Effects on Spacecraft Charging of Modification of Materials by Space Environment Interactions

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Abstract

While the effects on spacecraft charging from varying environmental conditions and from the selection of different construction materials have been studied extensively, modification of materials properties by the space plasma environment can also have profound effects on spacecraft charging. This presentation focuses on measurement methods and modeling employed to assess the effects of environment-induced material modifications on physical properties relevant to spacecraft charging simulations. It also reviews several specific studies in which environment-induced material modifications have significant impact on predicted spacecraft charging.

We present an overview of testing and modeling conducted by the Utah State University (USU) Materials Physics Group and other investigators to quantify the changes in charging, discharging and emission as materials properties are modified by variations in temperature, charge accumulation and electrostatic fields, radiation dose and damage, surface modifications including roughening and contamination, and the duration, rate and history of imposed environmental test conditions. Such changes have been shown to affect measurements of the following material properties: electron-, ion- and photon-induced electron emission yields, spectra, and yield decay curves; dark current and radiation induced conductivity; electrostatic discharge and charge decay curves; electron-induced surface charging, discharge and luminescence; and UV/VIS/NIR reflectivity, transmissivity, absorptivity, and emissivity. We also highlight a unified set of parameters and equations developed to relate these experimental methods to basic theories of electron transport.

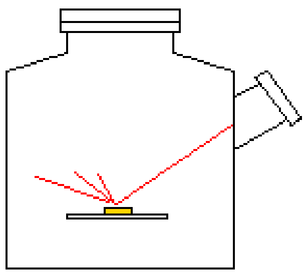
Abstract

Recent USU studies related to several specific missions have highlighted the operational effects of such environment-induced changes on material properties and ultimately on spacecraft charging. For example, studies of surface coatings for the 2005 concept of the Solar Probe Mission found that absolute and differential surface charging depended strongly on increased conductivity from higher temperatures and on radiation flux through enhanced charge accumulation and radiation induced conductivity; interplay between these effects led to the prediction of a maximum in charging at intermediate distances over the Probe's orbital range spanning from Jovian distances to within 4 solar radii of the Sun. Extreme demands dictated by the science objectives of the James Webb Space Telescope have placed particularly stringent requirements on materials and have potentially increased risks from spacecraft charging: low temperatures lead to low charge transport and dissipation rates; long mission duration, prolonged eclipse conditions, and inaccessibility for maintenance lead to extremely long charge accumulation times; large, unusually exposed surface areas lead to larger charge accumulation and increased probability of discharge; and very sensitive electronics and optics lead to low tolerance for charging, electrostatic discharge, and electron and photon emission. Extreme radiation dose rates and fluences for potential polar and Jovian missions have been found to substantially modify electron transport and to affect other properties such as reflectivity, emissivity and electrostatic discharge.

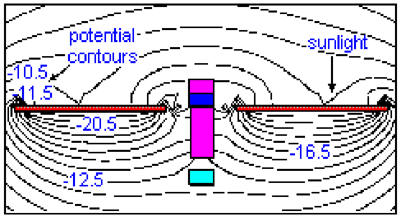
Given the increasingly demanding nature of space missions, there is clearly a need to extend our understanding of the dynamic nature of material properties that affect spacecraft charging and to expand our knowledgebase of materials' responses to specific environmental conditions so that we can more reliably predict the long term response of spacecraft to their environment.

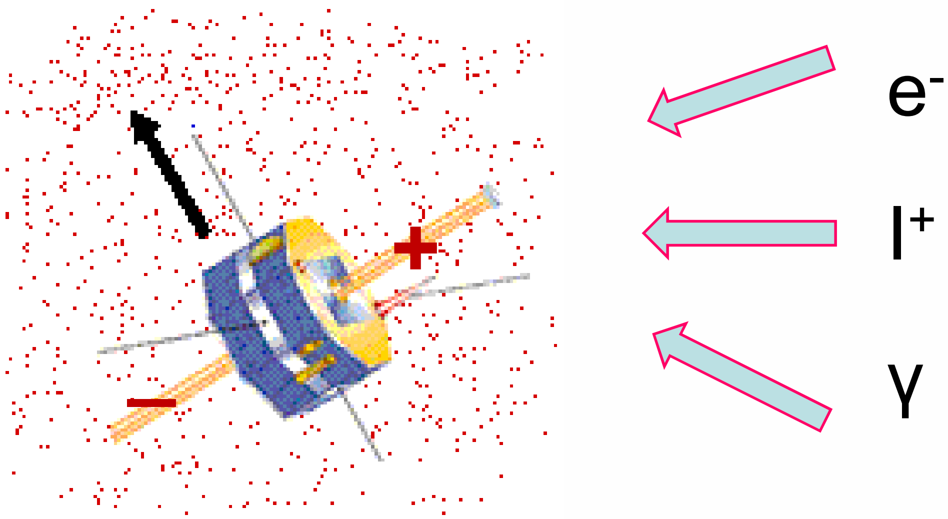
Let us assume a spherical satellite….

A simplified approach to spacecraft charging modeling…



Materials Properties





Spacecraft Potential Models

Satellite Moving through Space

Space Plasma Environment

What do you need to know about the materials properties?

