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Exploring the Universe … One Electron at a Time

JR Dennison
Utah State University

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Exploring the Universe…
One Electron at a Time

J.R. Dennison

Materials Physics Group
Physics Department, Utah State University

Supported by the NASA Space Environments & Effects Program and various other sources
Exploring the Universe with IR Space Telescopes

IR Space Telescopes

- SDL’s Wide-field Infrared Survey Explorer
- Herschel Space Observatory
- Spitzer Space Telescope
- James Webb Space Telescope

The James Webb Space Telescope will be a giant leap forward in our quest to understand the Universe and our origins. The Webb will examine every phase of cosmic history: from the first luminous glows after the Big Bang to the formation of galaxies, stars, and planets to the evolution of our own solar system. The science goals for the Webb can be grouped into four themes:

- **The End of the Dark Ages: First Light and Reionization** seeks to identify the first bright objects that formed in the early Universe, and follow the ionization history.

- **Assembly of Galaxies** will determine how galaxies and dark matter, including gas, stars, metals, physical structures (like spiral arms) and active nuclei evolved to the present day.

- **The Birth of Stars and Protoplanetary Systems** focuses on the birth and early development of stars and the formation of planets.

- **Planetary Systems and the Origins of Life** studies the physical and chemical properties of solar systems (including our own) and where the building blocks of life may be present.
What Is Different About JWST?

Extremely Faint Objects
- Large sensitive optics

**Large Open Structure**
- Size and weight constraints
- Minimal shielding
- Large fluxes

Observations in IR
- Penetration through intergalactic dust clouds
- Optimized for (0.6 –28 um)

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

**Large Sunshield**
- Large areas
- Constant eclipse with no photoemission

Stable, Low Light Environment
- Orbit at L2
- Large solar activity variations
- In and out of magnetotail

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

Complex, Sensitive Hardware
- Large sensitive optics
- Complex, cold electronics

Paradigm Shift in Design Methods
- To big for conventional ground tests
Images from JWST
NASA’s concern for spacecraft charging is caused by plasma environment electron, ion, and photon-induced currents. Charging can cause performance degradation or complete failure.

Majority of all spacecraft failures and anomalies due to the space environment result from plasma-induced charging

- Single event interrupts of electronics
- Arching
- Sputtering
- Enhanced contamination
- Shifts in spacecraft potentials
- Current losses
A Simplified Approach to Space Environment Interactions Modeling…

Materials Properties

Electron interactions with materials

Spacecraft Potential Models

Satellite Moving through Space

Space Plasma Environment

Materials Properties
## Simulating Space at USU

<table>
<thead>
<tr>
<th>JWST</th>
<th>USU Lab</th>
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</thead>
<tbody>
<tr>
<td>Sunshield</td>
<td>Small Test Samples (~1 cm²)</td>
</tr>
<tr>
<td>Space</td>
<td>UHV Chamber (~10⁻⁹ Torr)</td>
</tr>
<tr>
<td>Passive Cooling</td>
<td>Cryo Cooling (&gt;30 K)</td>
</tr>
<tr>
<td>Light Flux</td>
<td>No Light (dark room &amp; chamber)</td>
</tr>
<tr>
<td>Charge Flux</td>
<td>Monoenergetic e-Beam (20eV to 30keV)</td>
</tr>
<tr>
<td>Low Flux</td>
<td>Low Flux (&lt;0.05 nA/cm² to &gt;500 nA/cm²)</td>
</tr>
<tr>
<td>Mission Lifetime</td>
<td>Fountain of Youth and Pot of Au</td>
</tr>
<tr>
<td>(~20 yr)</td>
<td>➔ Accelerated Testing</td>
</tr>
</tbody>
</table>
Materials Physics Group Measurement Capabilities

Electron Emission  
Ion Yield

Photoyield  
Luminescence

Conductivity  
Electrostatic Discharge

Radiation Induced Cond.  
Radiation Damage

Dependence on:  Press., Temp., Charge, E-field, Dose, Dose Rate
Sample cooled with I-N_2 to 100-135 K. Chamber walls at ambient.
Diversity of Emission Phenomena in Time Domain

**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

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Ball Black Kapton

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

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**Sustained Glow**

**Arc**

**Flare**

**CCD Video Camera**
(400 nm to 900 nm)

**InGaAs Video Camera**
(900 nm to 1700 nm)
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.
A Simple Analogy for Corpuscular Charge Storage:

- The incident electron and ion fluxes act to fill the bucket.
- Electron (ion, and photon) emission determines how much charge splashes out of the bucket as it is being filled.
- Conductivity of insulating materials determines:
  - Where charge will accumulate
  - How charge will redistribute across the spacecraft
  - Time scale for charge transport and dissipation

Problem complicated by:

- Two types of charge
- Charge interactions
- Charge distributions
- Different incident species
- Materials properties of charge repository

Conductors—Grates
Semiconductors—Sieves
Leaky insulators—Leaky buckets
Good insulators—Good buckets
Extreme insulators—Frozen buckets

How full is the bucket?

