The Dynamic Interplay Between Spacecraft Charging, Space Environment Interactions and Evolving Materials

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AFRL
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Ball Aerospace
Orbital

National Research Council

USU Materials Physics Group
Nothing endures but change.

--Heraclitus of Ephesus  
(c. 495 BC)

Shit Happens.....
A simplified approach to spacecraft charging modeling…

- **Materials Properties**
  - **Spacecraft Potential Models**
  - **Satellite Moving through Space**
  - **Space Plasma Environment**

- **Mechanisms**:
  - Electron (e\(^{-}\))
  - Ion (I\(^{+}\))
  - Momentum (m)

Diagram illustrating the interaction between a spacecraft and the space plasma environment, highlighting the importance of considering materials properties and potential models for accurate modeling. 

[Diagram showing the movement of a satellite through space with annotations for electron and ion interactions, as well as momentum considerations.]
The Space Environment

Solar wind and Earth's magneto-sphere structure.

Typical Space Electron Flux Spectra [Larsen].

Incident Fluxes of:

- Electrons
- Ions
- Photons
- Particles

Solar Electro-magnetic Spectrum.
Non-static Spacecraft Materials Properties

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, position, energy, and charge:

- Time (Aging), $t$
- Energy
  - Temperature, $k_B T$
  - Deposited Energy (Dose), $D$
  - Energy Deposition (Dose) Rate, $\dot{D}$
- Charge
  - Accumulated Charge, $\Delta Q$ or $\Delta V$
  - Charge Profiles, $Q(z)$
  - Charge Rate (Current), $\dot{Q}$
  - Conductivity Profiles, $\sigma(z)$
What do you need to know about the materials properties?

Charging codes such as NASCAP-2K or SPENVIS and NUMIT2 or DICTAT require:

**Charge Accumulation**
- Electron yields
- Ion yields
- Photoyields
- Luminescence

**Charge Transport**
- Conductivity
- RIC
- Dielectric Constant
- ESD
- Range

ABSOLUTE values as functions of materials species, flux, fluence, and energy.

### Table 2.1. Parameters for NASCAP Materials Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Relative dielectric constant; ( \varepsilon_r ) (Input as 1 for conductors)</td>
<td>1, NA</td>
</tr>
<tr>
<td>[2] Dielectric film thickness; ( d )</td>
<td>0 m, NA</td>
</tr>
<tr>
<td>[3] Bulk conductivity; ( \sigma_o ) (Input as -1 for conductors)</td>
<td>-1; ((4.26 \pm 0.04) \cdot 10^7 \text{ohm}^{-1} \cdot \text{m}^{-1})</td>
</tr>
<tr>
<td>[4] Effective mean atomic number ( &lt;Z_{\text{eff}} &gt; )</td>
<td>50.9 \pm 0.5</td>
</tr>
<tr>
<td>[5] Maximum SE yield for electron impact; ( \delta_{\text{max}} )</td>
<td>1.47 \pm 0.01</td>
</tr>
<tr>
<td>[6] Primary electron energy for ( \delta_{\text{max}} ); ( E_{\text{max}} )</td>
<td>((0.569 \pm 0.07) \text{keV})</td>
</tr>
<tr>
<td>[7] First coefficient for bi-exponential range law, ( b_1 )</td>
<td>1 Å, NA</td>
</tr>
<tr>
<td>[8] First power for bi-exponential range law, ( n_1 )</td>
<td>1.39 \pm 0.02</td>
</tr>
<tr>
<td>[9] Second coefficient for bi-exponential range law, ( b_2 )</td>
<td>0 Å</td>
</tr>
<tr>
<td>[10] Second power for bi-exponential range law, ( n_2 )</td>
<td>0</td>
</tr>
<tr>
<td>[11] SE yield due to proton impact ( \delta''(1\text{keV}) )</td>
<td>0.3364 \pm 0.0003</td>
</tr>
<tr>
<td>[12] Incident proton energy for ( \delta''<em>{\text{max}} ); ( E''</em>{\text{max}} )</td>
<td>((1238 \pm 30) \text{keV})</td>
</tr>
<tr>
<td>[13] Photoelectron yield, normally incident sunlight, ( j_{\text{pho}} )</td>
<td>((3.64 \pm 0.4) \cdot 10^5 \text{A} \cdot \text{m}^{-2})</td>
</tr>
<tr>
<td>[14] Surface resistivity; ( \rho_s ) (Input as -1 for non-conductors)</td>
<td>-1 \text{ohms-square}^{-1}, NA</td>
</tr>
<tr>
<td>[15] Maximum potential before discharge to space; ( V_{\text{max}} )</td>
<td>10000 \text{V}, NA</td>
</tr>
<tr>
<td>[16] Maximum surface potential difference before dielectric breakdown discharge; ( V_{\text{punch}} )</td>
<td>2000 \text{V}, NA</td>
</tr>
<tr>
<td>[17] Coefficient of radiation-induced conductivity, ( \sigma_r ; k )</td>
<td>0 \text{ohms}^{-1} \cdot \text{m}^{-2}, NA</td>
</tr>
<tr>
<td>[18] Power of radiation-induced conductivity, ( \sigma_r ; \Delta )</td>
<td>0, NA</td>
</tr>
</tbody>
</table>
USU Experimental Capabilities