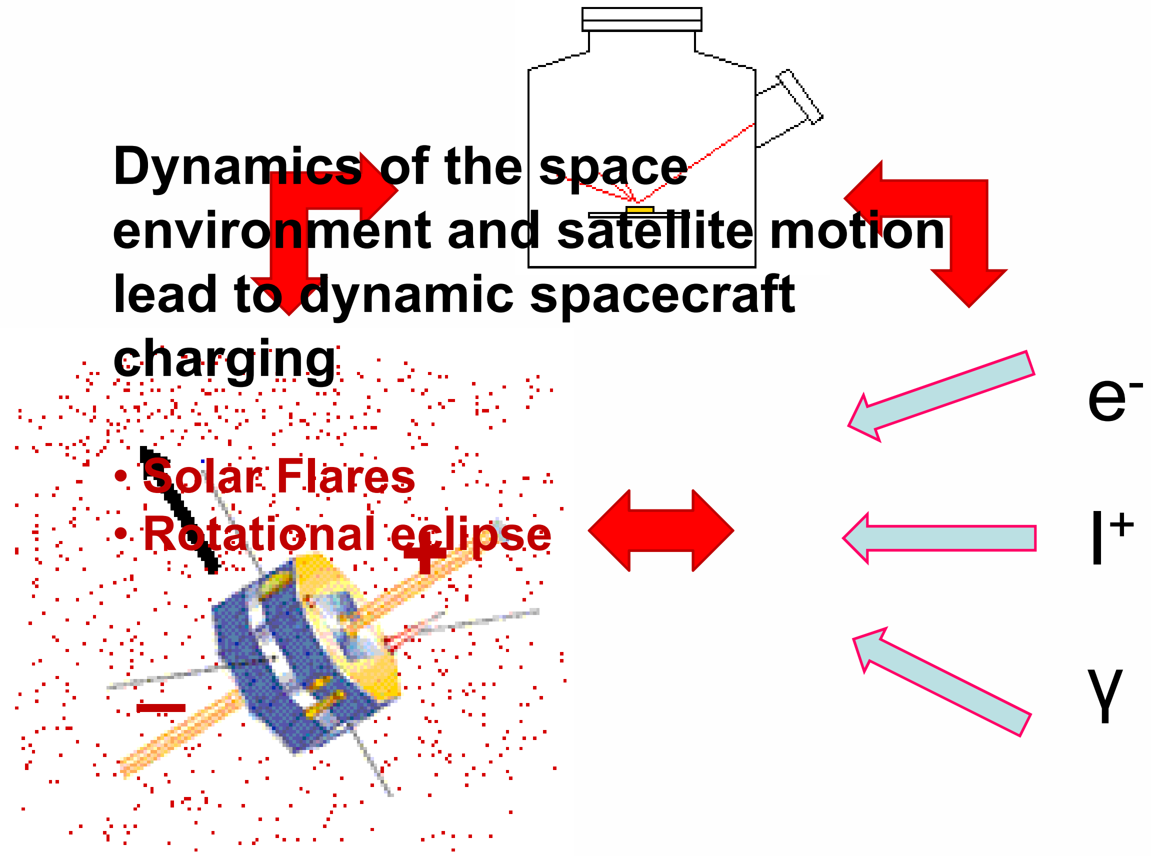
Charge Accumulation

- **Electron yields**
- **Ion yields**
- **Photoyields**

Charge Transport

- **Conductivity**
- **RIC**
- **Dielectric Constant**
- **ESD**

As functions of materials species, flux, and energy.



Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging

- **Solar Flares**
- **Rotational eclipse**

Complex dynamic interplay between space environment, satellite motion, and materials properties

Dale Ferguson's "New Frontiers in Spacecraft Charging"

#1 Non-static Spacecraft Materials Properties
#2 Non-static Spacecraft Charging Models

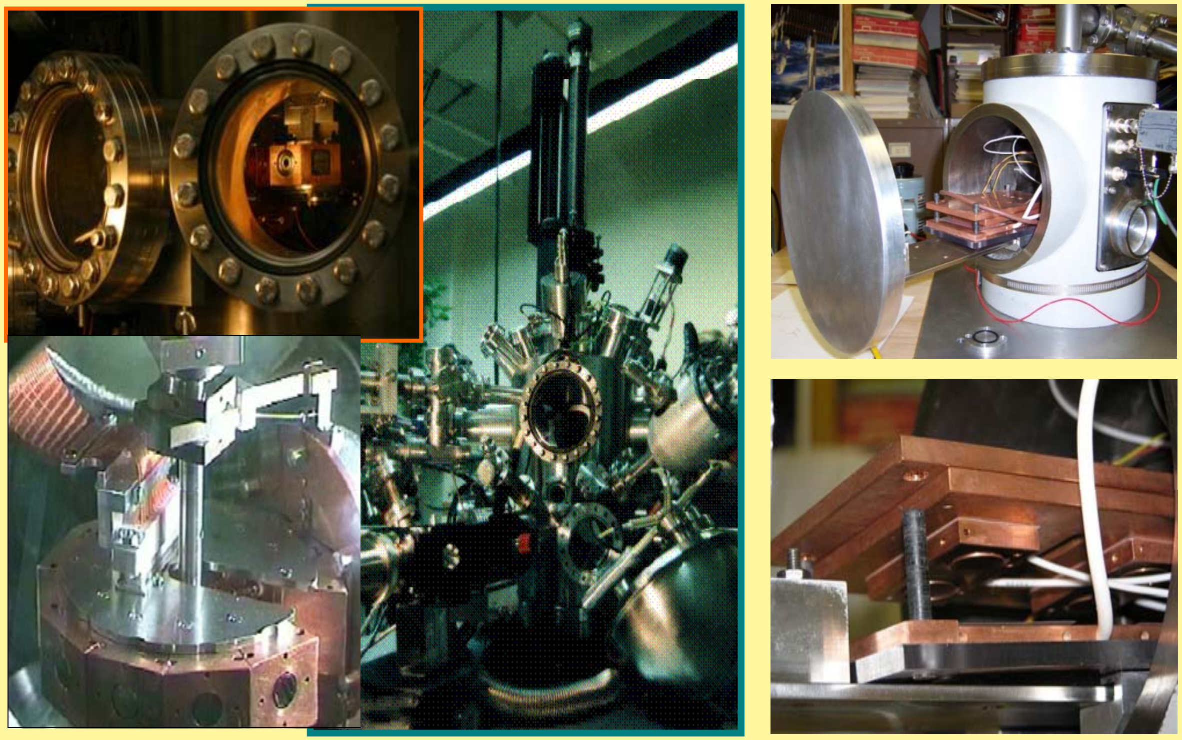
These result from the complex dynamic interplay between space environment, satellite motion, and materials properties

Specific focus of this talk is the change in materials properties as a function of:

- **Time (Aging), t**
- **Temperature, T**
- **Accumulated Energy (Dose), D**
- **Dose Rate, Ď**
- **Accumulated Charge, ΔQ or ΔV**
- **Charge Profiles, Q(z)**
- **Charge Rate (Current), Ŏ**
- **Conductivity Profiles, σ(z)**

Complex dynamic interplay between space environment, satellite motion, and materials properties

USU Studies



Environment Conditions ↔ Materials Conditions ↔ Materials Properties ↔ Spacecraft Charging

“New Frontiers” from a Materials Perspective

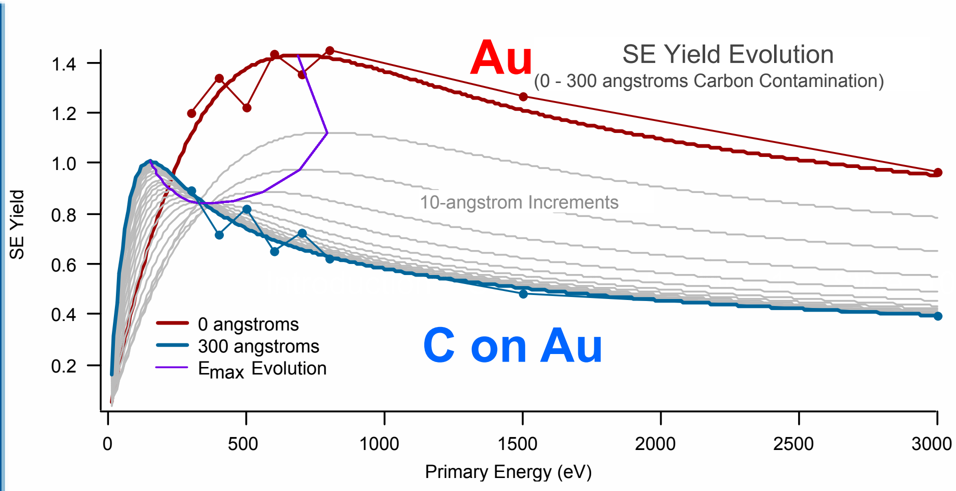
Consider 5 Cases of Dynamical Change in Materials:

