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Diverse Electron-induced Optical Emissions from Space Observatory Materials at Low Temperatures

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Diverse Electron-induced Optical Emissions from Space Observatory Materials at Low Temperatures

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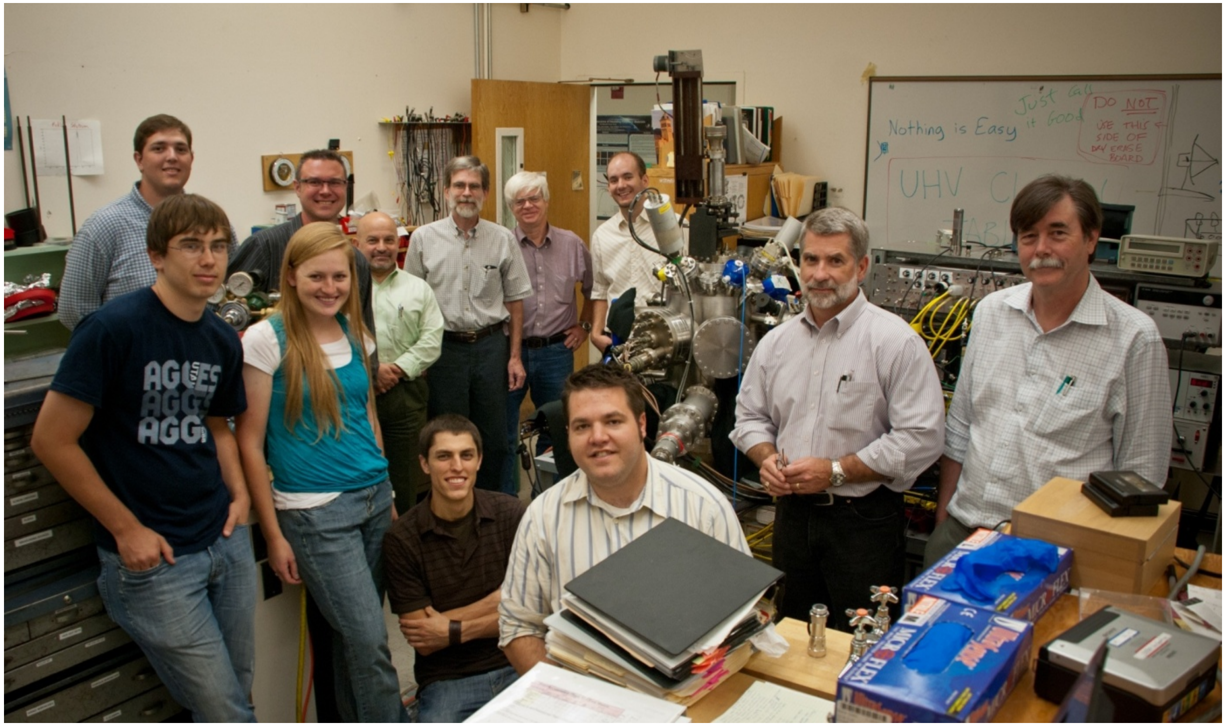


USU Materials Physics Group

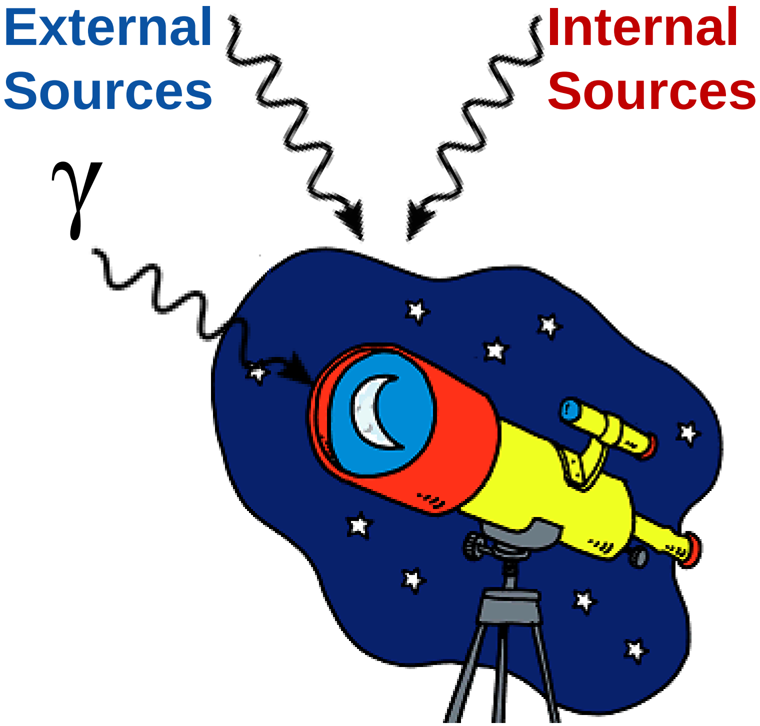
NASA Goddard Space Flight Center

Supported by the NASA Space Environments & Effects Program and various other sources

Central Question of This Presentation

Can interactions of the space environment electron flux with observatory materials make significant contributions to the stray light background and adversely affect the performance of space-based observatories?