Absolute Yields

• SEE, BSE, emission spectra , (<20 eV to 30 keV)

• Angle resolved electron emission spectra

• Photoyield (~160 nm to 1200 nm)

• Ion yield (He, Ne, Ar, Kr, Xe; <100 eV to 5 keV)

• Cathodoluminescence (200 nm to 5000 nm)

• No-charge “Intrinsic” Yields

• T (<40 K to >400 K)

• Conductivity (<10^{-22} [ohm-cm]^{-1})

• Surface Charge (<1 V to >15 kV)

• ESD (low T, long duration)

• Radiation Induced Conductivity (RIC)

• Multilayers, contamination, surface modification

• Radiation damage

• Sample Characterization
Consider 6 Cases of Dynamical Change in Materials:

I. Contamination and Oxidation
II. Surface Modification
III. Radiation Effects (and t)
IV. Temperature Effects (and t)
V. Radiation and Temperature Effects
VI. Multilayer/Nanocomposite Effects
“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

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

Before
After

Grounded Guard Plate
-5 VDC

Before
After

SUSpECS on MISSE-6

Grounded Guard Plate
-15 VDC

Before
After

Black Kapton

Ag coated Mylar with micrometeoroid impact

See poster by Dennison, Evans and Prebola
Case II: Surface Modification

Diffuse and Specular Reflectivity changes with surface roughness

Successive stages of roughened Cu

View photon (electron) scattering as a competition for deposited energy and charge:

- Reflectivity—γ out  (Luminescence—γ out )
- Photoyield—e out  (SE/BSE—e out )
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 → Contamination

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: RBSP, MMS, JUNO, JGO/JEO

“...auroral fields may cause significant surface things...” H. Garrett

Mechanical Modification of Electron Transport and Emission Properties

Caused by bondbreaking and trap creation

Examples: RBSP, JUNO, JGO/JEO (see Hoffmann & A Sim posters)

Mechanical and Optical Materials Damage

(see A Sim posters)
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
Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Transport
- Conductivity
- RIC
- Dielectric Constant
- ESD

\[ k(T) \]

\[ \sigma_{VRH} \sim \exp(T^{-1/4}) \]
\[ \sigma_{TAH} \sim \exp(T^{-1}) \]

Uniform Trap Density
\[ \Delta(T) \to 1 \]
\[ k(T) \to k_{RIC0} \]
\[ \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \]

Exponential Trap Density
\[ \Delta(T) \to \frac{T_c}{T + T_c} \]
\[ k(T) \to k_{RICI} \]
\[ k(T) = \frac{2 \left( \frac{m_e^* m_h^*}{2 \pi \hbar^2} \right)^{3/2} \left( \frac{m_e^* m_h^*}{m_e m_h} \right)^{3/4}}{T + T_c} \]

\( T_c \) and \( T \) are related to the critical temperature and the actual temperature, respectively.
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

Wide Temperature 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 4-1. Solar Probe mission summary.