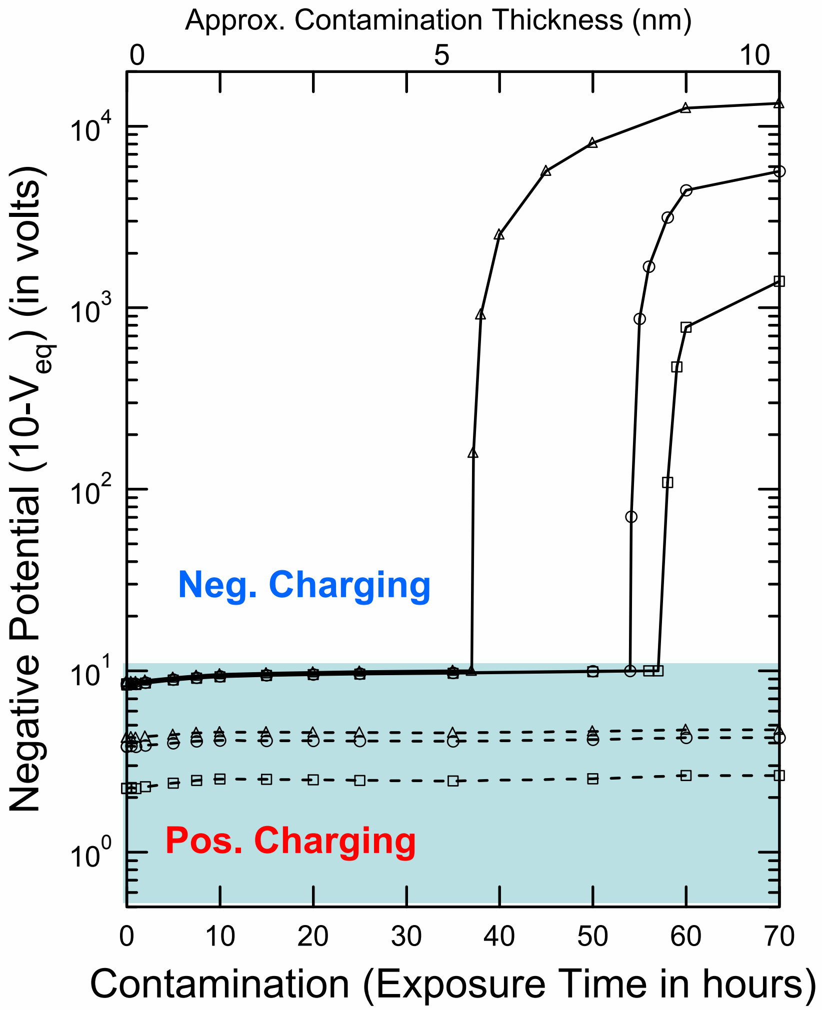
- Contamination and Oxidation
- Surface Modification
- Radiation Effects (and t)
- Temperature Effects (and t)
- Radiation and Temperature Effects

Case I: Evolution of Contamination and Oxidation

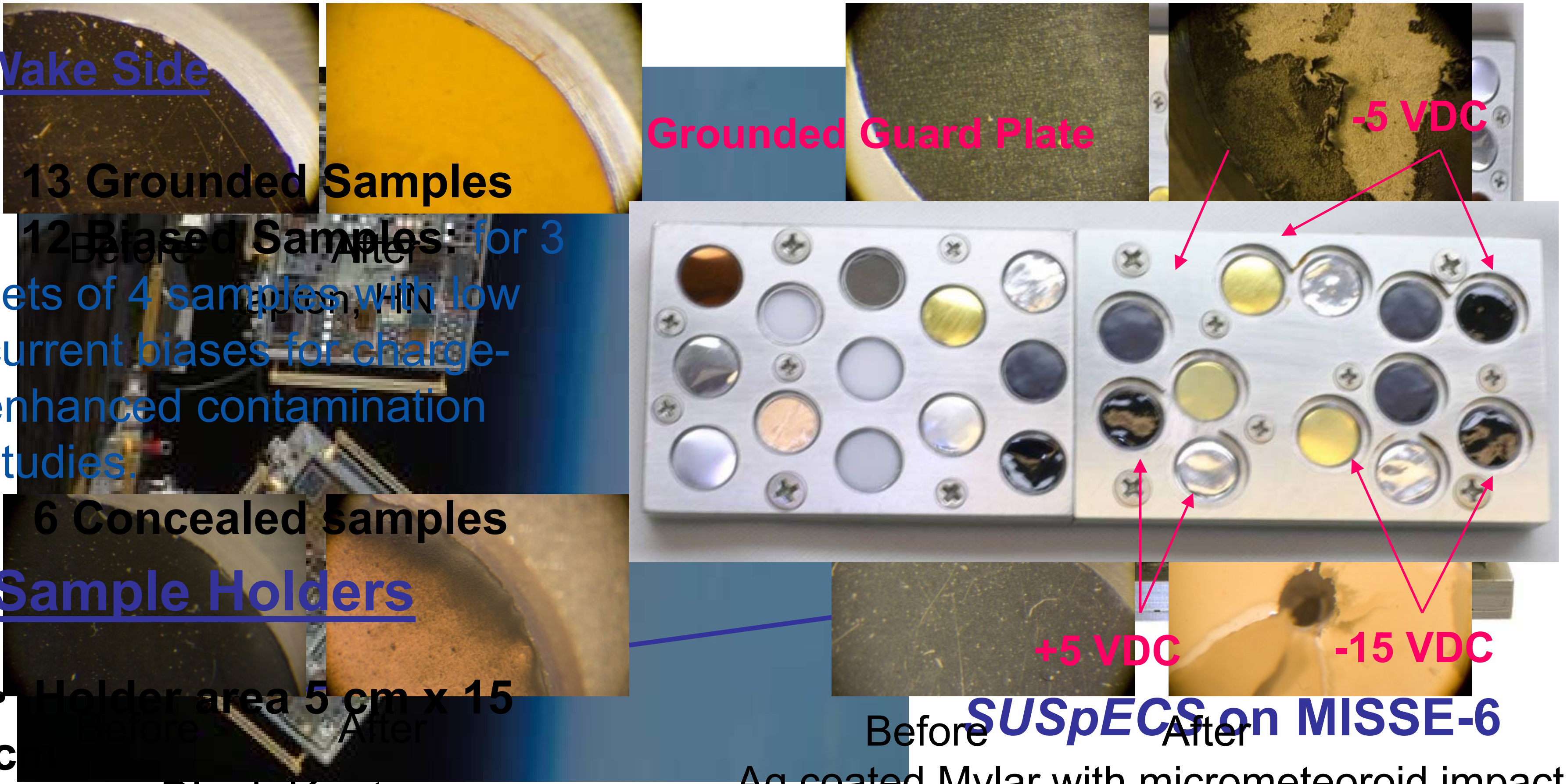
“All spacecraft surfaces are eventually carbon…”
--C. Purvis

This led to lab studies by Davies, Kite, and Chang





Case I: Evolution of Contamination and Oxidation



Ag coated Mylar with micrometeoroid impact

Wake Side

- **13 Grounded Samples**
- **12 Biased Samples:** for 3 sets of 4 samples with low current biases for charge-enhanced contamination studies.
- **6 Concealed samples**

