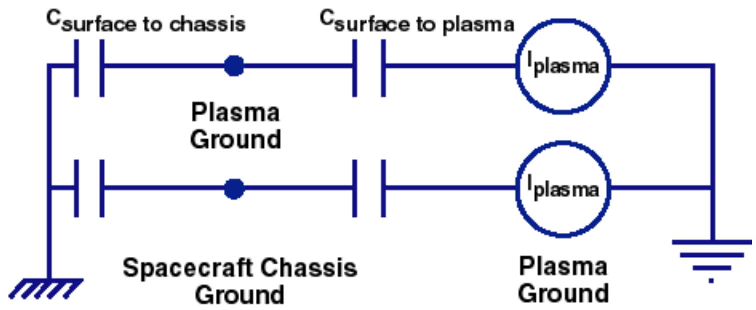
ANSWER: This charging is due to ambient thermal ionospheric plasma, but it becomes more complicated when higher energy electrons are in the environment.

Different types of S/C Surface Charging



Spacecraft Charging Calculation





Contributions from incident charged particles and resulting secondary, backscattered, and photo electrons

Capacitance of insulating surface to chassis is much greater than capacitance of insulating surface to plasma

$$\dot{\sigma} = j_{net} = j_e + j_{\sec} + j_{backscat} + j_i + j_{photo} + j_{conduction}$$

Why modeling spacecraft charging is difficult:

- Currents depend on potentials & fields
- Capacitive timescales vary by orders of magnitude
- Geometrical details are important
- Differential charging barriers limit secondary electrons

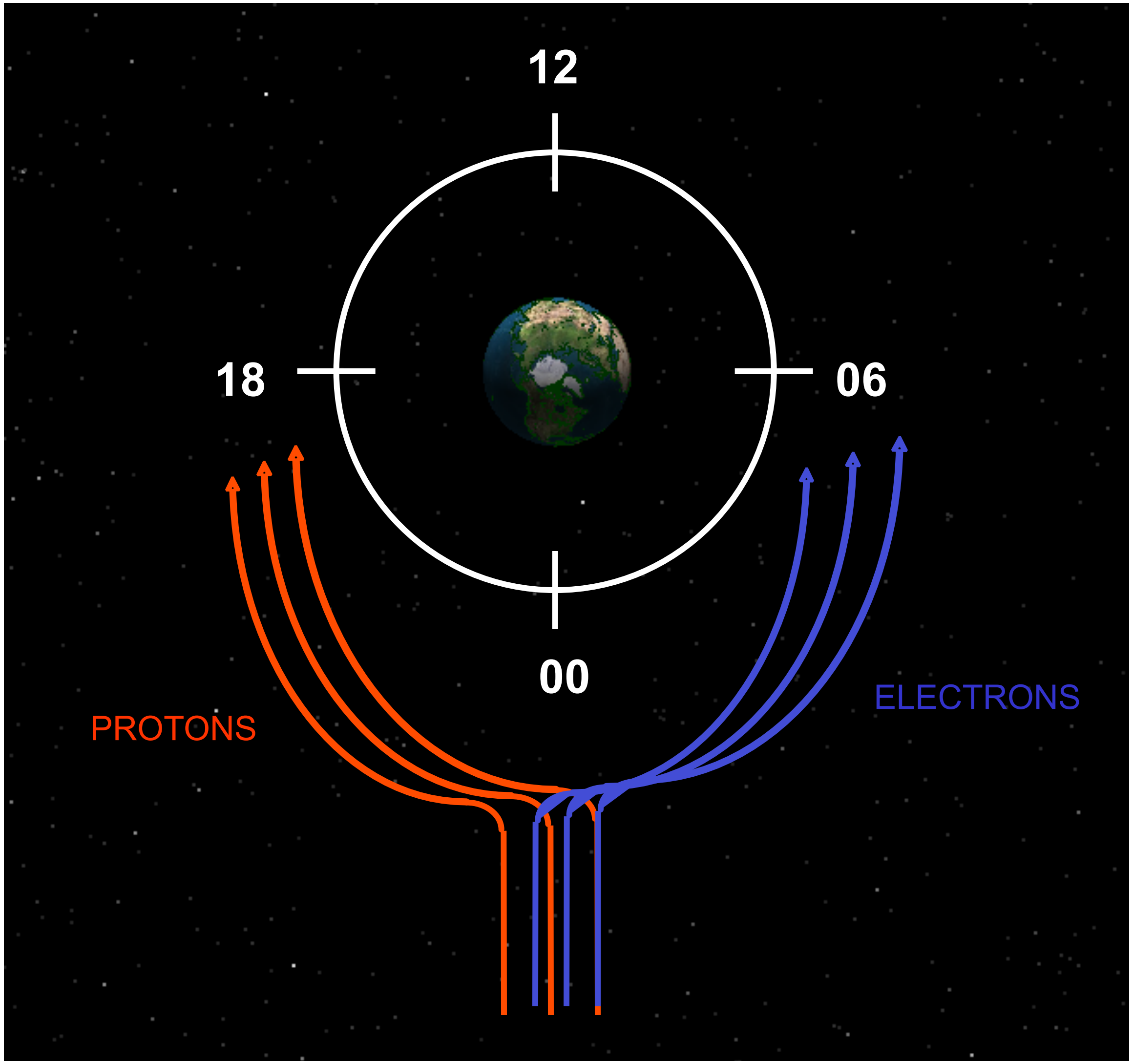
GEO S/C Surface Charging

GEO Environment

- Geosynchronous Earth Orbit (GEO) is located at 6.6 R_E
- Popular orbit for low-latitude communication satellites