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

- Mission design by APL/GSFC
- Materials testing by Dennison and Hoffmann
- Evolutionary Charging Study by Donegan, Sample, Dennison & Hoffmann
  (See Donegann et al, JSR 2009)
- Revised mission design and new charging study
  (See Donegann 11th SCTC Poster for update)
Case V: Temperature and Dose Effects

Wide Orbital Range
- Earth to Jupiter Flyby
- Solar Flyby to 4 Rs

Wide Temperature Range
- <100 K to >1800 K

Wide Dose Rate Range
- Five orders of magnitude variation!
Case V: Temperature and Dose Effects

**Dark Conductivity**

\[ \sigma_{DC}(T) = \sigma_{o}^{DC} e^{-\frac{E_o}{k_B T}} \]

**RIC**

\[ \sigma_{RIC}(T) = k_{RIC}(T) \Delta(T) \]

**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

A fascinating trade-off

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

General Trends

Dose rate decreases as $\sim r^{-2}$

$T$ decreases as $\sim e^{-r}$

$\sigma_{DC}$ decreases as $\sim e^{-1/T}$

$\sigma_{RIC}$ decreases as $\sim e^{-1/T}$

and decreases as $\sim r^{-2}$
Case VI: Multilayer/Nanocomposite Effects

Consider the Effects of Multilayer Materials, Composites, Contamination, or Oxidation

**Length Scale**
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

**Time Scales**
- Deposition times
- Dissipation times
- Mission duration

### Coated Mirror Structure

- ~100 nm SiO₂ Coating
- ~10 nm Non-conducting Coating #2
- ~10 nm Non-conducting Coating #1
- ~200 nm Ag FSS99 Coating
- ~20 nm Conducting Coating
- ~20 nm Non-conducting Coating

2.54 cm thick fused silica substrate

### Power Deposition Graph

- Disordered SiO₂ (120 nm)
- Ag (220 nm)
- Disordered SiO₂ (6250 µm)

**Deposited Power (J/m²)** vs **Beam Energy (eV)**
Why Does Glow Scale with Flux, Energy and Power?

In a simple, but reasonably accurate CSDA, used to model energy loss of electrons traversing solids and their penetration range, the rate of energy loss (dE/dz) is assumed constant.

Assuming emission intensity is proportional to energy deposition (dose), emission scales as:
- Incident e-flux, for non-penetrating radiation
- Incident power, for penetrating radiation

Emission scaling depends on sample geometry and materials properties. May lead to:
- Power or flux scaling at different incident energies
- Energy or flux thresholds and/or cutoffs
- Significant emission from high energy e⁻
- Significant emission from back sides or interior surfaces
Diversity of Emission Phenomena in Black Kapton

### Ball Black Kapton

<table>
<thead>
<tr>
<th>Runs 131 and 131A</th>
<th>22 keV</th>
<th>110 or 4100 uW/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>135 K</td>
<td>5 or 188 nA/cm²</td>
<td></td>
</tr>
</tbody>
</table>

### Surface Glow
- Relatively low intensity
- Always present over full surface when e-beam on
- May decay slowly with time

### Edge Glow
- Similar to Surface Glow, but present only at sample edge

### “Flare”
- 2-20x glow intensity
- Abrupt onset
- 2-10 min decay time

### Arc
- Relatively very high intensity
- 10-1000X glow intensity
- Very rapid <1 us to 1 s
Glow Increases with Increasing Flux, Energy and Power

- Surface Glow, Edge Glow, and Arcing Frequency are all found to increase with increasing incident electron flux and energy.
- Insufficient data for trends to establish functional dependence and possible thresholds or cut-offs
Emission Increases with Decreasing Temperature