Sample Holders

- **Holder area 5 cm x 15 cm**
- **9 mm diameter exposed sample area**

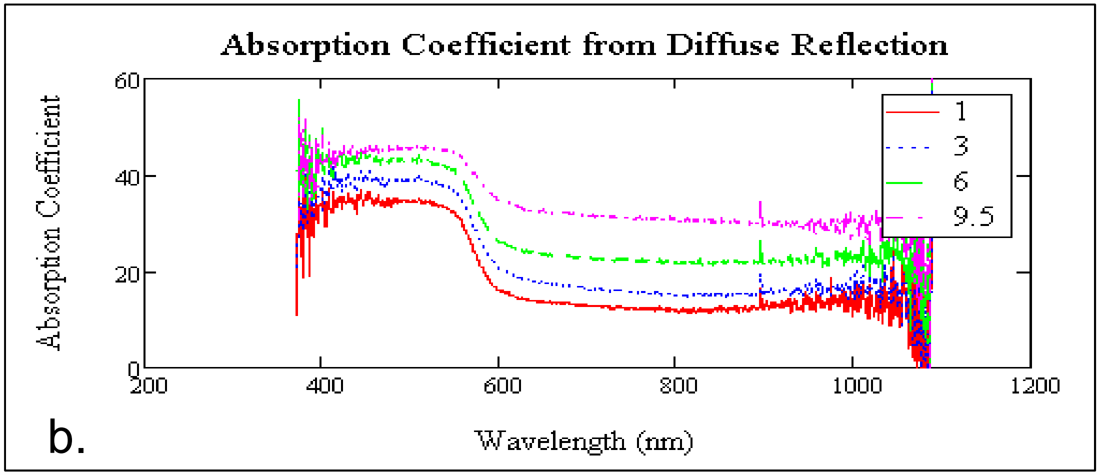
SUSpECS on MISSE-6

See poster by Dennison, Evans and Prebola

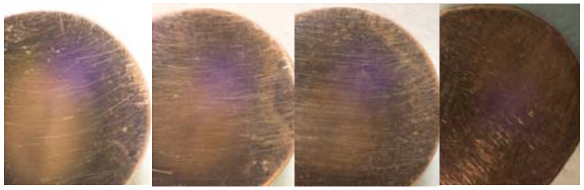
Case II: Surface Modification

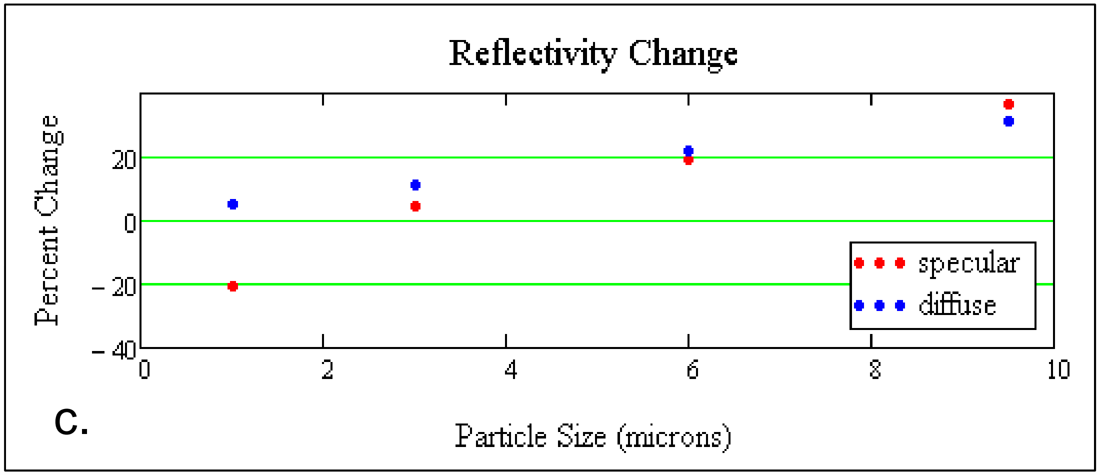
Reflectivity changes with surface roughness

See poster by Evans



Successive stages of roughenied of Cu





Cases I and II: Reflectivity as a Feedback Mechanism

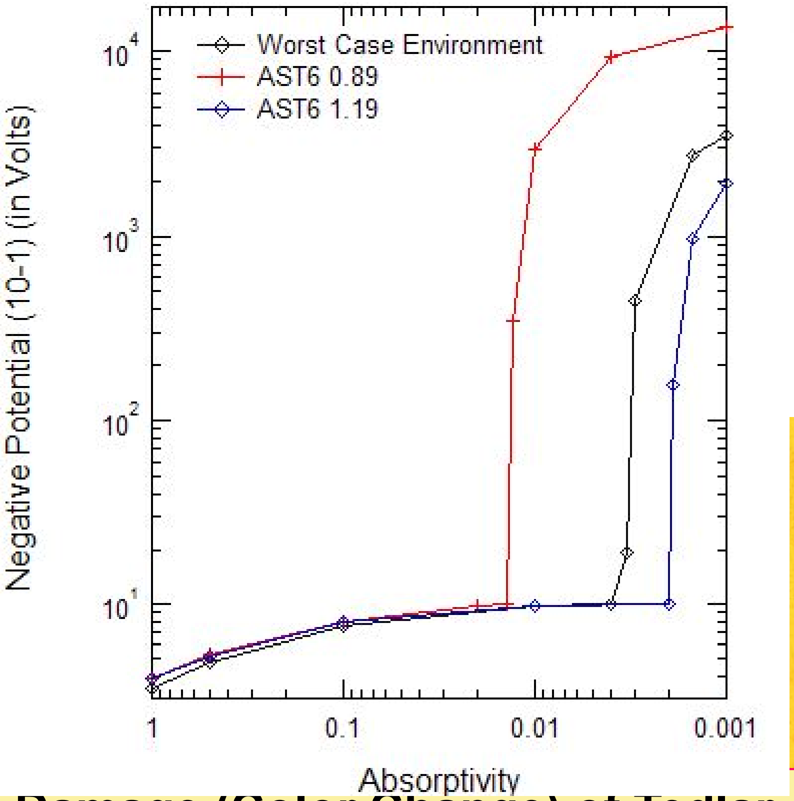
Reflectivity changes with surface roughness and contamination

Reflect→Charging→Contamination

Reflect→Emissivity→Temp→Contamination

Charging→ Reflectivity

Radiation → Reflect→Emissivity→Temp→Contamina



Radiation Damage (Color Change) of Tedlar

B. Mihaljcic in Guild's 11th SCTS Talk

See Lai & Tautz, 2006 & Dennison 2007

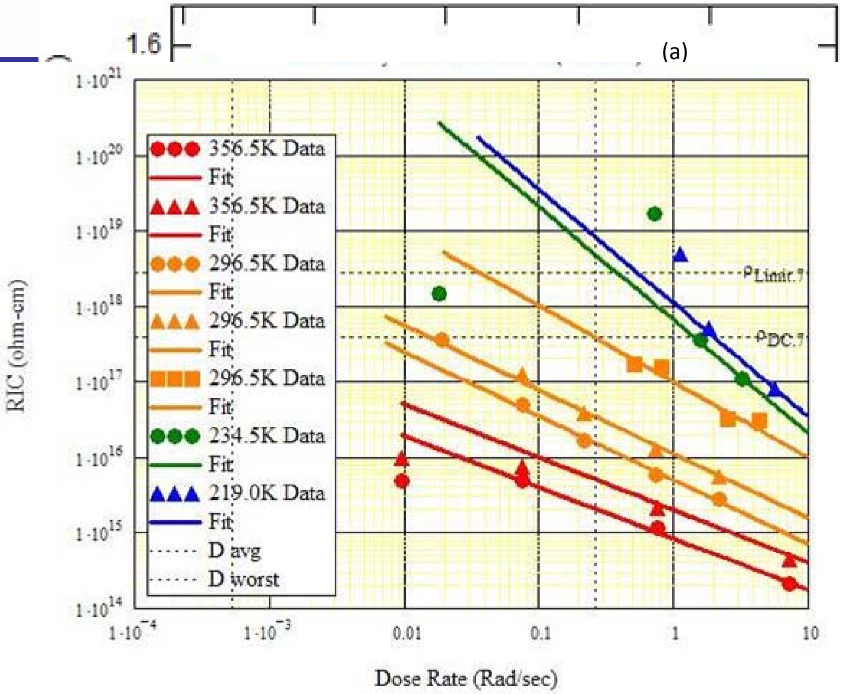
JWST Structure: Charging vs. Ablation

Case III: Radiation Effects

Large Dosage (>10^8 Rad)