Magnetic Storm ⇒ Particle injection into the ring current

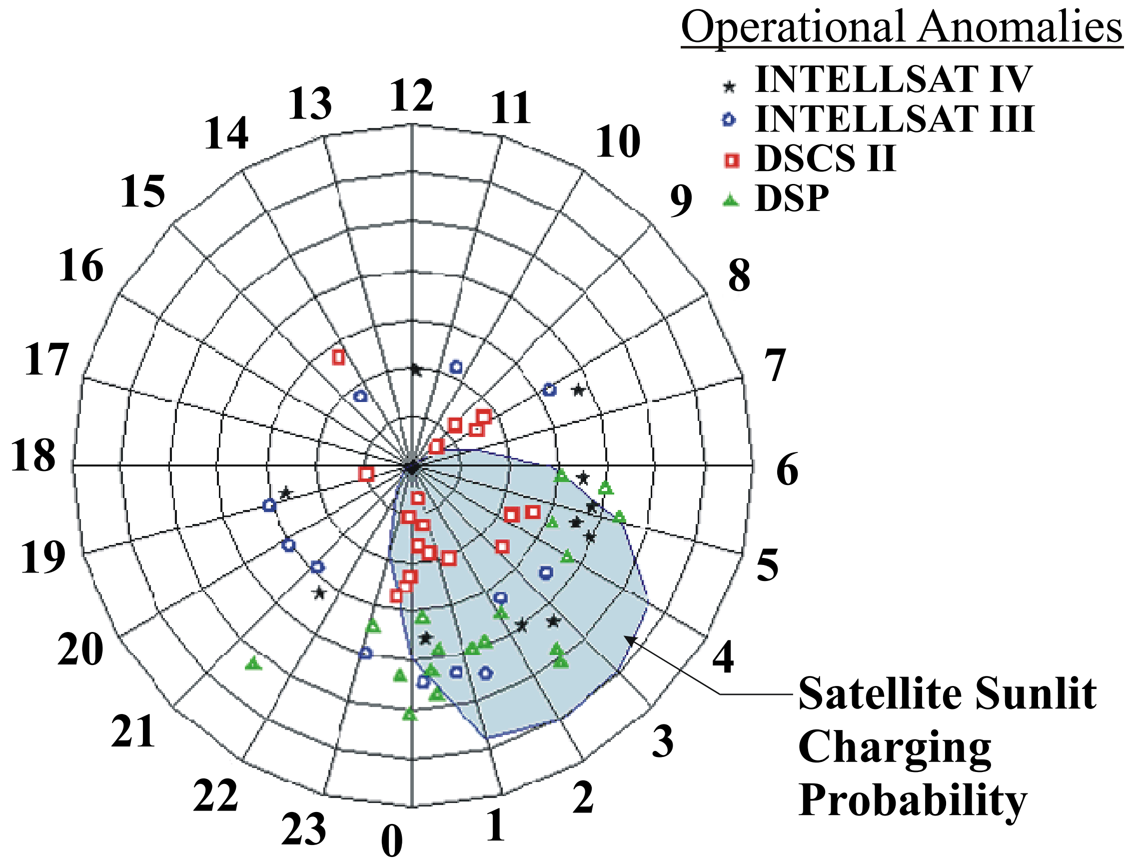
- Ring Current is westward
- Particles energized as they approach Earth
- Energetic Electrons injected into post-midnight



S/C Charging Concentrated Post-Midnight

Satellite Surface Charging

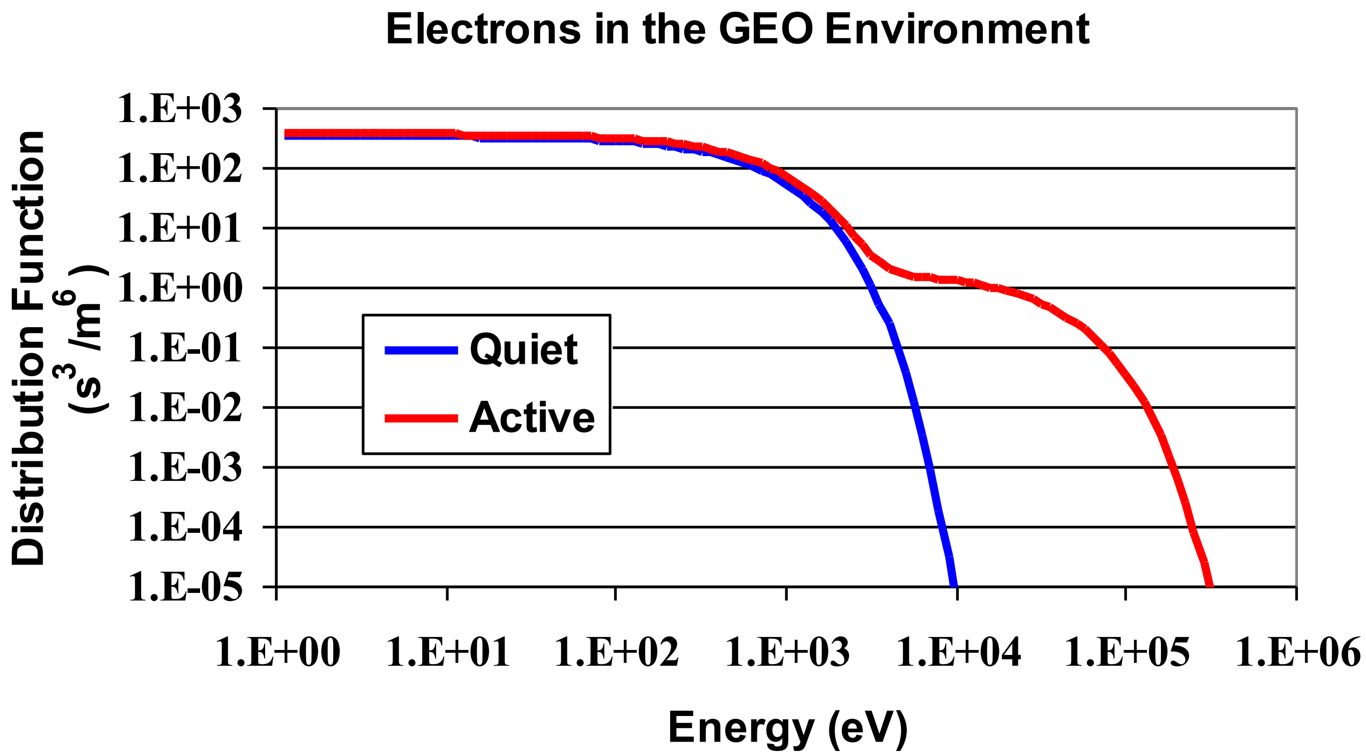
- Injection of energetic (E ~ 10s keV) electrons into GEO concentrated in post-midnight region
- Statistics show both S/C charging and operational anomalies are concentrated in the same local time sector