**T300 Glow seen at MSFC**
Flux density = 1 nA/cm²  
Energy = 22 keV  
Power = 22 uW/cm²  
Temp = 296 K and 90 K

$I_{90}/I_{296} \sim 4$
Similar behavior seen for M55J and Black Kapton

**M55J Glow seen at USU**
Flux density = 5 nA/cm²  
Energy = 22 keV  
Power = 110 uW/cm²  
Temp = 294 K and 130 K

"Flare"  
130 K
Model for Luminescence Intensity in Fused Silica

Fig. 2. Qualitative two-band model of occupied densities of state (DOS) as a function of temperature during cathodoluminescence. (a) Modified Joblonski diagram for electron-induced phosphorescence. Shown are the extended state valence (VB) and conduction (CB) bands, shallow trap (ST) states at $\varepsilon_{ST}$ within $\sim k_B T$ below the CB edge, and two deep trap (DT) distributions centered at $E_{DT}=E_{red}$ and $E_{DT}=E_{blue}$. Energy depths are exaggerated for clarity. (b) At $T=0$ K, the deeper DT band is filled, so that there is no blue photon emission if $E_{blue}<E_{eff}$. (c) At low $T$, electrons in deeper DT band are thermally excited to create a partially filled upper DT band (decreasing the available DOS for red photon emission) and a partially empty lower DT band (increasing the available DOS for blue photon emission). (d) At higher $T$, enhanced thermal excitations further decrease red photon emission and increase blue photon emission. Radiation induced

$$I_y(J_b,E_b,T,\lambda) \propto \dot{D}(J_b,E_b) \left[ \frac{1}{D+D_{sat}} \left( \frac{\varepsilon_{ST}}{k_B T} \right) \right] \{A_f(\lambda)[1 + R_m(\lambda)] \} \quad (1)$$

where dose rate $\dot{D}$ (absorbed power per unit mass) is given by

$$\dot{D}(J_b,E_b) = \frac{E_b J_b [1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} \frac{1}{L} & ; R(E_b) < L \\ \frac{1}{R(E_b)} & ; R(E_b) > L \end{cases} \quad (2)$$

Fig. 3. Range and dose rate of disordered SiO$_2$ as a function of incident energy using calculation methods and the continuous slow-down approximation described in [5].
Fig. 1. Optical measurements of luminescent thin film disordered SiO₂ samples. (a) Three luminescence UV/VIS spectra at decreasing sample temperature. Four peaks are identified: red (~645 nm), green (~500 nm), blue (~455 nm) and UV (275 nm). (b) Peak amplitudes as a function of sample temperature, with baseline subtracted and normalized to maximum amplitudes. (c) Peak wavelength shift as a function of sample temperature. (d) Total luminescent radiance versus beam current at fixed incident energy fit by (1). (e) Total luminescent radiance versus beam energy at fixed incident flux fit by (1). (f) Total luminescent radiance versus beam energy at fixed 10 nA/cm² incident flux for epoxy-resin M55J carbon composite (red; linear fit), SiO₂ coated mirror (green; fit with (1)), and...
Arcs Observed in Black Kapton and M55J

Arc Characteristics

- **Arc duration:** ~0.2 to 0.8 s in electrometers and video cameras
- **Arc Freq. at 110 µW/cm²:**
  - ~10 arcs/hr for Black Kapton
  - ~30 arcs/hr for M55J
- **Arc Intensity:**
  - ~10X to 1000X glow amplitude
  - ~5% to 20% of glow power

**Ball Black Kapton**
- 22 keV
- 135 K
- 110 or 4100 uW/cm²
- 5 or 188 nA/cm²

**Runs 131 and 131A**

Rapid Arcing at 4 mW/cm²
- ~20000 arcs/hr

**Electrometer**

**InGaAs Video**

**CCD Video**

**CCD camera (400nm-900nm)**

**InGaAs camera (900nm-1700nm)**
“Flares” Observed in Black Kapton

**“Flare” Characteristics**

- **“Flare” duration:** Abrupt onset
  - ~2-10 min exp. decay time in electrometers and video cameras

- **“Flare” Frequency:**
  - 0-2 flares/hr

- **“Flare” Intensity:**
  - ~2X to 20X glow amplitude
  - ~5% to 20% of glow power

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![Electrometer](image1)