Medium Dosage (>10^7 Rad)

Low Dose Rate (>10^0 Rad/s)



“…Earth is for Wimps…” H. Garrett

Examples:

Examples: RBSP, MMS, JUNO, JGO/JEO

“…auroral fields may cause significant surface charging…” H. Garrett

Radiation induced Conductivity (RIC)

Mechanical Modification of Electron Transport and Emission Properties

Temperature dependant

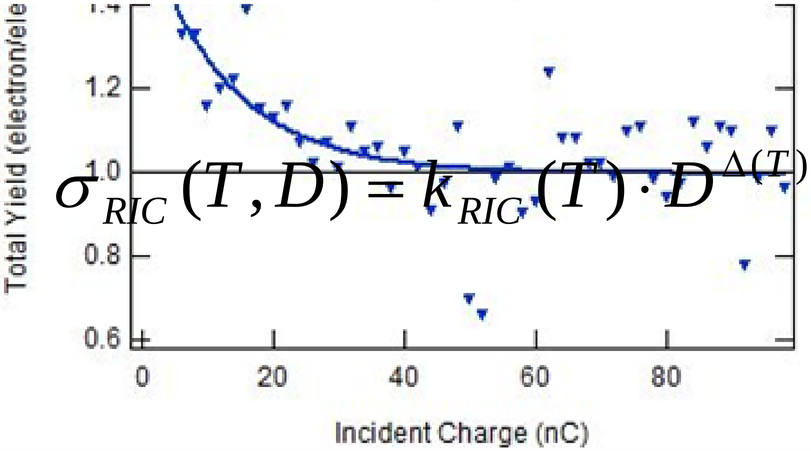
Examples: RBSP, JUNO, JGO/JEO

Caused by bondbreaking and trap creation

(see A Sim posters)

Mechanical and Optical Materials Damage

(see Hoffmann & A Sim posters)



$$\sigma_{RIC}(T,D) = k_{RIC}(T) \cdot D^{\Delta(T)}$$

Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Transport

- **Conductivity**
- **RIC**
- **Dielectric Constant**
- **ESD**

Examples:

IR and X-Ray Observatories
JWST, WISE, WMAP, Spitzer, Herscel, IRAS, MSX, ISO, COBE, Planck

Outer Planetary Mission
Galileo, Juno, JEO/JGO. Cassini, Pioneer, Voyager,

Inner Planetary Mission
SPM, Ulysses, Magellan, Mariner

(see A Sim and C Sim posters)

Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Transport

- Conductivity
- RIC
- Dielectric Constant
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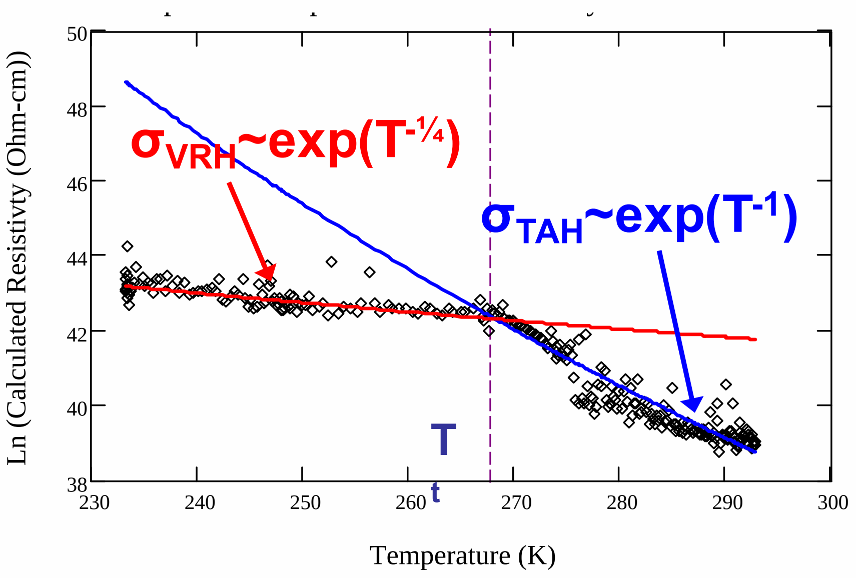
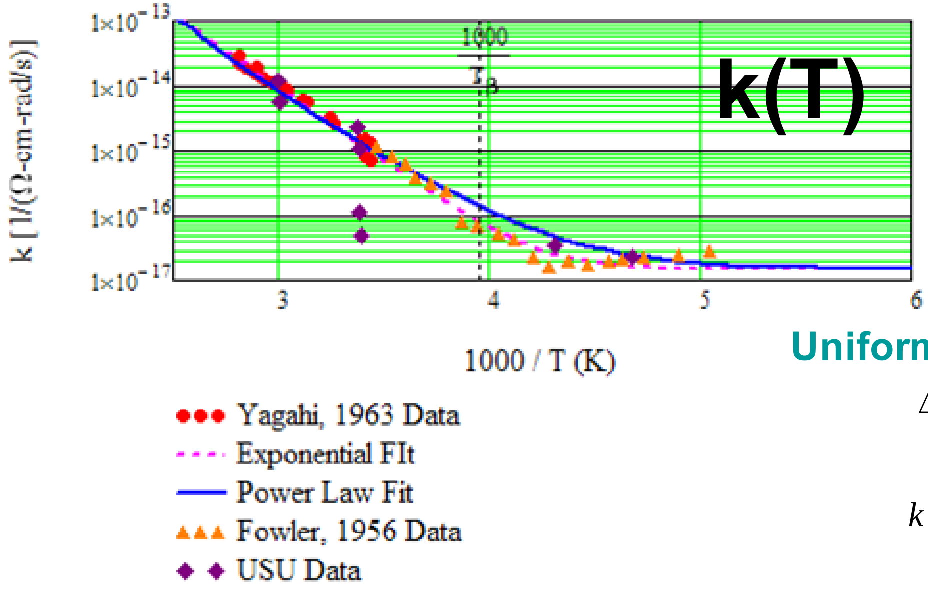