e^-

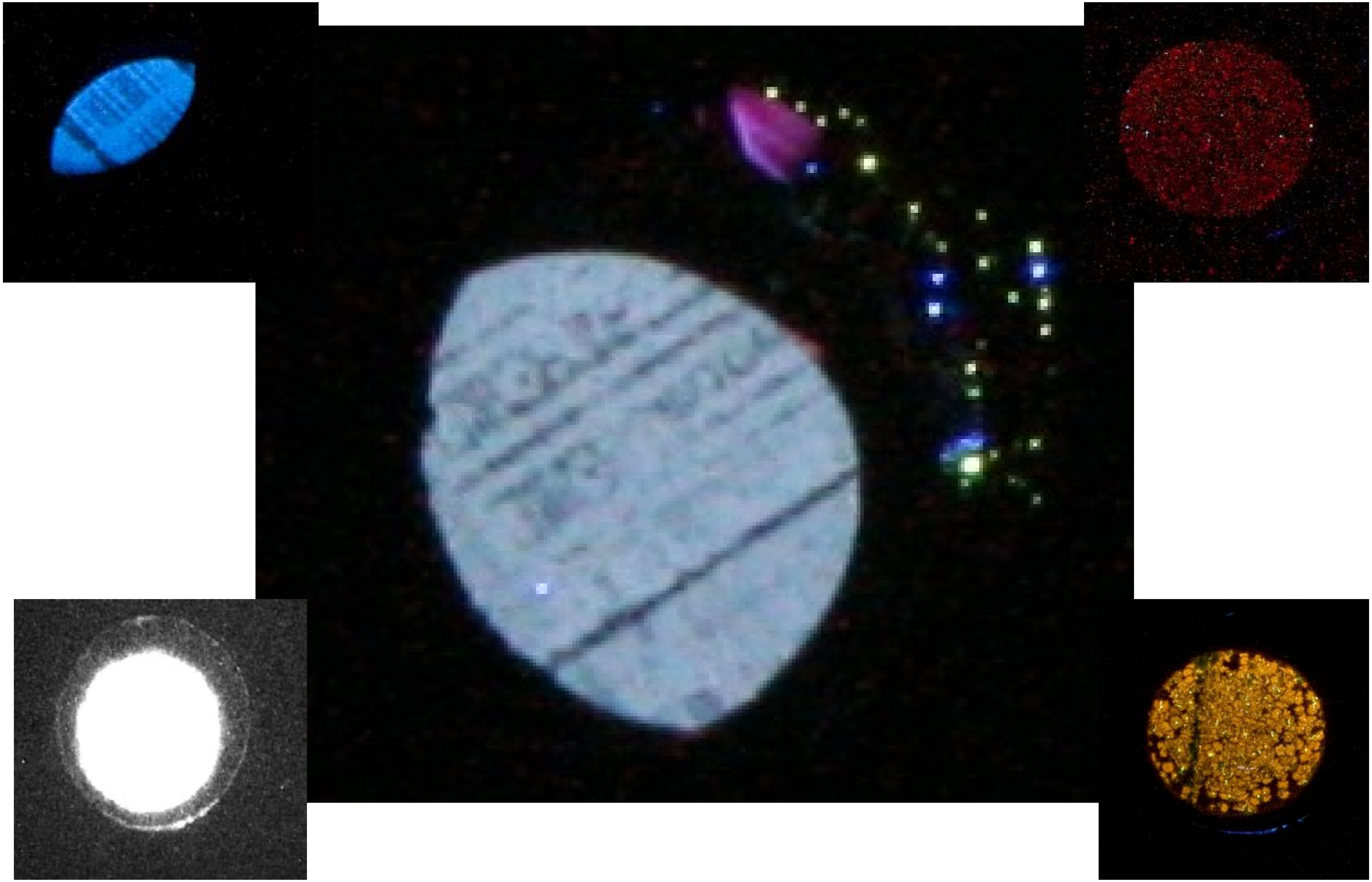


Space Environment Fluxes

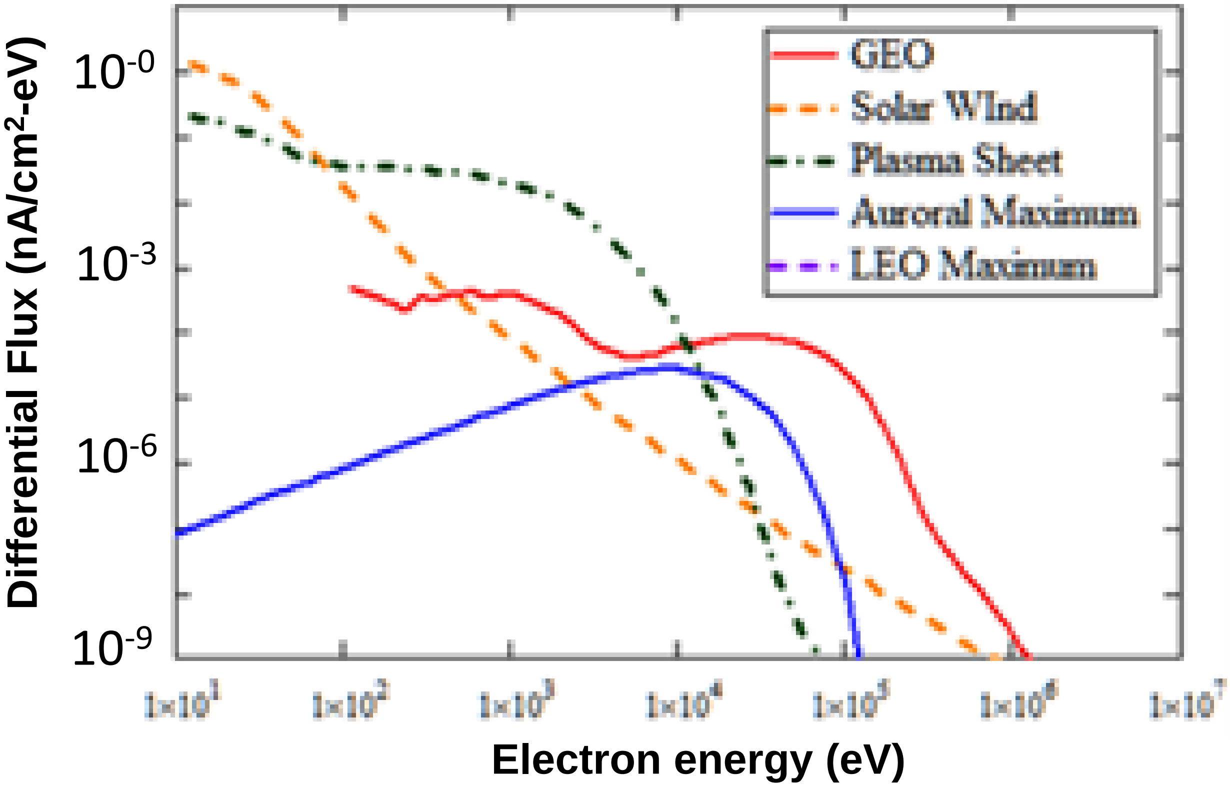
Space-based Observatory Moving through Space

Stray Light Background

The short answer is YES!



The Space Plasma Environment



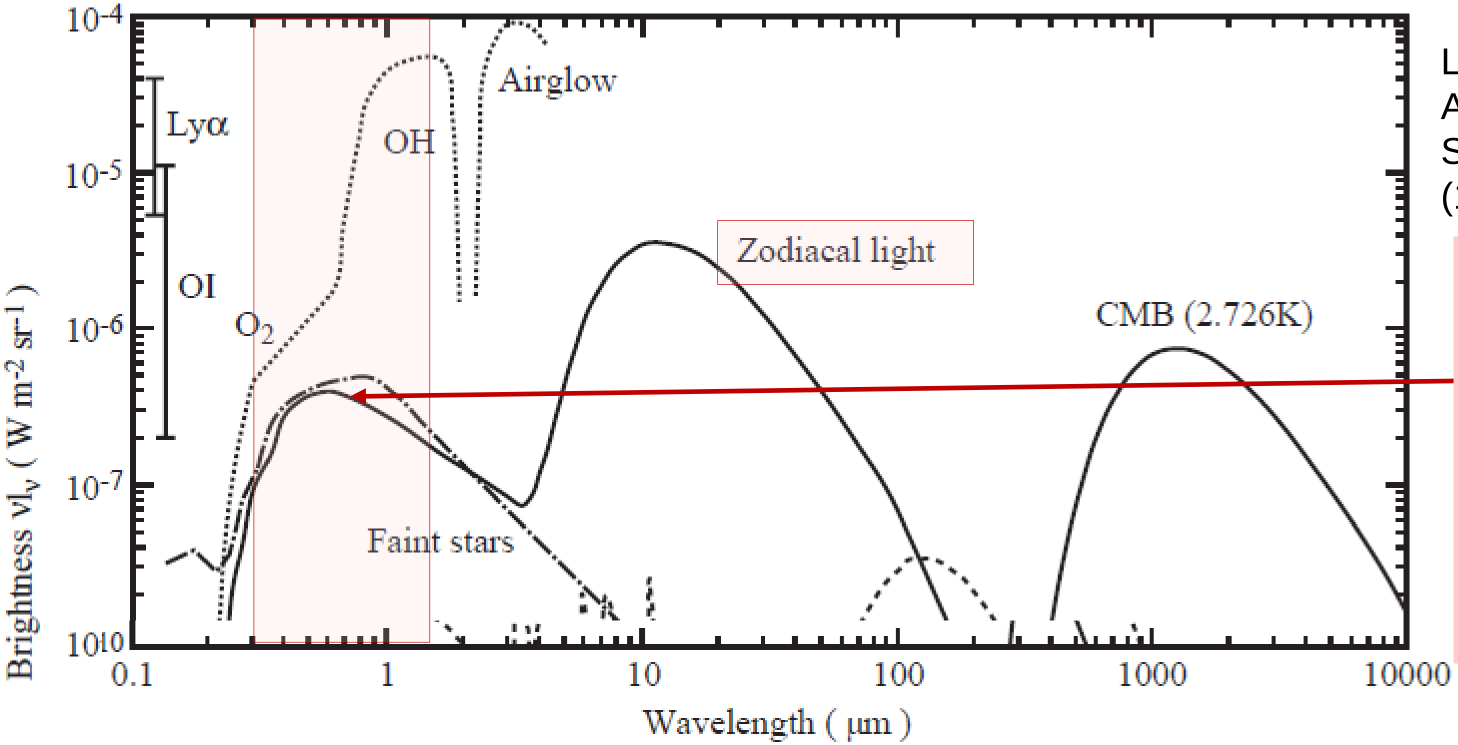
Typical "Worst Case" Environments have:

- **Peak fluxes: <10 nA/cm^2**
- **Energy range: <1 keV to > 1 MeV**
- **Peak power density: <10 μW/cm^2**

Flux exposures vary significantly with:

- **Time**
- **Space weather**
- **Mission orbit**
- **Satellite geometry and design**

Comparison with External Sources of Stray Light



Leinert , *et al.*, Astron. Astrophys. Suppl. Ser. 127, 1-99 (1998).