Satellite charging probability is compared with operational anomalies, both plotted as a function of spacecraft local time. Each circular ring represents 5% probability of DSCS-III charging to at least -50 V relative to the background plasma (see *Habash Krause, 2000*). Anomalies are from *Jursa, 1985*.

S/C Surface Charging Electrons: 10’s of keV

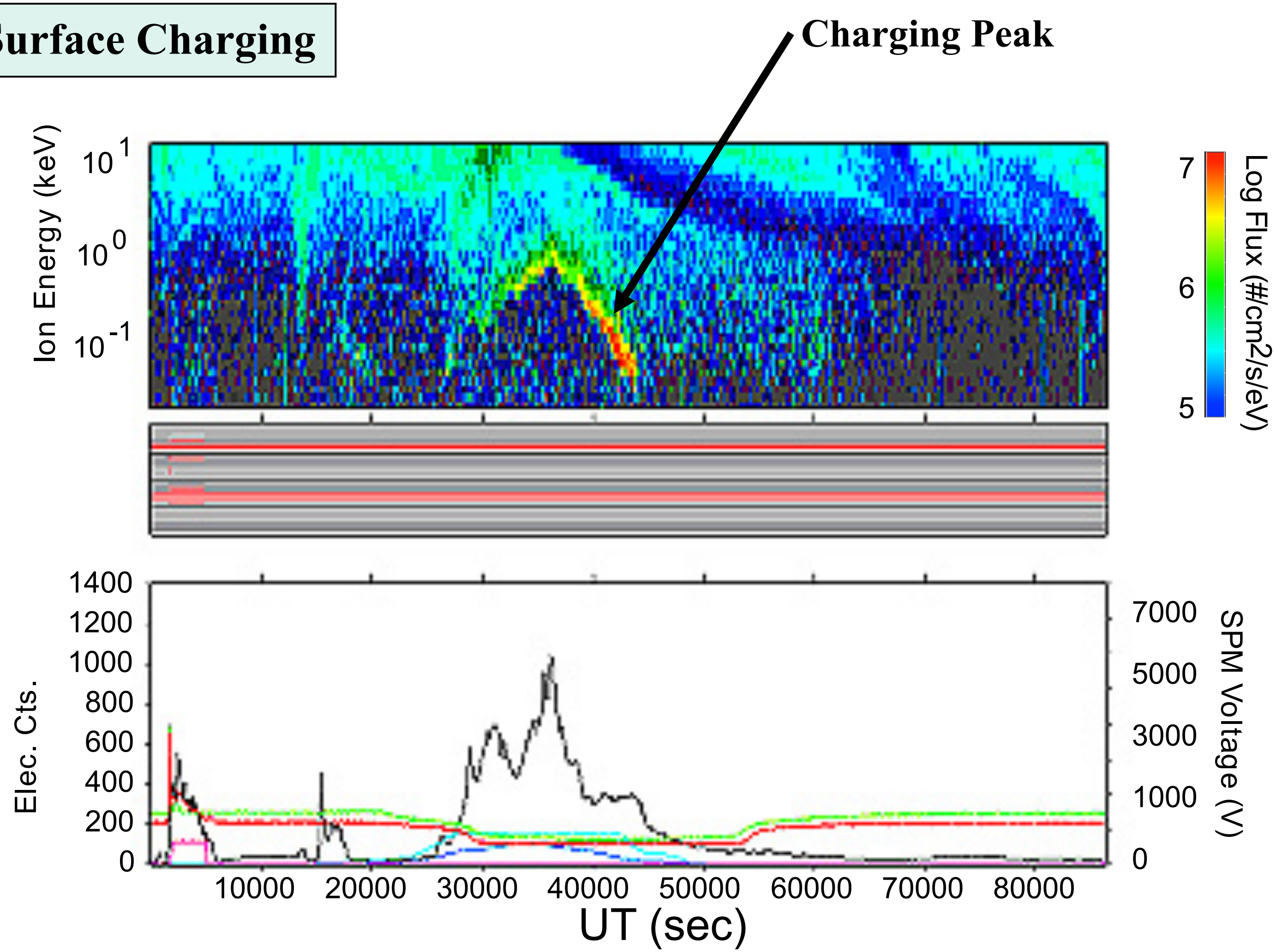
Magnetosphere: Geosynchronous Earth Orbit (GEO) Environment