Uniform Trap Density

$$\Delta(T)\rightarrow 1$$

$$k(T)\rightarrow k_{RICo}$$

Exponential Trap Density

$$\Delta(T)\rightarrow {T_c}/{T+T_c}$$

$$k(T)\rightarrow k_{RIC1}\left[2\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2}\left(\frac{m_e^* m_h^*}{m_e\, m_e}\right)^{3/4}\right]^{\frac{T}{T+T_c}}$$

$$\sigma_{RIC}(T,D)=k_{RIC}(T)\cdot D^{\Delta(T)}$$

Case IV: Temperature Effects—JWST

JWST

Very Low Temperature
Virtually all insulators go to infinite resistance—perfect charge integrators

Long Mission Lifetime (10-20 yr)
No repairs
Very long integration times

Large Sunshield
Large areas
Constant eclipse with no photoemission

Large Open Structure
Large fluxes
Minimal shielding

Variation in Flux
Large solar activity variations
In and out of magnetotail

Complex, Sensitive Hardware
Large sensitive optics
Complex, cold electronics

Case V: Temperature and Dose Effects

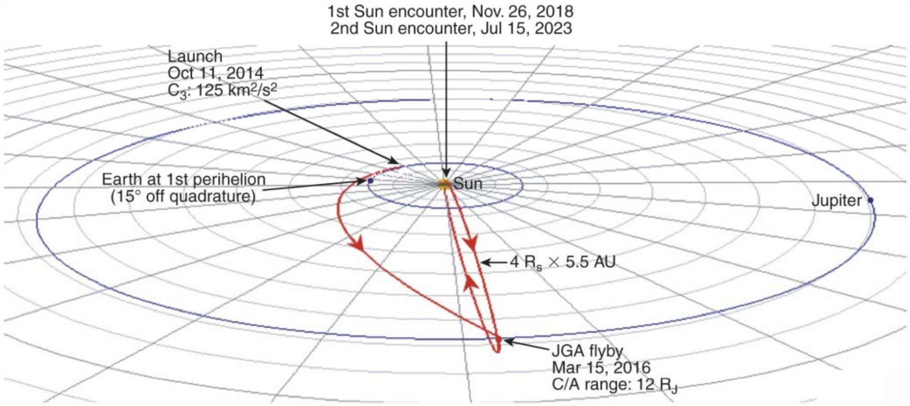


Figure 4-1. Solar Probe mission summary.

WideTemperature Range

<100 K to >1800 K

Wide Dose Rate Range

Five orders of magnitude variation!

Wide Orbital Range

Earth to Jupiter Flyby

Solar Flyby to 4 R_s

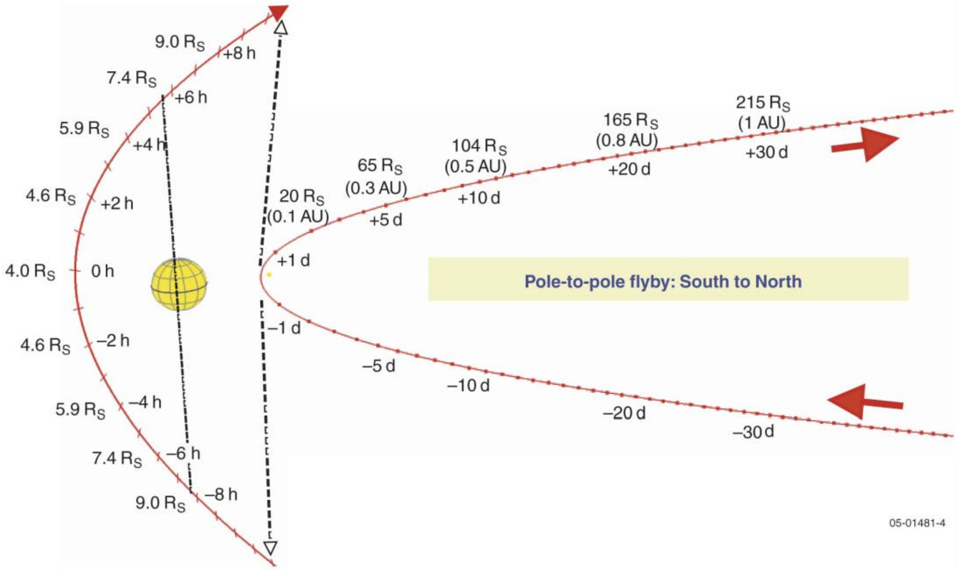
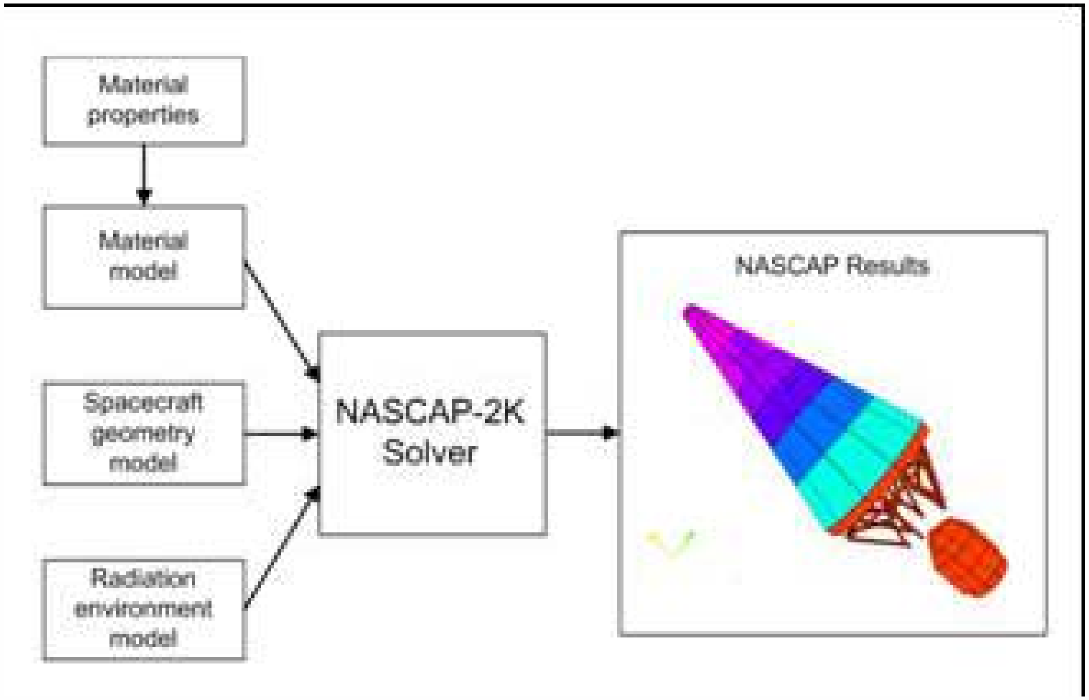


Figure 4-2. Solar encounter trajectory and timeline. Science operations begin at perihelion —5 days (65 R_s) and continue until perihelion +5 days.

Case V: Temperature and Dose Effects

"We anticipate significant thermal and charging issues."