Zodiacal Background Spectral Radiance

$\sim 1\text{-}7 \cdot 10^{-14}$ [W-(cm-nm-sr)$^{-1}$]

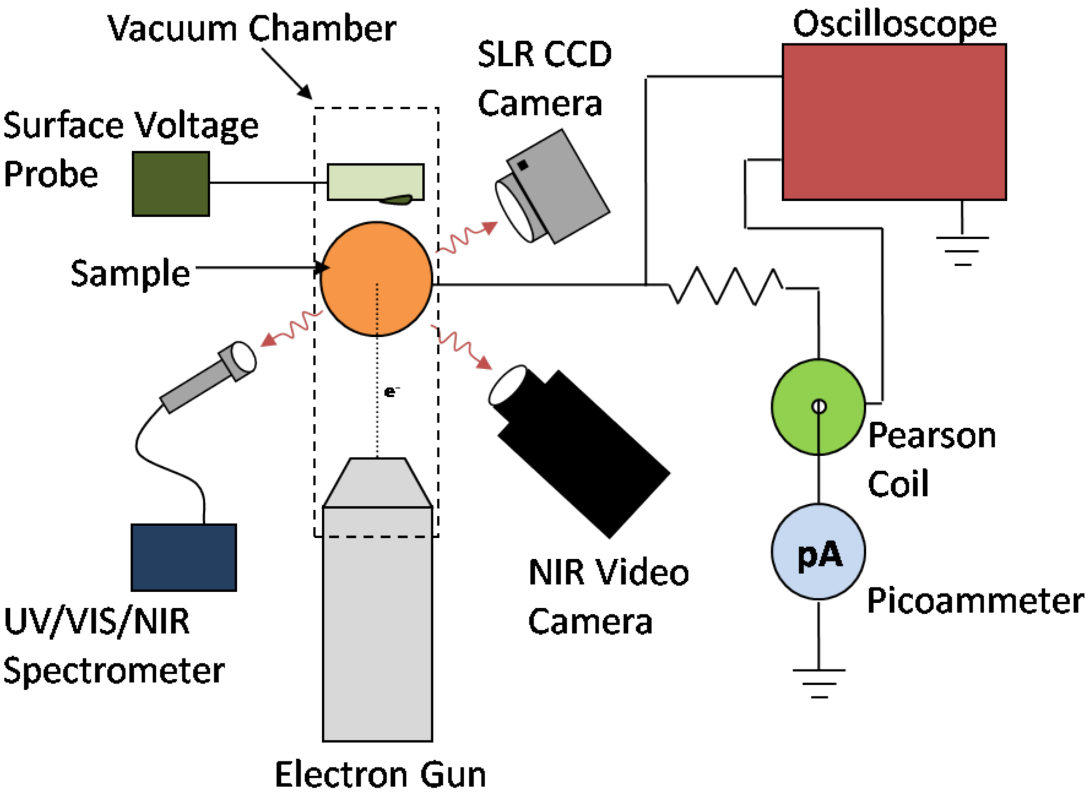
External Sources

- **Atmospheric air glow**
- **Zodiacal light (dust scatter & thermal emission)**
- **Integrated diffuse starlight**
- **Extragalactic diffuse light**
- **Cosmic microwave background**

Internal Sources

- **Thermal emission from telescope**
- **Electron-induced emissions**

Instrumentation



System Specifications

- Samples: 1-5 cm^2, grounded holder
- Vacuum: <10^{-7} Torr
- Temperature: <40 K to >350 K
- e-Beam: <20 eV to 30 keV
  <10 pA/cm^2 to >10 μA/cm^2

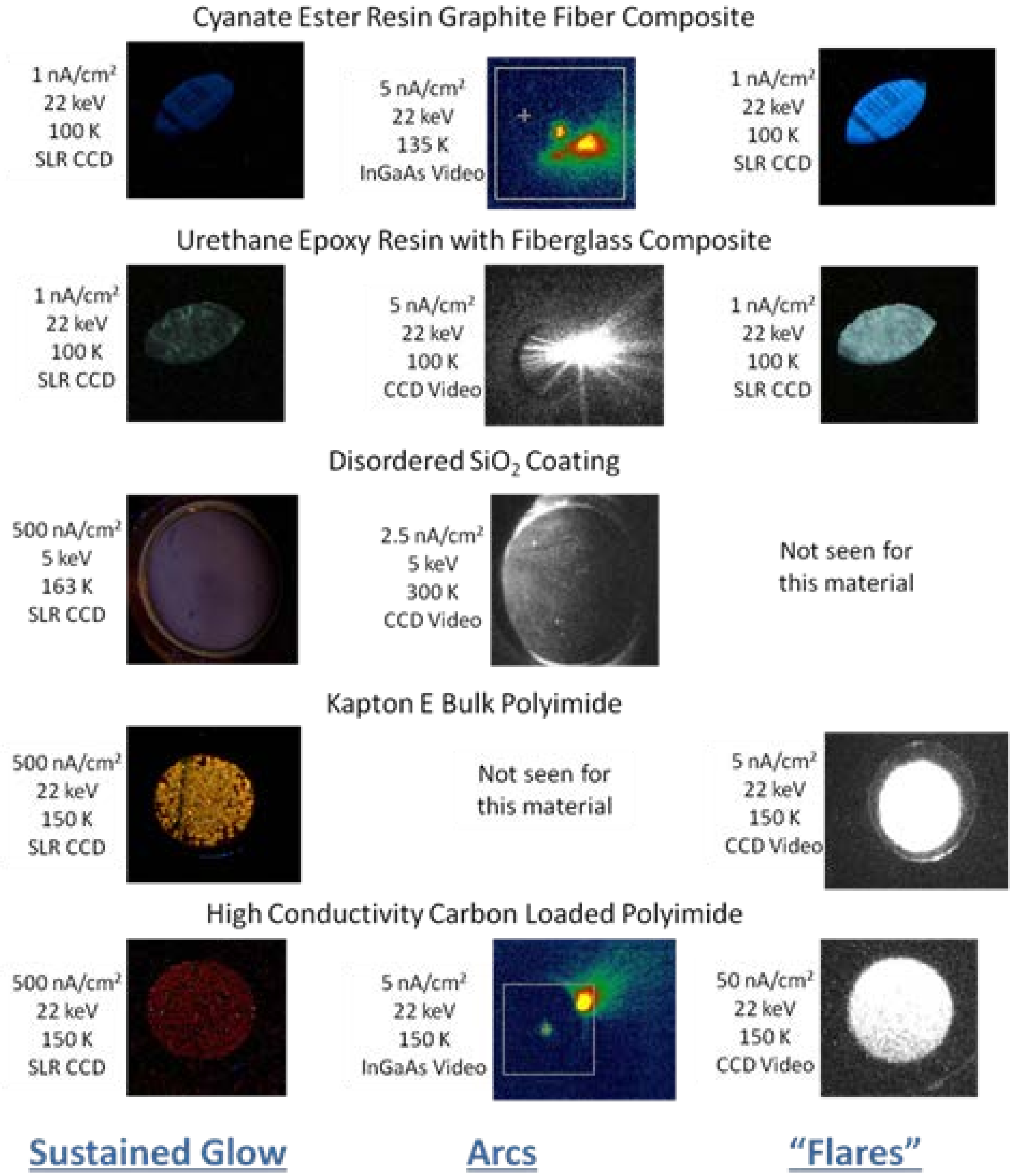
Photon and Electron Detection

- 4 cameras with absolute calibration
- <2 fW/cm^2-nm-sr sensitivity
- ~200 nm to ~1900 nm λ range
- 0.03 Hz to 60 Hz sampling rate
- UV/Vis and NIR spectrometers
- Currents to < 0.1 pA at up to 2 Ghz