During periods of significant geomagnetic activity, the electron environment in GEO is best represented by a two-temperature Maxwellian. See *Mullen et al., 1986*, for further information. **Surface Charging Electrons tend to have energies from 10-50 keV.**

EXAMPLE: DSCS III Charging

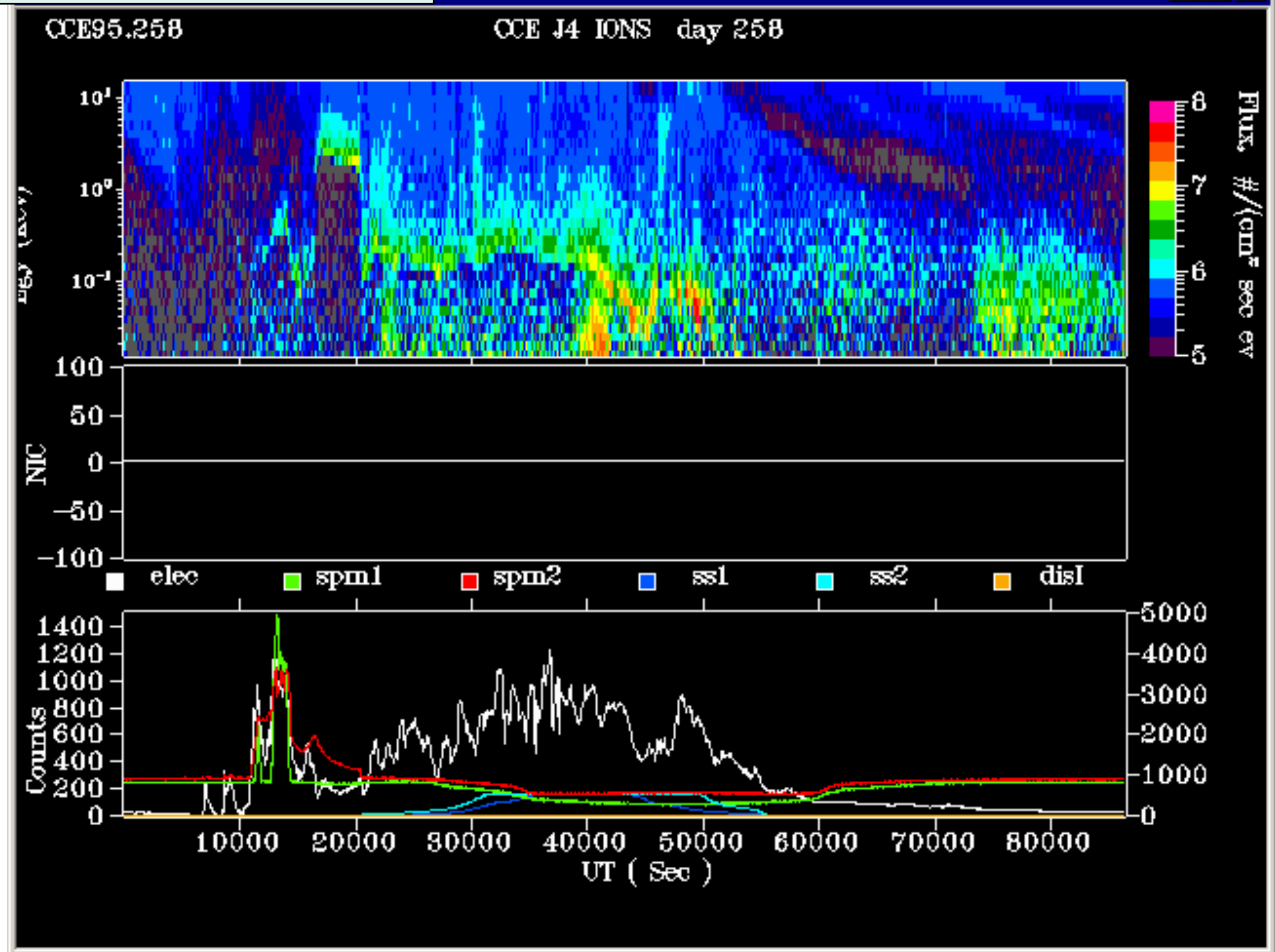
Satellite Surface Charging



During periods of significant ring current injection, spacecraft may become significantly charged relative to background plasma. Electron counts are integrated over 20keV-50keV. We use "ion peak" method to determine frame potential V_f

Satellite Charging Alarms and Mitigation

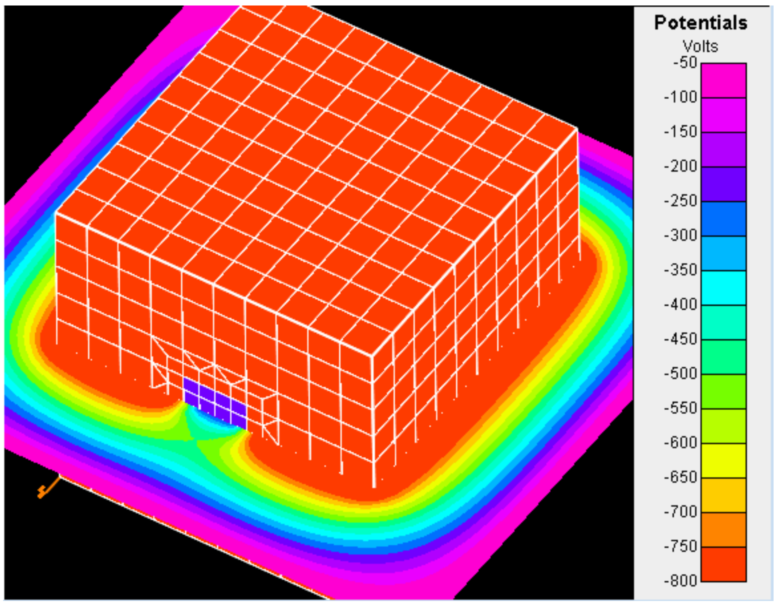
- Xe plasma thrusters have been used for differential charging neutralization based on "alarm" system
- Complex combination of frame and differential component charging mandate delicacy in neutralization.
    - Using pure electron source to reduce negative frame charging may exacerbate differential charging