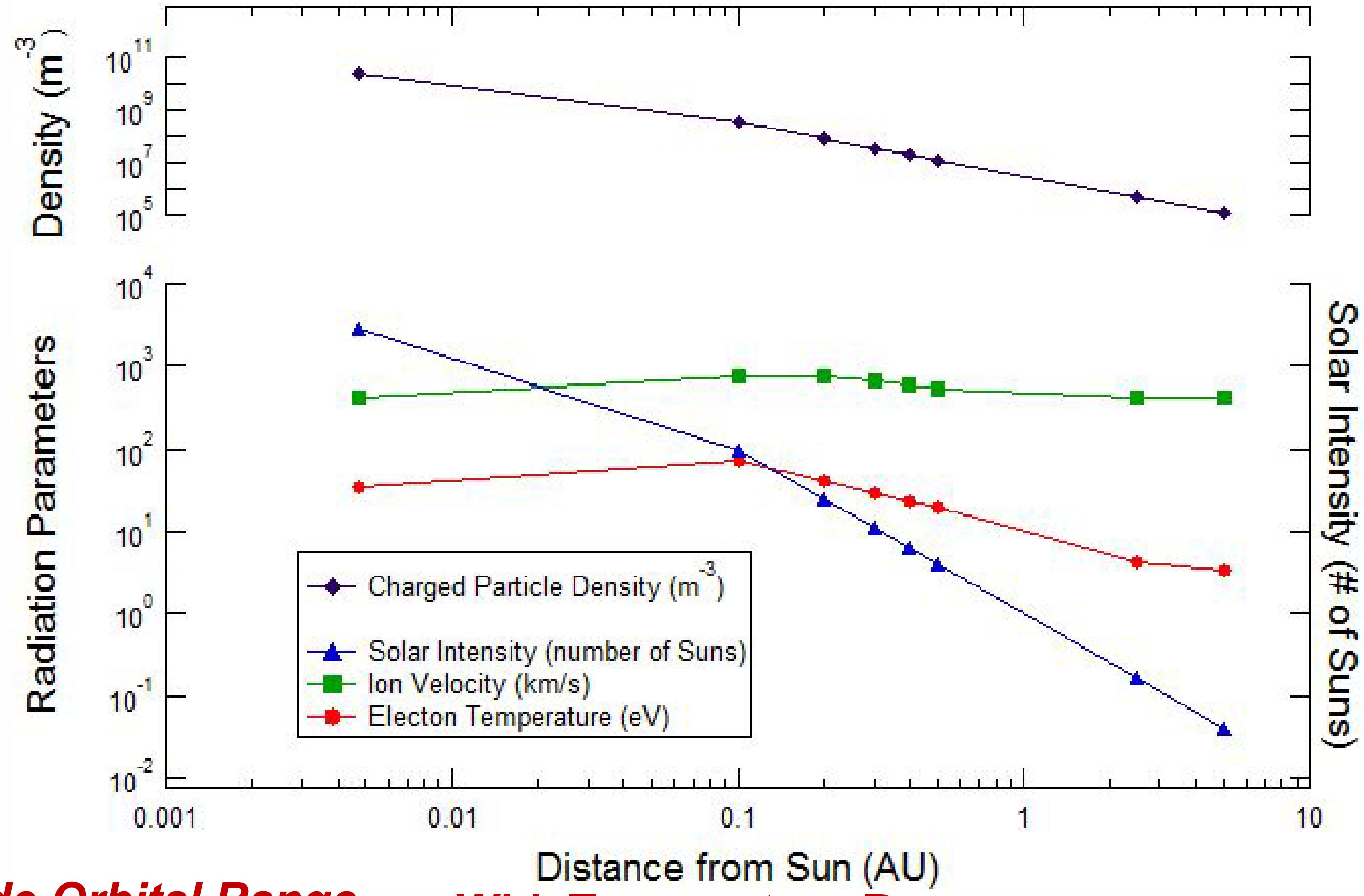
J. Sample



Charging Study by Donegan, Sample, Dennison and Hoffmann

(See Donegann Poster for update)

Case V: Temperature and Dose Effects



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Earth to Jupiter Flyby

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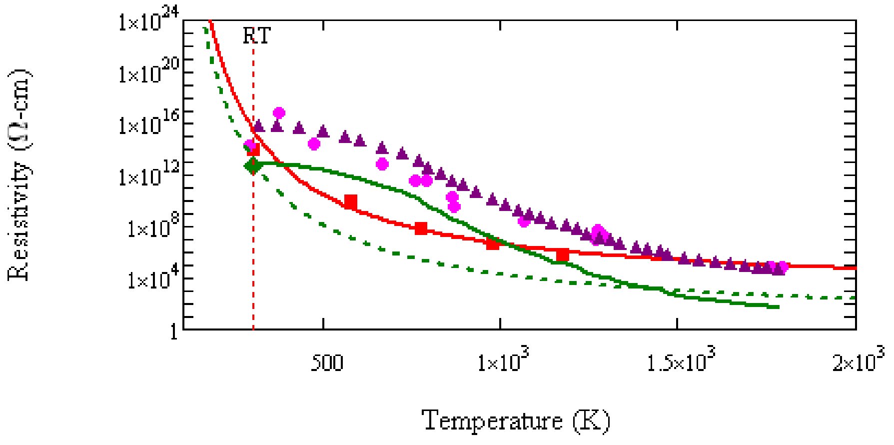
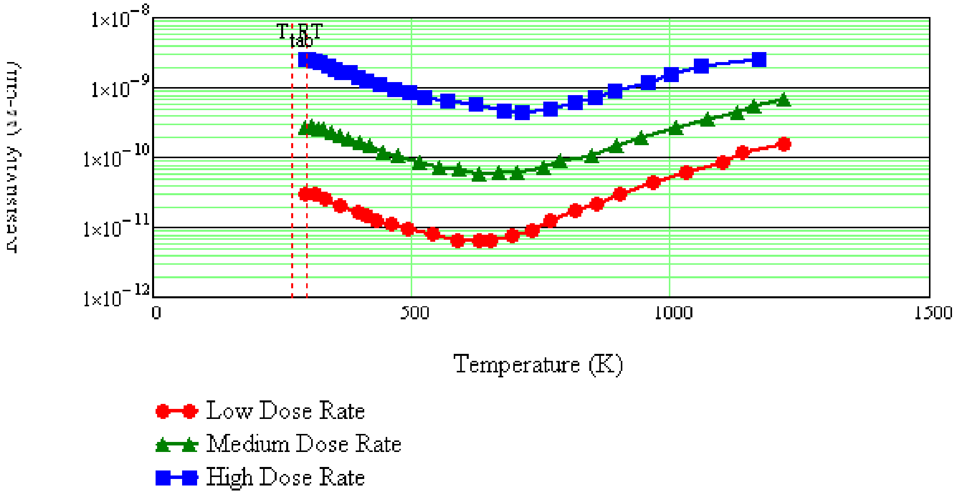
Five orders of magnitude variation!