Examples of Electron-Induced Optical Emission

Electron-Induced Emissions Observed

- **Sustained Cathodoluminescence**
- **Short duration arcing**
- **Intermediate duration “Flares”**



Glowing Dielectric Materials

Polymers

- **Polyimide (Kapton$^{\text{TM}}$ HN and E)**
- **Urethane Epoxy**
- **Amine Epoxy**

Glasses

- **Disordered SiO$_2$**

Composites

- **Carbon-loaded polyimide**
- **Cyanate ester/ graphite fiber composite**
- **Urethane Epoxy/ Carbon fiber composite**
- **Epoxy/Fiberglass composite**

Multilayer Dielectric/Conductor Composites

Diversity of Emission Phenomena in Time Domain

Surface Glow

- Relatively low intensity
- Glows when e-beam on
- Present over full surface
- May decay slowly with time
- Dependant on space charge

Edge Glow

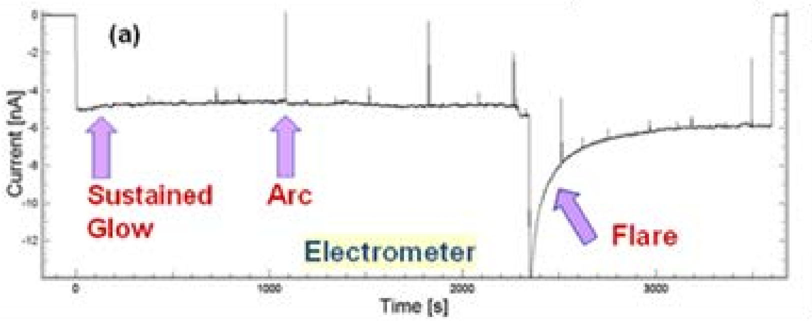
- Similar to surface glow
- Less intense than surface glow
- Only at sample edges

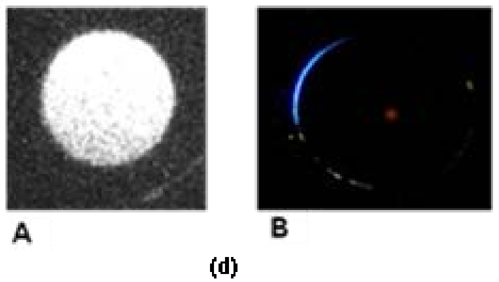
Arcs

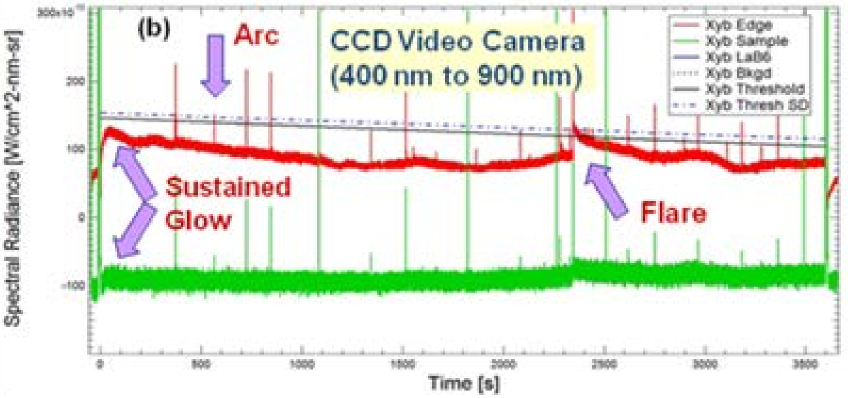
- Coincident with electric discharge
- Relatively very high intensity
- 10-1000X glow intensity
- Abrupt onset, <100 ns
- Very short duration, <1 us to 1 s

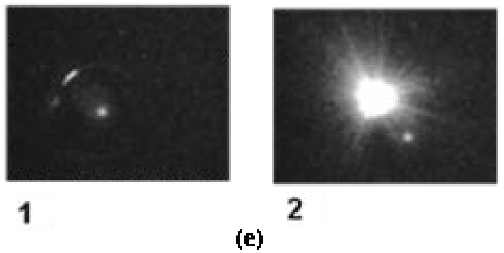
“Flares”

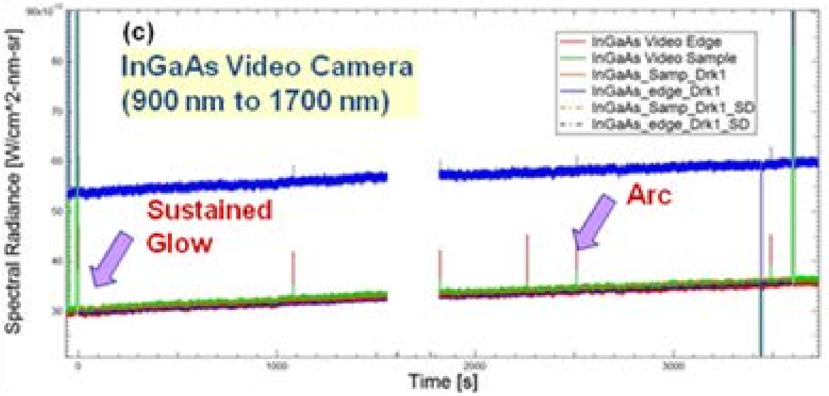
- 2-20x glow intensity
- Present over full surface
- Abrupt onset
- 1-10 min decay times

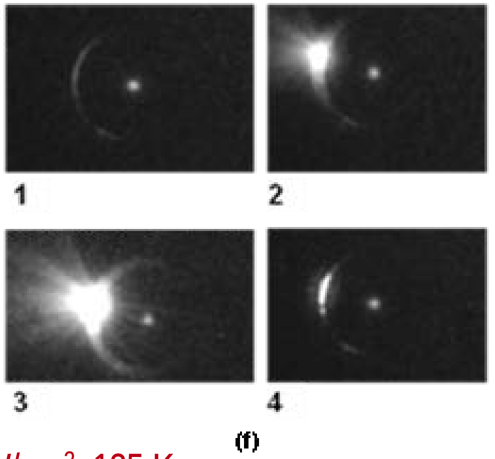










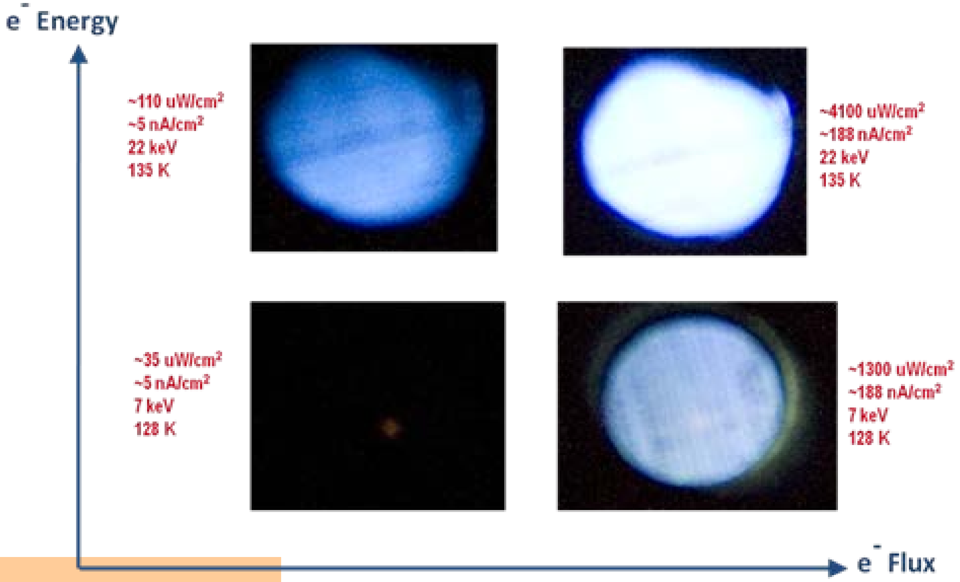


Carbon-loaded Polyimide 22 keV, 5 nA/cm^{2,}, 110 uW/cm^2, 135 K

Dependencies of Cathodoluminescence Intensity

- **Linearly increases with deposited current, energy and power**
- **Linearly increases with decreasing T**
- **Emissions in VIS/NIR, peaked in VIS**