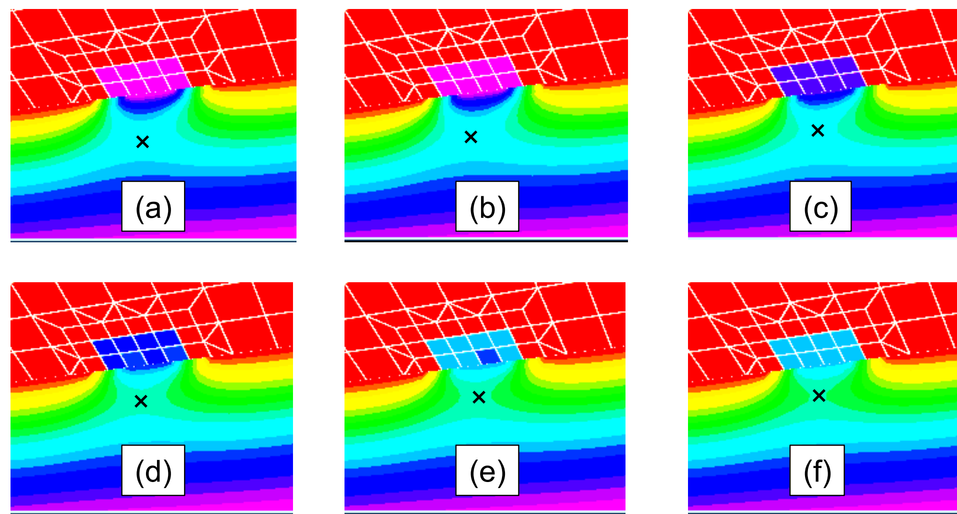
S/C "Bootstrap" Charging

"Bootstrap Charging"

Sheath formation of small isolated patch results in suppression of photo-electron escape from neighboring surfaces



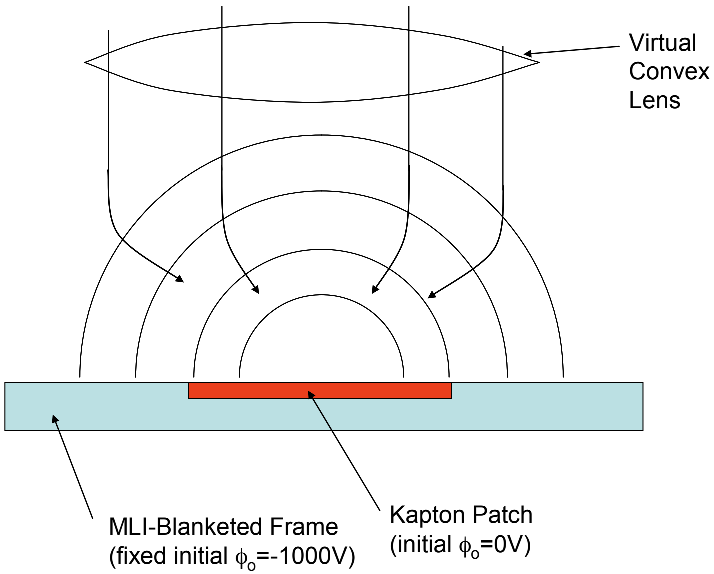
Demonstration of bootstrap charging of a Kapton patch electrically floating relative to a blanketed frame fixed at -1000 V relative to a background quiescent plasma. The patch face is sunlit.



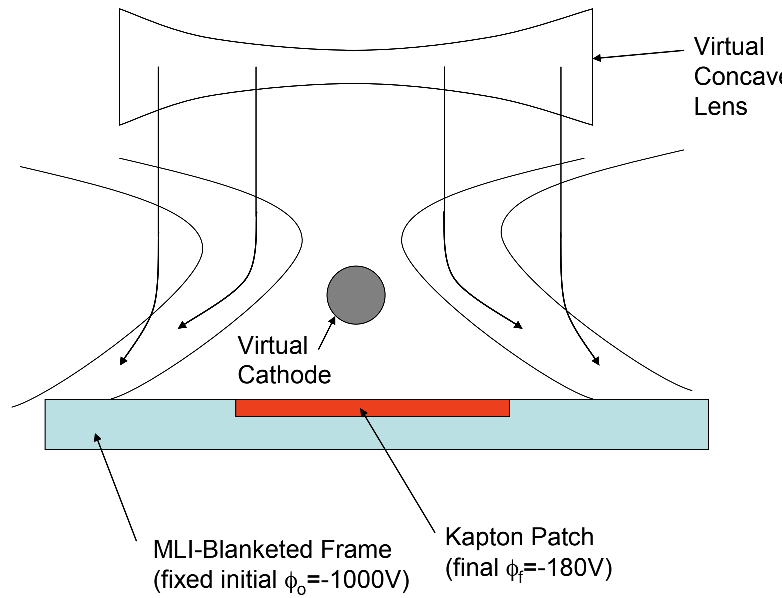
Formation of saddle point as evident from the sequence of spatial potential maps in time. Panels (a) through (f) correspond to 1.0, 5.0, 25, 100, 200, and 300 seconds, respectively.