Electrons as particles

- ions
- electrons
- photons

BSE
SE
leakage
Three Critical Processes in Charging

Range

Electron Yield

Conduction

Depth electrons penetrate is energy dependent

Conductivity determines deposited charge layer movement

It’s all about where the electrons are--\(n_e(z)\)
Three Critical Processes in Charging

1. **Range**
   - Depth electrons penetrate is energy dependent.

2. **Electron Yield**
   - Embedded Charge: $V_{bias} = 0$
   - Backscattered Electrons: $V_{bias} < 0$
   - Secondary Electrons: $V_{bias} > 0$

3. **Conduction**
   - Conductivity determines deposited charge layer movement.

It’s all about where the electrons are--$n_e(z)$
Charging of a Dielectric Coated Optical Mirror

Charging Scenarios

- Low Energy
  - Grounded
  - Ungrounded

- High Energy
  - Grounded
  - Ungrounded

Electron Beam

SiO₂ Coating

Conducting Mirror

SiO₂ Substrate

1 cm Mirror sample
Low Energy - Grounded

\[ V_s(t) = V_o \left[ 1 - e^{-t \sigma_{DC}/\varepsilon_0 \varepsilon_r} \right] \]

\[ V_o = \frac{\bar{J}_0[1 - Y(E_b)]}{\sigma_{DC}} R(E_b) \frac{[D - R(E_b)]}{D} \]
Low Energy - Ungrounded

Electron Beam

![Graph showing voltage over time and current over time](image-url)
High Energy - Grounded

Electron Beam

Sample nA

Constant Charging Region

Beam Off

Voltage (V)

Current (nA)

Time (s)
High Energy - Ungrounded

Electron Beam

Graphs showing voltage and current vs. time.
High negative net potentials led to breakdown and arcing

Ungrounded POM Mirror Test Results

![Graph showing current (nA) over time (s) with regions labeled as Constant Charging region, After possible breakdown, and Beam Off.]
Example of POM Arc-Video

Frame before arc

Frame of arc

Frame after arc

Difference between frame before and frame of arc
Complete set of dynamic transport equations

\[ J = q_e n_e(z, t) \mu_e F(z, t) + q_e D \frac{dn_{tot}(z,t)}{dz} \]  \{Sum of electron drift and diffusion current densities \( J_i \)\}

\[ \frac{\partial}{\partial z} F(z, t) = q_e n_{tot}/\varepsilon_0 \varepsilon_r \]  \{1D Gauss’s Law\}

\[ \frac{\partial n_{tot}(z,t)}{\partial t} - \mu_e \frac{\partial}{\partial z} [n_e(z, t)F(z, t)] - q_e D \frac{\partial^2 n_e(z,t)}{\partial z^2} = N_{ex} - \alpha_e r \ n_e(z, t)n_{tot}(z, t) + \alpha_e n_e(t)[N_t(z) - n_t(z, t)] \]  \{1D Continuity equation with drift, diffusion and source terms\}

\[ \frac{dn_h(z,t)}{dt} = N_{ex} - \alpha_e r \ n_e(z, t)n_h(z, t) \]  \{1D hole continuity equation with Generation and recombination terms\}

\[ \frac{dn_t(z,\varepsilon,t)}{dt} = \alpha_e n_e(z, t)[N_t(z, \varepsilon) - n_t(z, \varepsilon, t)] - \alpha_e n_e \ varepsilon \ kT \ n_t(z, \varepsilon, t) \]  \{1D trapping continuity equation for electrons\}

A **quantum mechanical model**
of the spatial and energy distribution of the electron states
Band Theory of (Crystalline) Conductors, Insulators and Semiconductors

At the atomic scale, the density of states is represented as a graph showing the number of atoms. Groups of atoms are further analyzed to determine conduction and valence bands.