- **Saturates at high dose rates (above space conditions)**
- **Plateaus and decreases below ~100 K**
- **Decreases with increasing energy for penetrating radiation**



Luminescence power P_γ is:

$$P_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D}+\dot{D}_{sat}} \left\{\left[e^{-(\varepsilon_{ST}/k_B T)}\right]\left[1 - e^{-(\varepsilon_{ST}/k_B T)}\right]\right\} ,$$

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

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

E_b, incident beam energy temperature
J_b, incident e-Beam current density
T, temperature
λ, photon wavelength
q_e, electron charge
ρ_m, mass density
$R(E_b)$, electron range
L, sample thickness

ε_{ST}, shallow trap energy
$\dot{D}_{sat}$, saturation dose rate

Approximate Relative Sp. Rad. (X Zodi Background)

Polymers

- **Polyimide (Kapton™ HN and E) X0.05**
- **Urethane Epoxy X50**
- **Amine Epoxy X20**

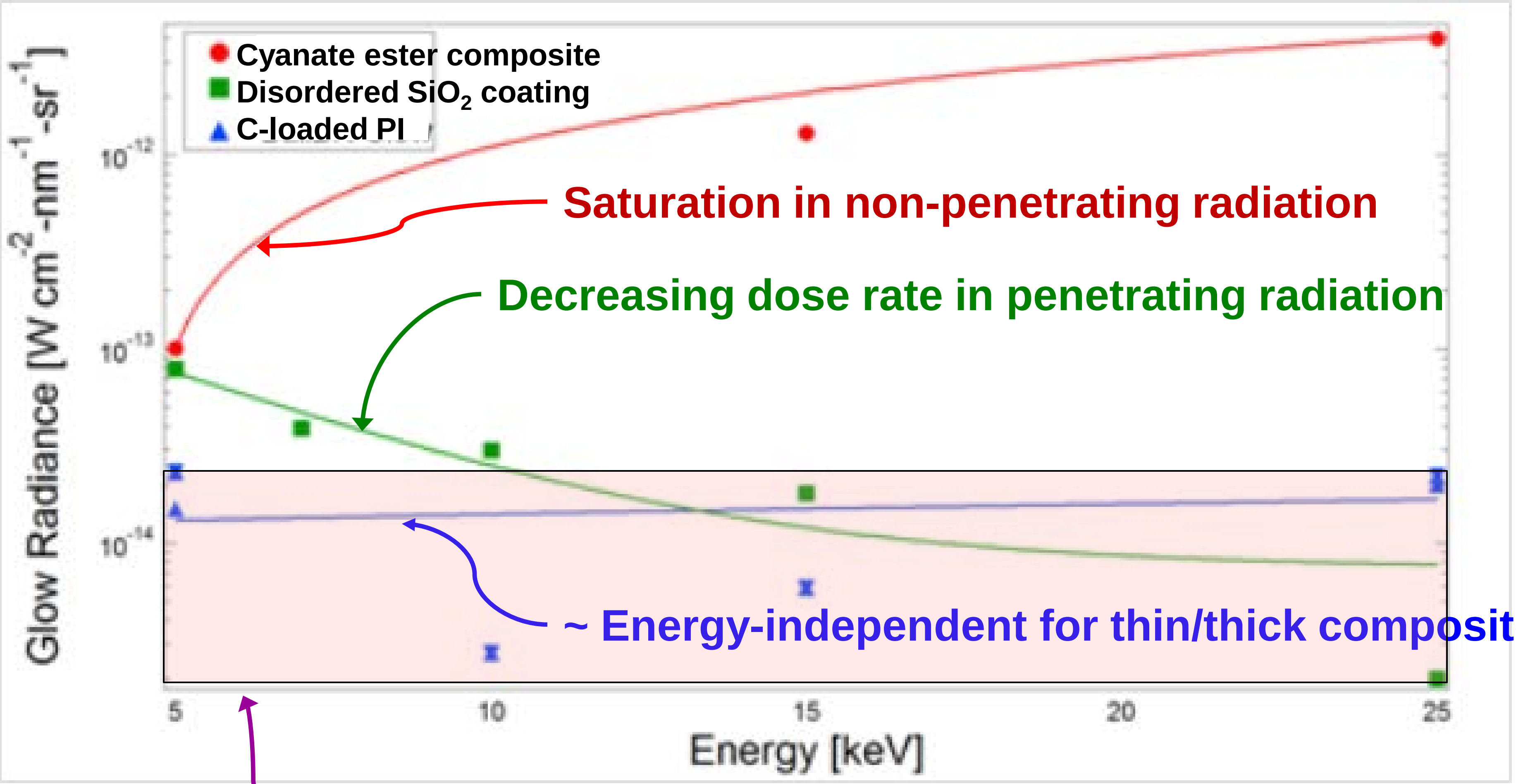
Glasses

- **Disordered SiO_2 X1**

Composites

- **Carbon-loaded polyimide X0.5 to X0.1 (conductivity)**
- **Cyanate ester/ graphite fiber X20**
- **Urethane Epoxy/Carbon fiver X4**
- **Epoxy/Fiberglass X5**

Varying Intensity Dependence on Incident Energy



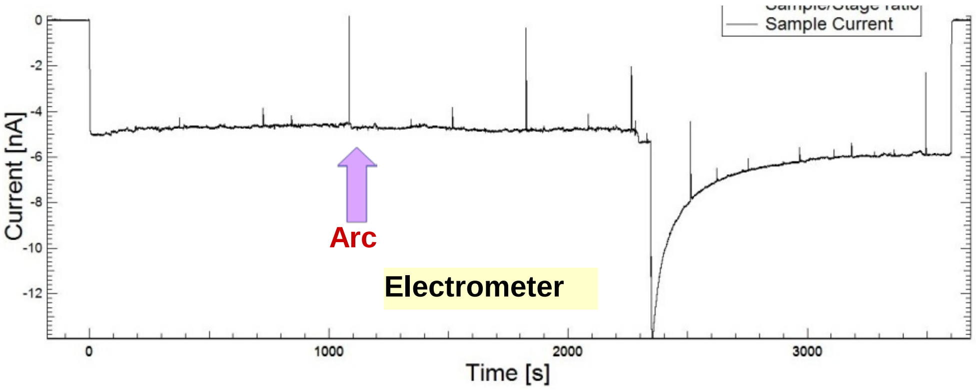
Saturation in non-penetrating radiation

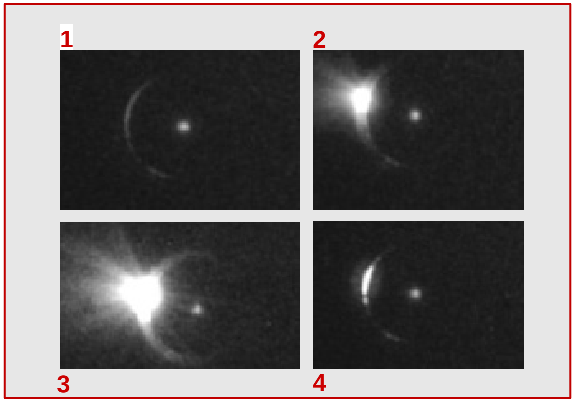
Decreasing dose rate in penetrating radiation