Charged Patches: Electrostatic Lenses

Formation of "Virtual Cathode"



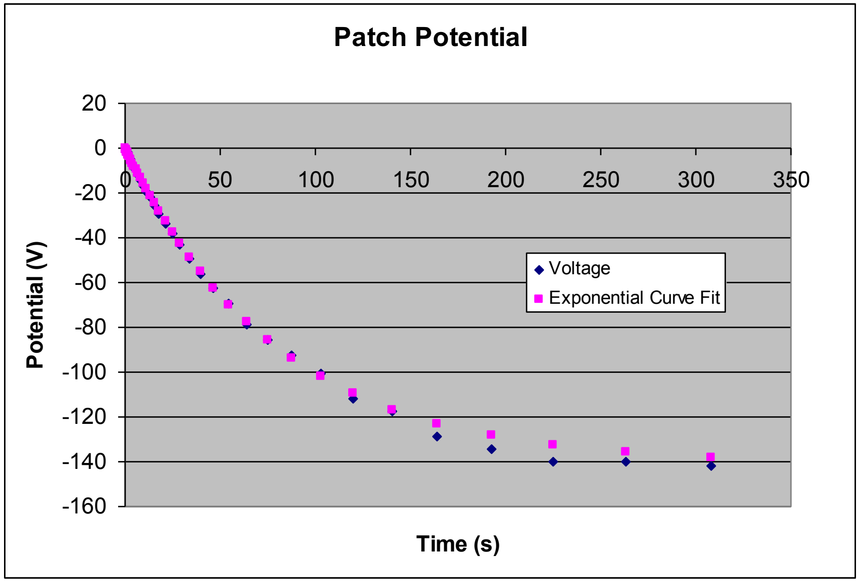
Before the formation of the virtual cathode in front of the Kapton patch, initially at a zero potential relative to the plasma, the approximately concentric semi-circles forms a virtual convex lens that guides incoming charging electrons toward the patch, resulting in rapid patch charging.

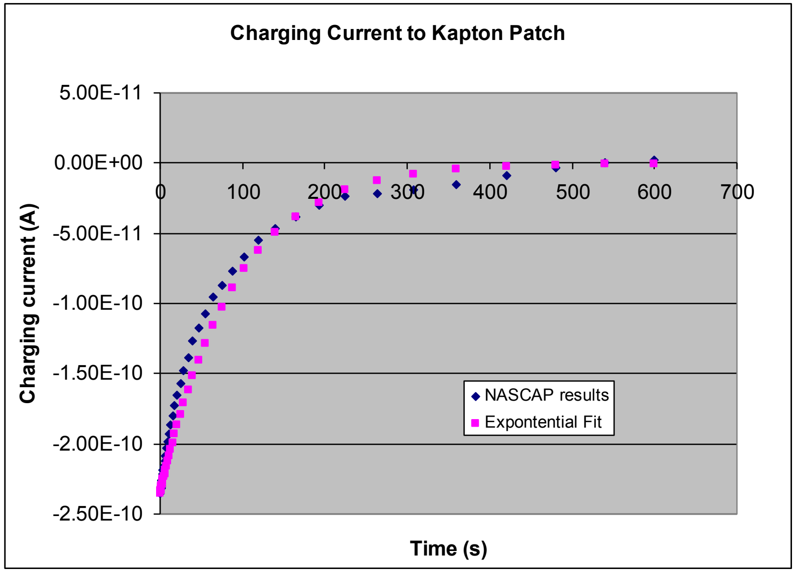


Strong saddle point configuration of spatial equipotentials results in electron optics resembling a concave lens. Divergent trajectories of electrons result in replusion of charging electrons away from the Kapton patch.