**Ball Black Kapton**

- Runs 131
- 110 uW/cm²
- 5 nA/cm²
- 22 keV
- 135 K

---

**CCD Camera (RGB)**

- 1 cm
- 5 nA/cm²
- 22 keV
- 135 K

---

**InGaAs Video**

- M55J
- 5 nA/cm²
- 22 keV
- 135 K
Details of Electrometer “Flare” Signature

Electrometer Data

Total Beam Time: 3204 s
# of Arcs: >50

High Conductivity
C-loaded Kapton
25keV 38nA ~1 hr
Conclusions

• 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

• Environment/Materials Modification feedback mechanisms can cause many new problems

• Use available modeling tools with broader materials knowledgebase and a conscious awareness of the dynamic nature of materials to foresee and mitigate potential spacecraft charging problems
End with a Bang
Extremely Low Conductivity
Surface Voltage

(a) Sample Current Lead (R)

(b) EFP 6 axis Translator

Diagram showing the surface voltage setup with labels for T, P, U, V, E, D, H, L, Q, P, F.
Fig. 2. Hemispherical Grid Retarding Field Analyzer (HGRFA). (a) Photograph of sample stage and HGRFA detector (side view). (b) Cross section of HGRFA. (c) Photograph of sample stage showing sample and cooling reservoir. (d) Side view of the mounting of the stepper motor. (e) Isometric view of the HGRFA detailing the flood gun, optical ports, and wire harness.
Low Charge Capabilities

Figure 5. (top) Interior of Hemispherical grid retarding field analyzer detector showing sample and “flipper” to measure surface voltages with electrostatic field transfer probe. (bottom) Surface voltage decay curve for Kapton E sample after electron beam
Luminescence/Arc/Flare Test Configuration

Sample cooled with l-N$_2$ to 100-135 K. Chamber walls at ambient.
• λ range: detectors (700-5500 nm), cameras (400-5000 nm), and spectrometers (200-1700 nm)

• Current range: (0.1 pA to 1 mA)

• Temporal range: <10⁻⁹ s to >10⁴ s
Comparison of Luminescence Images

**Sustained Glow**
- **Kapton XC**
  - 500 nA/cm²
  - 22 keV
  - 150 K
- **M55J**
  - 1 nA/cm²
  - 22 keV
  - 100 K
- **IEC Shell Face Epoxy Resin with Carbon Veil**
  - 1 nA/cm²
  - 22 keV
  - 100 K
- **Kapton E**
  - 500 nA/cm²
  - 22 keV
  - 150 K

**“Flare”**
- **Kapton XC**
  - 50 nA/cm²
  - 22 keV
  - 150 K
- **M55J**
  - 1 nA/cm²
  - 22 keV
  - 100 K
- **IEC Shell Face Epoxy Resin with Carbon Veil**
  - 1 nA/cm²
  - 22 keV
  - 100 K
- **Kapton E**
  - 5 nA/cm²
  - 22 keV
  - 135 K

**Arcs**
- **LaB6 Thermal Spot**
  - 5 nA/cm²
  - 22 keV
  - 1350 K
- **Arc**
  - 5 nA/cm²
  - 22 keV
  - 135 K

1 cm Dia test samples
- 30 s Exposure SLR Camera (400nm-640nm)
- 33 ms Exposure CCD Video Camera (500nm-900nm)
- 17 ms Exposure InGaAs Video Camera (900nm-1700nm)
Electrostatic Breakdown

Diagram showing the setup of the experiment and the resulting data on the relationship between electric field strength and current. The diagram includes labels for different components such as Vacuum Chamber, Aluminum Cold Reservoir, Sample Plate, Test Sample, and Electrode. The graphs display the critical field and endurance time as a function of electric field strength.
EV Spec worst case (Minow)

2004 GEO and L2 Bulk Charging Environments - Electrons

These values are 10 x the model input values, adjusted in the model per recent Geotail and WIND data.
Sample 275XC/Kevlar/275XC cross section view
Ball Kapton/Kevlar Composite—SEM Inspection (GSFC)

Sample 275XC/Kevlar/275XC cross section view