~ Energy-independent for thin/thick composite

Zodiacal Background Light

Short Duration Arcs





CCD camera (400nm-900nm) 30 frames/s

Arc Duration

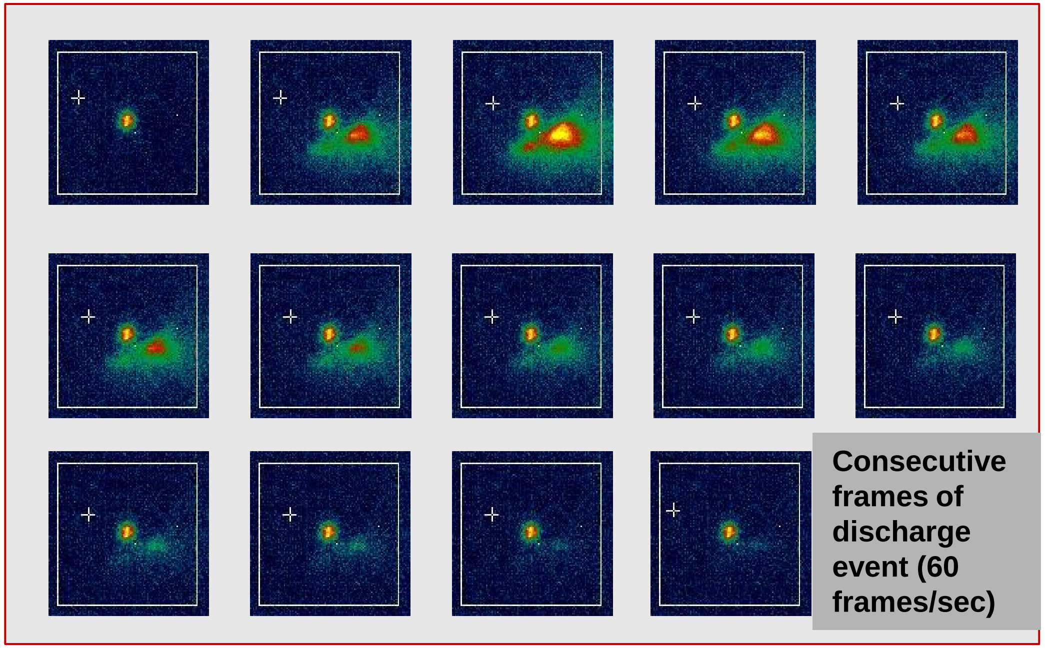
- Abrupt onset
- ~100 ns to ~100 ms exp. decay time
- Seen in electrometers and video cameras

Arc Frequency

- ~10-100 arcs/hr at ~10 uW/cm^2
- Rate proportional to current density
- Rate proportional to deposited power
- Varies with material, geometry, conductivity and temperature

Arc Intensity

- ~ 10X to 1000X glow amplitude
- ~5% to 20% of glow power
- Seen in radio to UVA λ range
- Optical signature at local point
- Discharge to closest ground

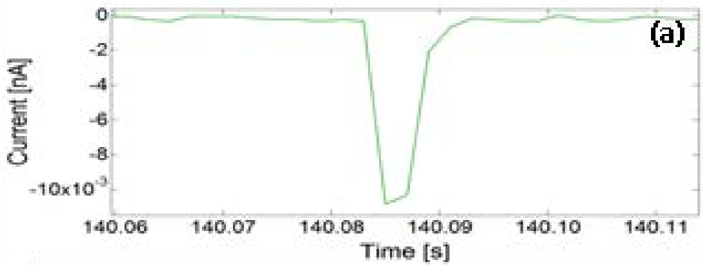


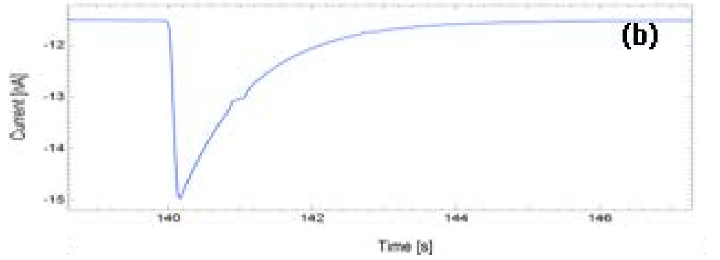
Consecutive frames of discharge event (60 frames/sec)

InGaAs camera (900nm-1700nm)

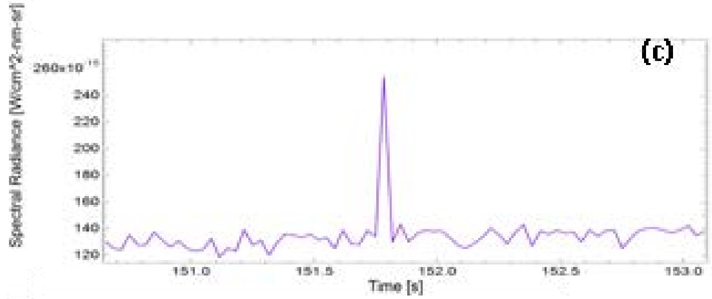
Short Duration Arcs and Arc Rates

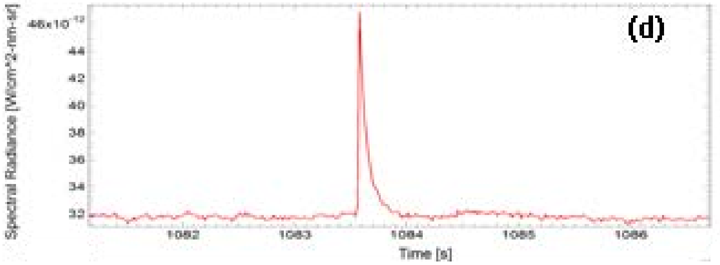
Arc duration in oscilloscopes is often ~ 1 us.



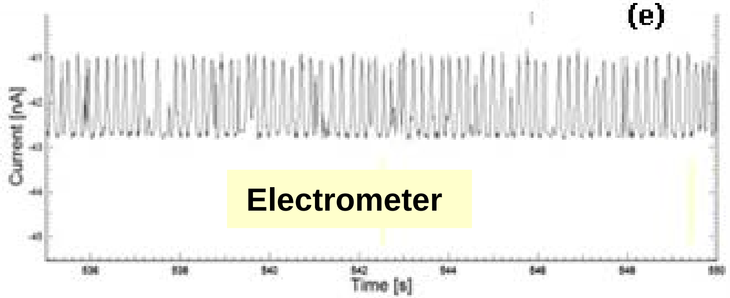


Longer time signatures in electrometer and videos most likely instrumental effect.



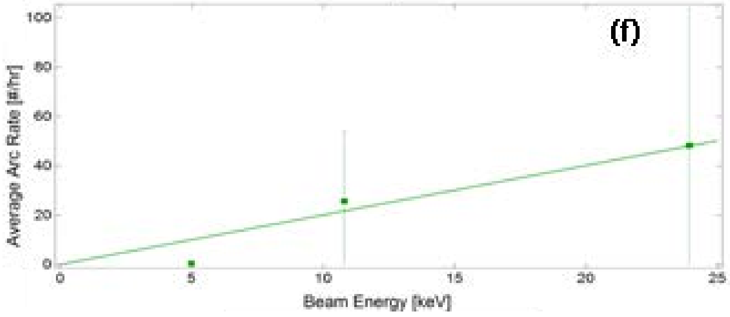


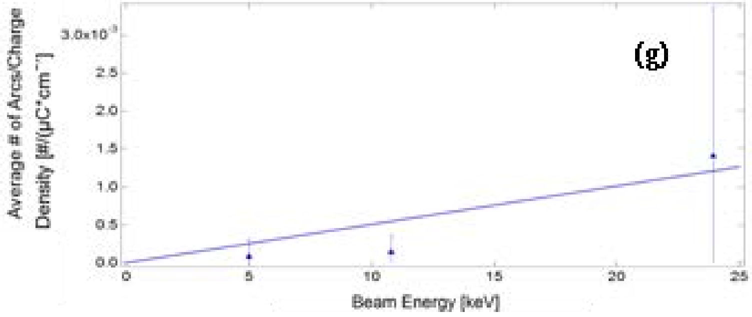
Rapid arcing at 4 mW/cm^2 ~20000 arcs/hr scales with deposited power and charge