Differential Charging Characteristics

Isolated Patch charging acts like RC Circuit

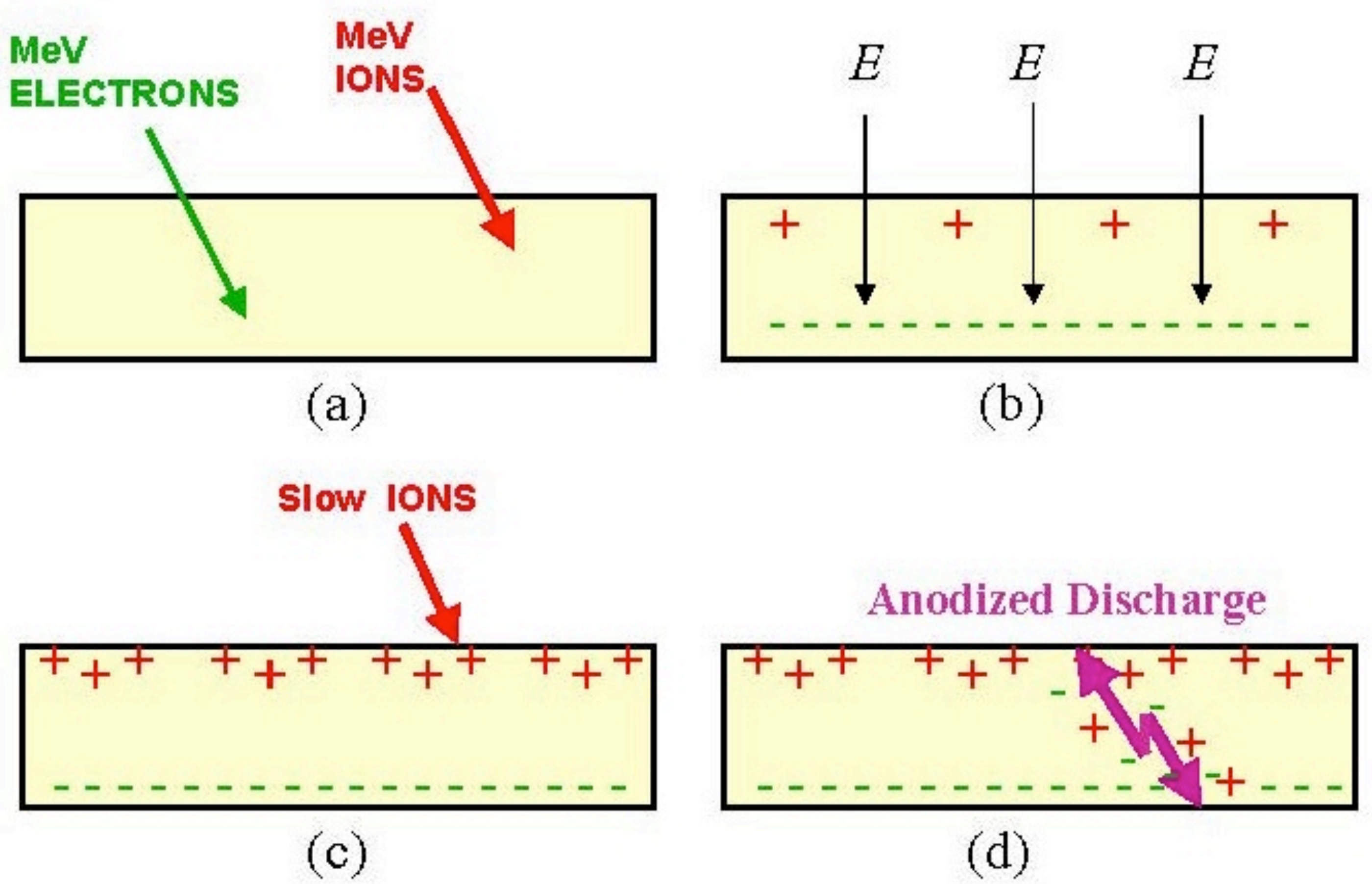




Potential of a sunlit Kapton patch as a function of time, when the blanketed satellite frame was fixed at -1000 V. An exponential curve was fit to the data, indicating behavior similar to that of an RC equivalent circuit.

Charging current to Kapton patch as a function of time. The blanketed satellite frame was fixed at -1000 V. An exponential curve was fit to the data, indicating behavior similar to that of an RC equivalent circuit.

Deep Dielectric Charging



(a) High energy electrons and ions bombardment. (b) Formation of deep electron layer. (c) Attraction of slow ions. (d) Anodized discharge. An impact by a high energy ion or meteoroid may trigger a discharge.

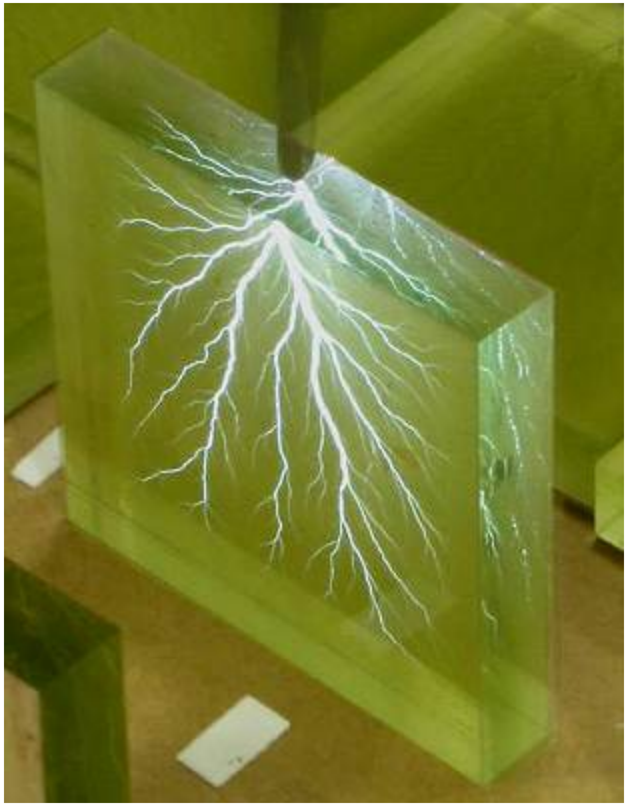
(From Lai et al., J. Spacecraft & Rockets, 39, 1, 2002.)