Case V: Temperature and Dose Effects

Dark Conductivity vs T



RIC vs T



Dark Conductivity

$$\sigma_{DC}(T) = \sigma_o^{DC}\, e^{-E_o / k_B T}$$

RIC

$$\sigma_{\mathrm{RIC}}(\mathrm{T}) = \mathrm{k}_{\mathrm{RIC}}(T)\, \dot{D}^{\Delta(T)}$$

Dielectric Constant

$$\varepsilon_r(T) = \varepsilon_{RT} + \Delta_\varepsilon (T - 298\,K)$$

Electrostatic Breakdown

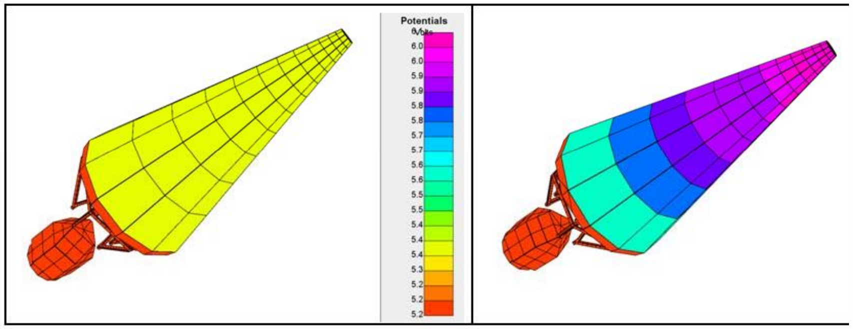
$$E_{ESD}(T) = E_{ESD}^{RT}\, e^{-\alpha_{ESD}(T-298\,K)}$$

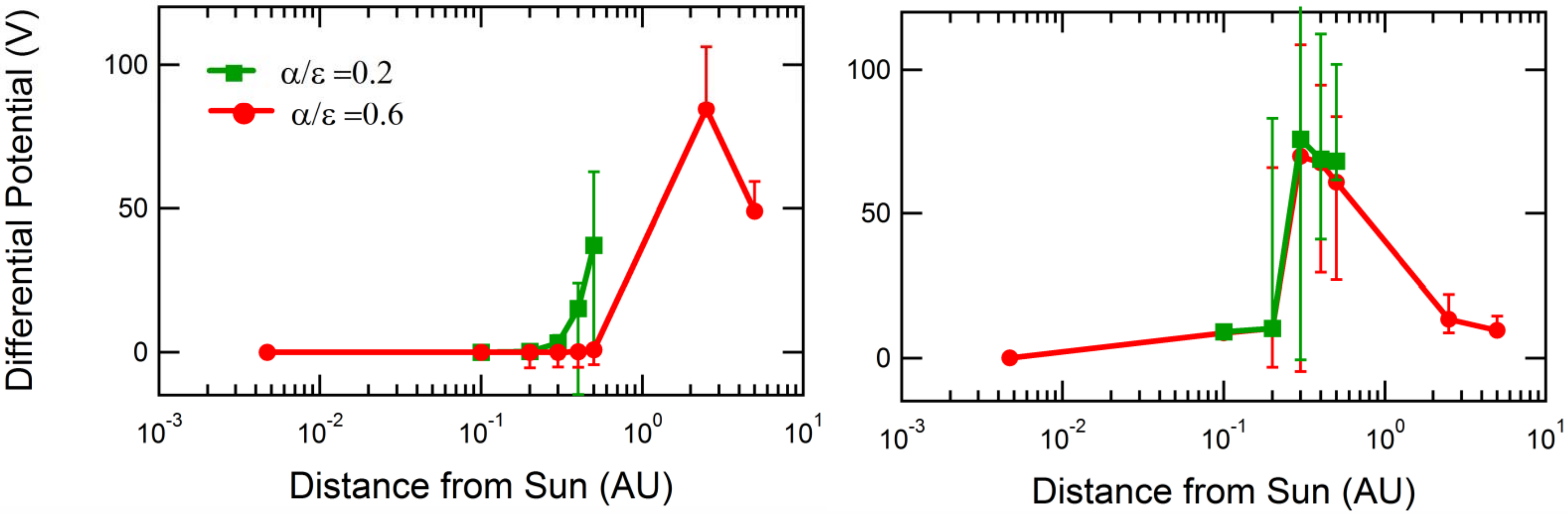
Case V: Temperature and Dose Effects

A peak in charging at ~0.3 to 2 AU

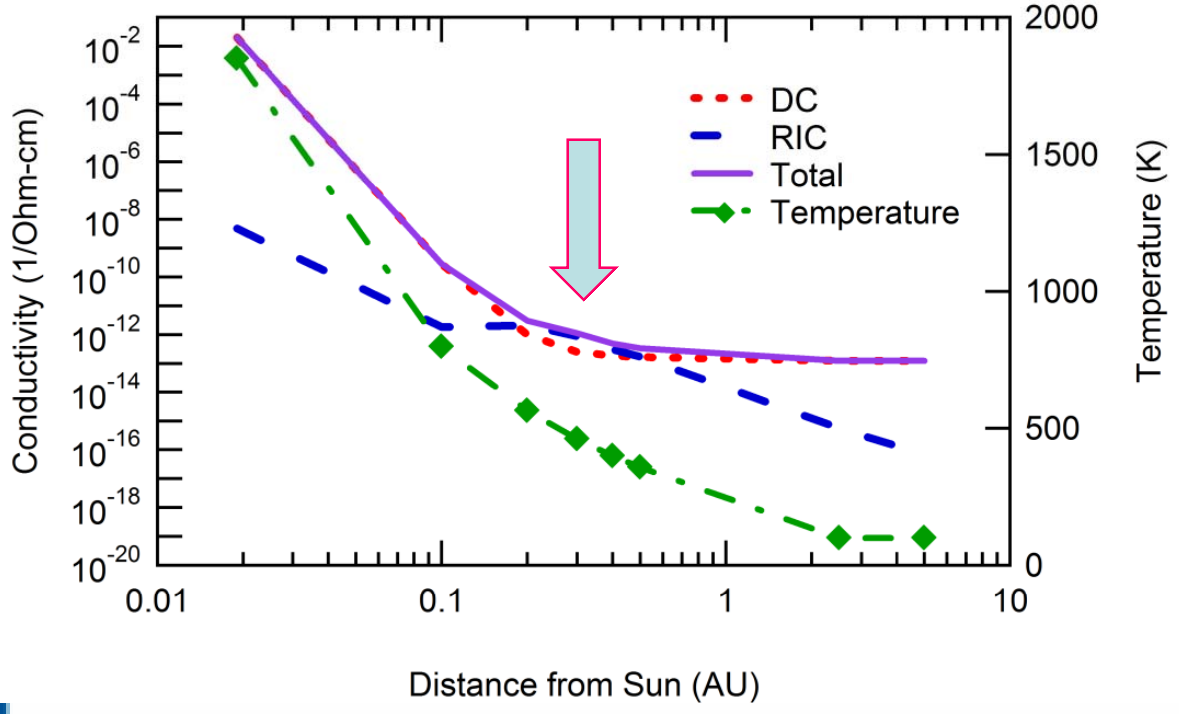
"…Curiouser and curiouser…

--Alice





Case V: Temperature and Dose Effects



General Trends

Dose rate decreases as ~r^{-2}

T decreases as ~e^{-r}

σ_{DC} decreases as ~ e$^{-1/T}$

σ_{RIC} decreases as ~ e$^{-1/T}$
and decreases as ~r^{-2}

A fascinating trade-off

- *Charging increases from increased dose rate at closer orbits*
- *Charge dissipation from T-dependant conductivity increases faster at closer orbits*

Conclusions

- Satellites are not cows…

  Complex satellites require:
  - Complex materials configurations
  - More power
  - Smaller, more sensitive devices
  - More demanding environments

- There are numerous clear examples where accurate dynamic charging models require accurate dynamic materials properties

- It is not sufficient to use static (BOL or EOL) materials properties

- Enivronment/Materials Modification feedback mechanisms can cause a whole herd of new problems

Acknowledgements

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