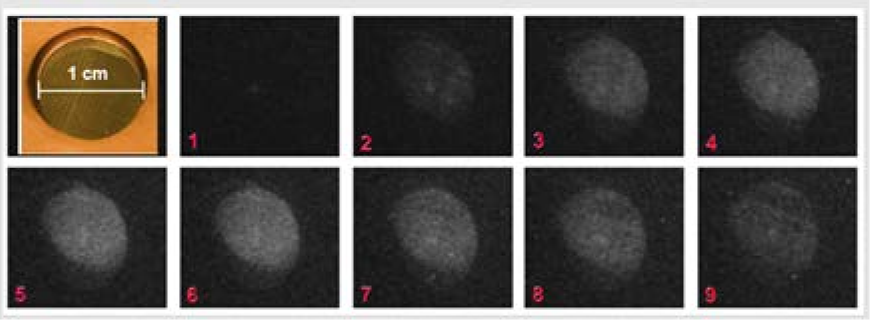
Electrometer

- **Rate proportional to current density**
- **Rate proportional to deposited power**
- **Rate varies with material, geometry, conductivity and temperature**





Intermediate Duration "Flares"



SLR CCD Camera (400 nm to 900 nm)   30 s/frame

"Flare" Duration

- Only after ~10 min charging
- Abrupt onset
- ~1-10 min exp. decay time
- Seen in electrometers and video cameras

"Flare" Frequency

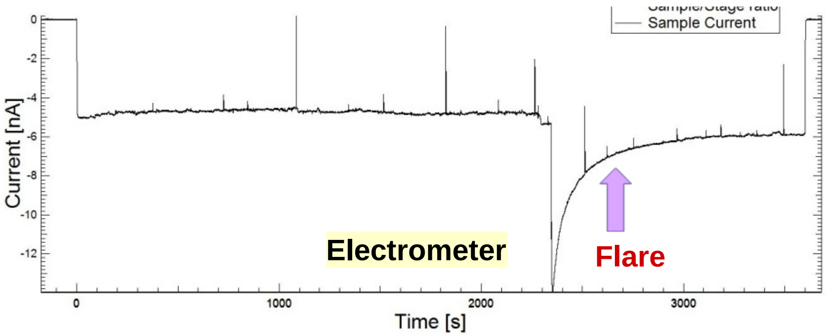
- 0-2 flares/hr

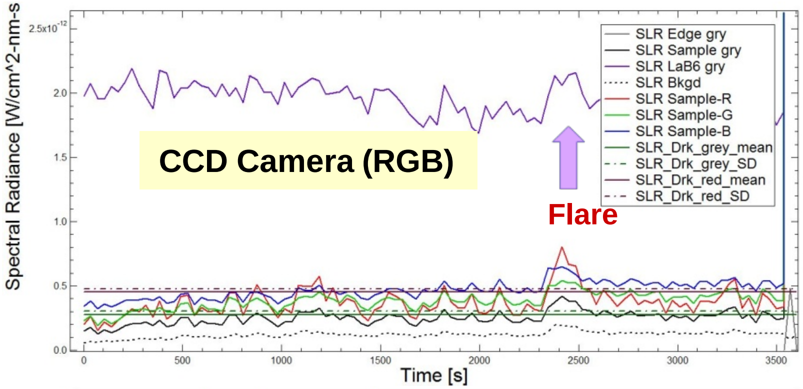
"Flare" Intensity

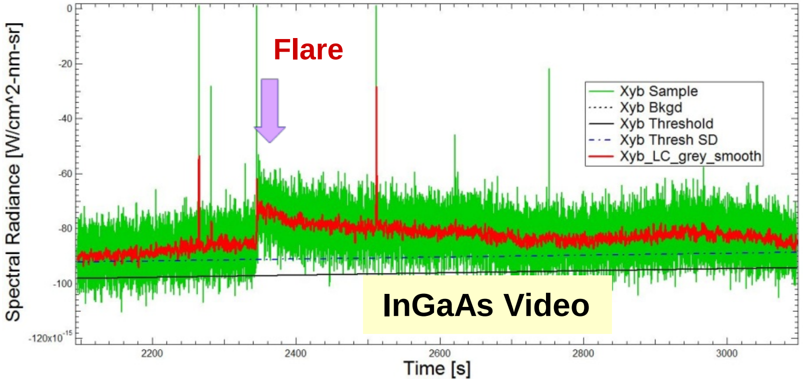
- ~ 2X to20X glow amplitude
- ~5% to 20% of glow power
- Seen in ~300 nm to ~1200 nm range
- Seen over full surface

"Flare" Properties

- Not seen in glasses
- Origin with large area discharge/charge???







Carbon-loaded Polyimide   22 keV, 5 nA/cm^{2}, 110 uW/cm^{2}, 135 K

Summary

I. Space environment electron fluxes produce optical emissions:
   - Sustained cathodoluminescence
   - Short duration arcs
   - Intermediate duration “flares”

II. Many dielectric materials produce electron-induced optical emissions.

III. Studies conducted for emission dependence on:
   - Incident electron energy, current density, power
   - Temperature
   - Emission wavelength
   - Film thickness/range
   - Material
   - Conductivity

IV. Optical emissions can exceed zodiacal background levels in certain conditions

Concluding Remarks

Space-based observatory designers should consider space environment electron-induced optical emissions as a potential internal source of stray light.

Space observatory conditions enhancing impact of these emissions include:

- **High flux and high variability environments**
- **High sensitivity imaging**
- **Complex, sensitive optical systems and electronics**
- **Low temperature operations**
- **Large areas**
- **Open architectures**
- **Long, remote missions**

Additional References

Disordered SiO_2

A.E. Jensen, *et al*., "Properties of Cathodoluminescence for Cryogenic Applications of SiO_2-based Space Observatory Optics and Coatings," *SPIE 2013* Paper No. 8863-11.

JR Dennison, *et al*., "Electron Beam Induced Luminescence of SiO_2 Optical Coatings," IEEE-CEIDP, 2012.

A. Evans, *et al*., "Low Temperature Cathodoluminescence of Space Observatory Materials," *Proc.*12*th* *Spacecraft Charging Tech. Conf.,* 2012; IEEE-TPS, in press.

Carbon-filed Polyimide

A.E. Jensen, *et al*., "Nanodielectric Properties of High Conductivity Carbon-Loaded Polyimide Under Electron-Beam Irradiation," *IEEE-ICSD,* 730-735. *2013.*

Multilayer Dielectric/Conductor Composites

G. Wilson, *et al*., "Charging Effects of Multilayered Dielectric Spacecraft Materials: Surface Voltage, Discharge and Arcing," *Proc.*12*th* *Spacecraft Charging Tech. Conf.,* 2012; IEEE-TPS, in press.

Observation of Emissions

D.C. Ferguson, *et al*., "On the Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing," AIAA-ASE, Paper Number, AIAA-2013-2828, 2013.

Theory

A.M. Sim and JR Dennison, "Comprehensive Theoretical Framework for Modeling Diverse Electron Transport Experiments in Parallel Plate Geometries," AIAA-ASE, Paper Number, AIAA-2013-2827, 2013.