ESD: Results of Deep Dielectric Charging

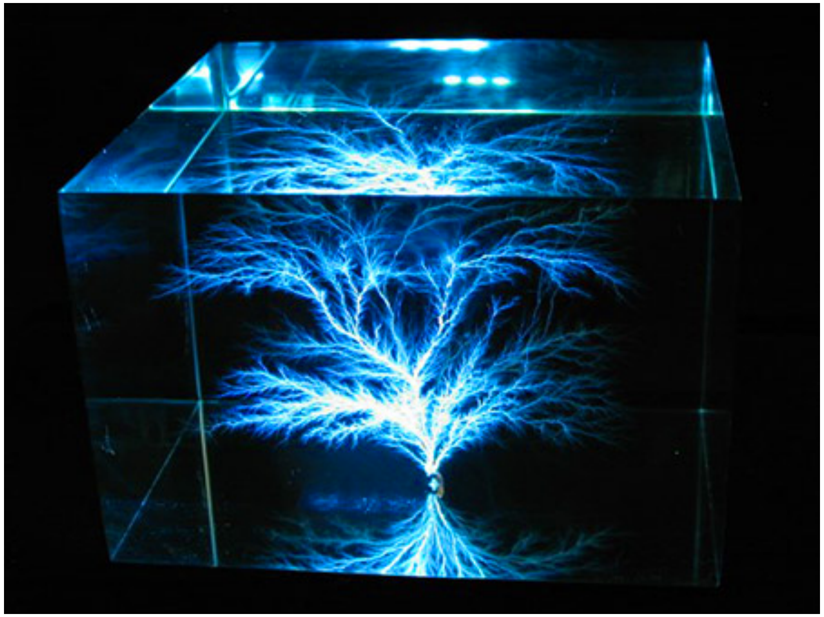
Possible Results of Deep Dielectric Charging

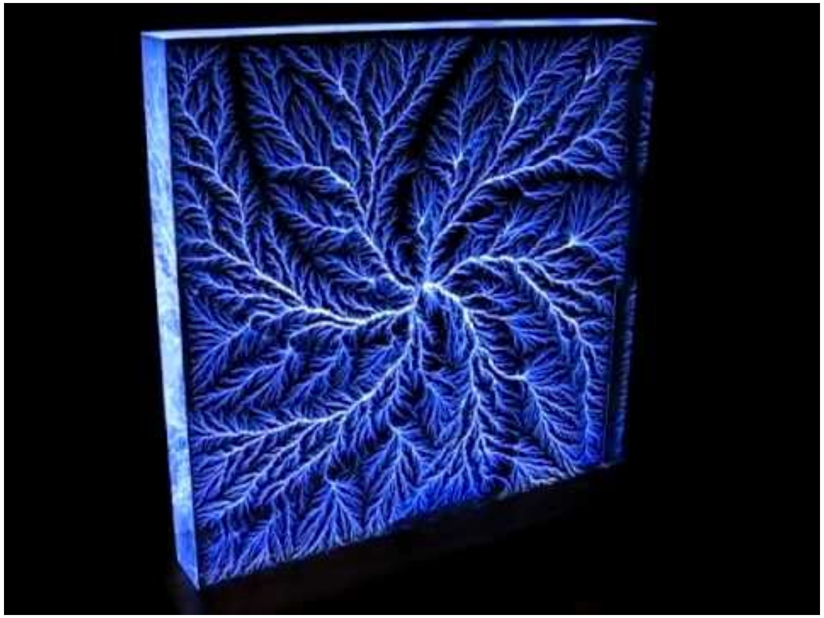
- Acrylic specimen is irradiated by energetic electrons
- Electrons accumulate inside, creating a cloud-like layer of negative electrical space charge.
- As space charge builds, the internal electrical field increases dramatically.
- Eventually, the immense electrical stress overcomes the dielectric strength of the acrylic, and electrons are ripped off
- Newly-freed electrons also accelerated by the electric field, ionizing even more acrylic molecules

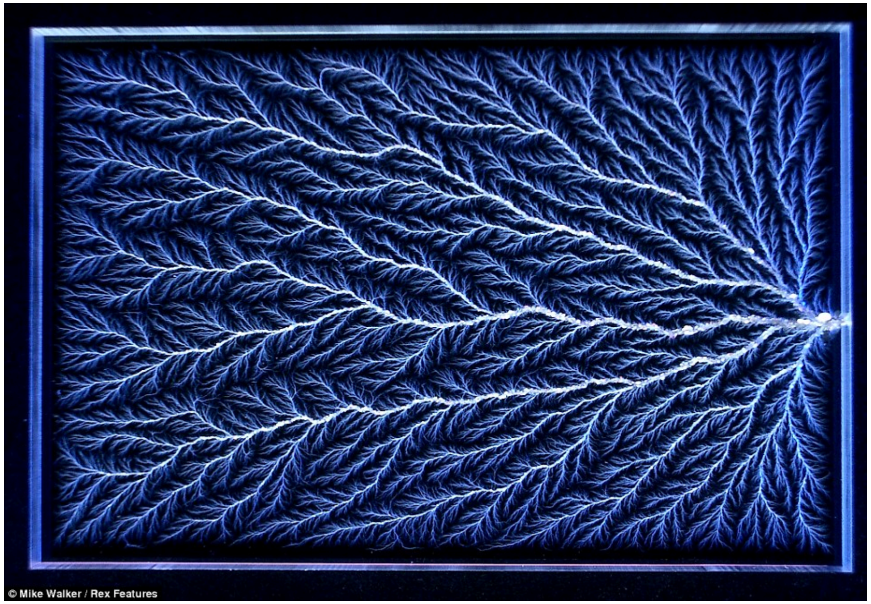
→ RUNAWAY BREAKDOWN (AKA Discharge)



ESD ART: Possible New Funding Source







SUMMARY

- The Spacecraft Charging Problem is a complex system of engineering and science (e.g. "What is ground?")
- Spacecraft charging comes in three basic forms: Surface frame, Surface differential, and Deep Dielectric.
- The surface charging electrons range in energy from 20 keV to 50 keV
- These electrons are most prevalent in GEO in the post-midnight sector
- Deep dielectric charging can result in static buildup of charge on surfaces of internal s/c components, such as cables and circuit components
- Surface charging mitigation is proven to be effective
- Deep dielectric charge mitigation remains to be a challenge

***** THANK YOU *****