- **Conductor**: Partially filled bands
- **Insulator**: Completely filled bands
- **Semiconductor**: Insulators at finite T

The diagram illustrates the concept of band theory, distinguishing between conduction, band gap, and valence bands.
Disorder introduces localized states

**SINGLE POTENTIAL**

- **Position** $r$
  - Delocalized in real space
  - $|\psi(r)|^2$
- **Momentum** $q$
  - Localized in momentum space
  - $|\psi(q)|^2$

**SPREAD OF POTENTIALS**

- **Position** $r$
  - Localized in real space
  - $|\psi(r)|^2$
- **Momentum** $q$
  - Delocalized in momentum space
  - $|\psi(q)|^2$
Conductivity in Highly Disordered Insulation Materials

\[ \sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t) \]

Polarization

\[ \sigma_{Pol}^o e^{-t/\tau_{Pol}} \]

- Electronic (a)
- Distortional (b)
- Orientational (c)
- Interfacial (d)
Drift and hopping conductivity

\[ \sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t) \]

\[ \sigma_{Diff}^{-1} \]

\[ \sigma_{hop}(E,T) = \left[ \frac{2 \cdot n(T) \cdot v \cdot a \cdot e}{E} \right] \exp \left[ -\frac{\Delta H}{k_B \cdot T} \right] \sinh \left[ \frac{\varepsilon \cdot E \cdot a}{2 \cdot k_B \cdot T} \right] \]
Conductivity Model

\[ \sigma(t) = \sigma_{DC} + \sigma_{\text{Polarization}}(t) + \sigma_{\text{Diffusion}}(t) + \sigma_{\text{Dispersion}}(t) + \sigma_{\text{Transit}}(t) + \sigma_{\text{RIC}}(t) \]

\[ \sigma_{\text{Disp}} t^{-(1-\alpha)} + \sigma_{\text{Trans}} t^{-(1+\alpha)} \]

\[ I(t) \sim \begin{cases} \frac{t^{-(1-\alpha)}}{t_T}, & t < t_T \\ \frac{t^{-(1+\alpha)}}{t_T}, & t > t_T \end{cases} \]

\[ \text{LOG } I \text{ (relative)} \]

SLOPE = -1.50

SLOPE = -0.43

holes 79μm
RIC and Luminescence

\[ \sigma(t) = \sigma_{DC} + \sigma_{\text{Polarization}}(t) + \sigma_{\text{Diffusion}}(t) + \sigma_{\text{Dispersion}}(t) + \sigma_{\text{Transit}}(t) + \sigma_{\text{RIC}}(t) \]

\[ \sigma_{\text{RIC}}(D) = k \cdot \left( \frac{D}{\Delta} \right) \]
Electron-Induced Luminescence of SiO$_2$ Mirror

Beam off

Beam on
Luminescence: Excitation and Relaxation

Injected Charge

$E_F, E_F^{\text{eff}}, \text{photon}$
Luminescence: Effect of Beam Energy
Multi-Photon Luminescence
Multi-Photon Relaxation

Injected Charge

$e^-$

$E_F^{\text{eff}}$

$E_F$

$\text{CB}$

$\text{VB}$

Photon

Photon

Arrow
Luminescence: Temperature Dependence

-4 C

-80 C

-110 C
Blue increases with increasing T
Green decreases with increasing T
Red decreases with increasing T
Temperature Dependent UV-Vis Spectra
Temperature Model for Multiphonon Luminescence

\[ T = 0 \]

Injected Charge

\[ E_F \]

\[ E_F^{\text{eff}} \]
Low Temperature Model

Low T

Injected Charge

$E_F$

$E_F^{\text{eff}}$

$e^-$
High Temperature Model

High T

\[ e^{-} \]

Injected Charge

\[ E_{F} \]

\[ E_{F}^{eff} \]
Luminescence: Conclusions

- Identify specific defect mechanisms
- Quantify luminescence intensities, peak positions, and peak shifts with $T$
- Study initial time dependence as traps fill to $E_{\text{eff}}$
- Make lower $T$ (<30 K) and higher (<400 K) $T$ measurements
Materials Physics Group Measurement Capabilities

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Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate
Just a drop in the bucket…

Complete set of dynamic transport equations

\[ J = q_e n_e(z, t) \mu_e F(z, t) + q_e D \frac{dn_{tot}(z, t)}{dz} \]

\[ \frac{\partial}{\partial z} F(z, t) = q_e n_{tot} / \epsilon_0 \epsilon_r \]

\[ \frac{\partial n_{tot}(z, t)}{\partial t} - \mu_e \frac{\partial}{\partial z} [n_e(z, t) F(z, t)] - q_e D \frac{\partial^2 n_e(z, t)}{\partial z^2} = N_{ex} - \alpha_{er} n_e(z, t) n_{tot}(z, t) + \alpha_{et} n_e(t) [N_t(z) - n_t(z, t)] \]

\[ \frac{dn_h(z,t)}{dt} = N_{ex} - \alpha_{er} n_e(z, t) n_h(z, t) \]

\[ \frac{dn_t(z,e,t)}{dt} = \alpha_{et} n_e(z, t) [N_t(z,e) - n_t(z,e,t)] - \alpha_{te} N_e \exp \left[ - \frac{\epsilon}{kT} \right] n_t(z,e,t) \]

A quantum mechanical model of the spatial and energy distribution of the electron states