Supplemental Slides

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

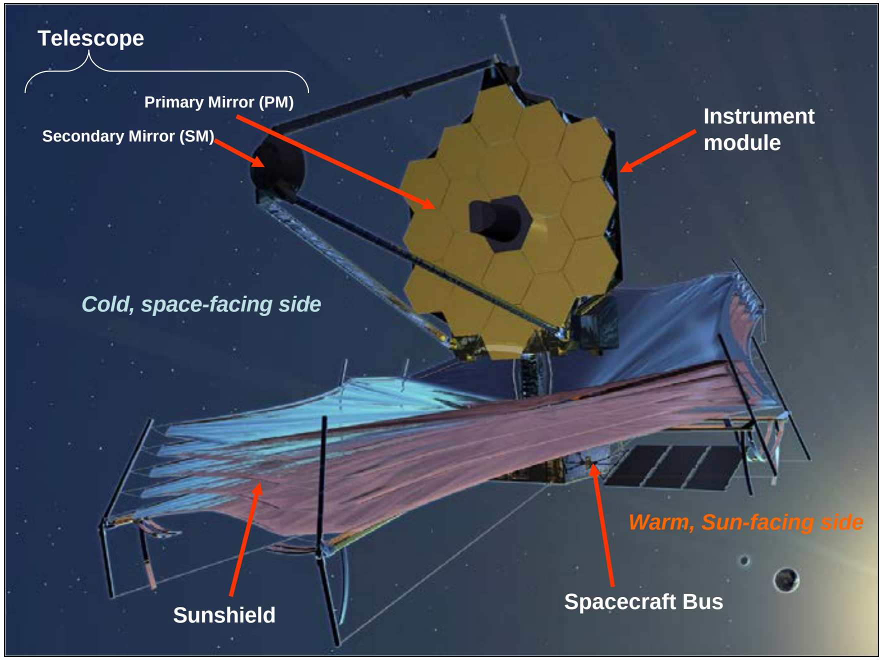
Constant eclipse with no photoemission

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

Simulating Space at USU

JWST	**USU Lab**
Sunshield	Small Test Samples (~1 cm^2)
Space	UHV Chamber (~10^{-9} Torr)
Passive Cooling	Cryo Cooling (>30 K)
Light Flux	No Light (dark room & chamber)
Charge Flux	Monoenergetic e-Beam (20eV to 30keV)
Low Flux	Low Flux (<0.05 nA/cm^2 to >500 nA/cm^2)
Mission Lifetime	Fountain of Youth and Pot of Au
(~20 yr)	➔ Accelerated Testing

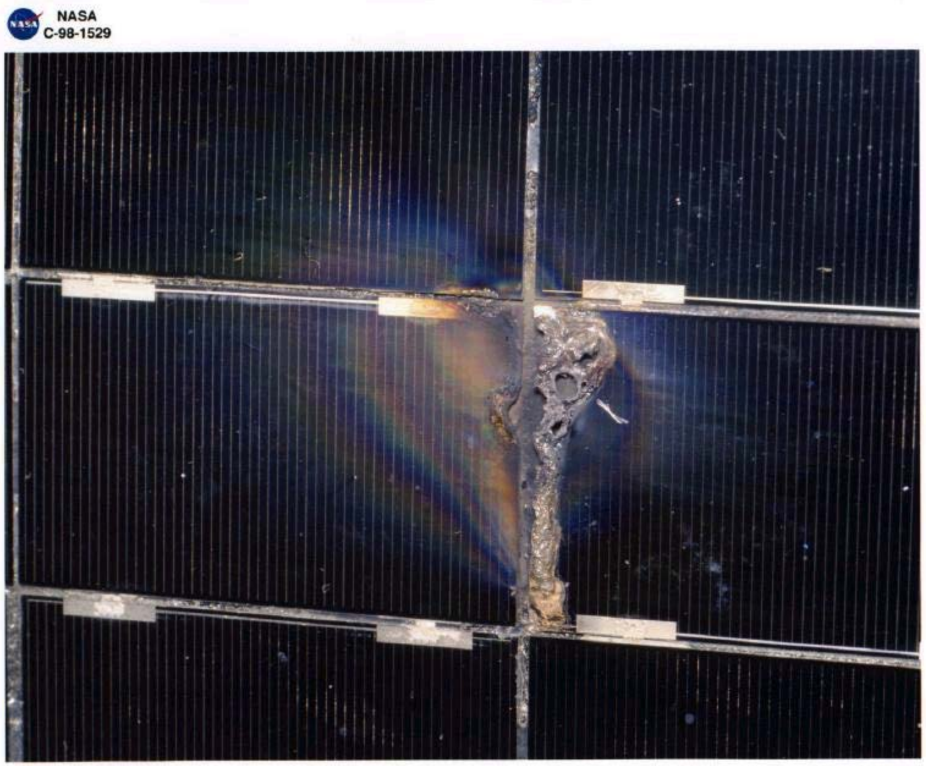
Primary Motivation For Our Research—Spacecraft Charging

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***

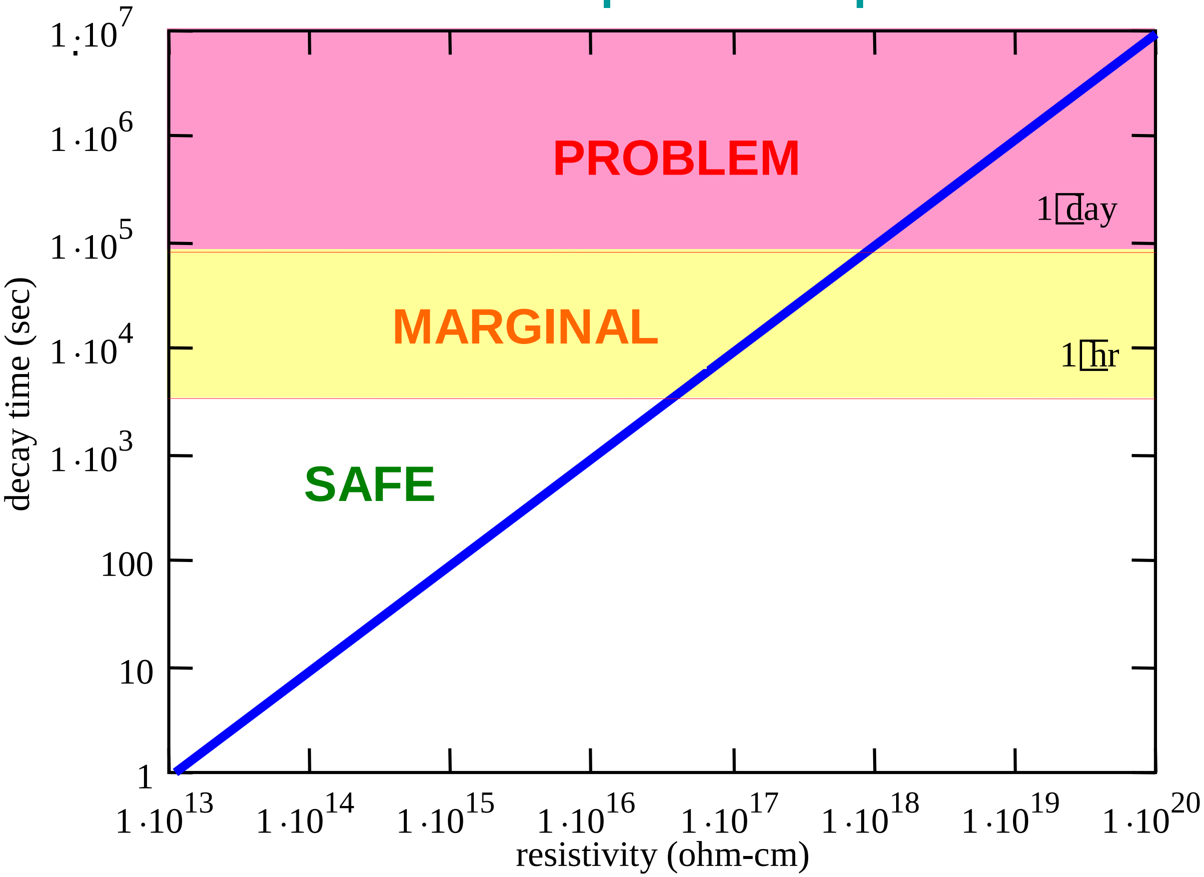

NASA
C-98-1529

Solar panel damaged by localized charging event

National Aeronautics and Space Administration
Lewis Research Center

Critical Time Scales and Resistivites

<---Electrometer----|-----CV------|-----CSM--->



Range of
Charge Storage Method

1 min → ρ•ε_o ~1•10^{15} Ω-cm

1 hr → ρ•εo ~4•1016 Ω-cm

1 day → ρ•ε_o ~1•10^{18} Ω-cm

1 yr → ρ•ε_o ~4•10^{20} Ω-cm

10 yr → ρ•ε_o ~4•10^{21} Ω-cm

----

500 yr → ρ•εo ~1•10^{23} Ω-cm

Decay time vs. resistivity base on simple capacitor model.

$$\tau = \rho \, \varepsilon_r \, \varepsilon_o$$

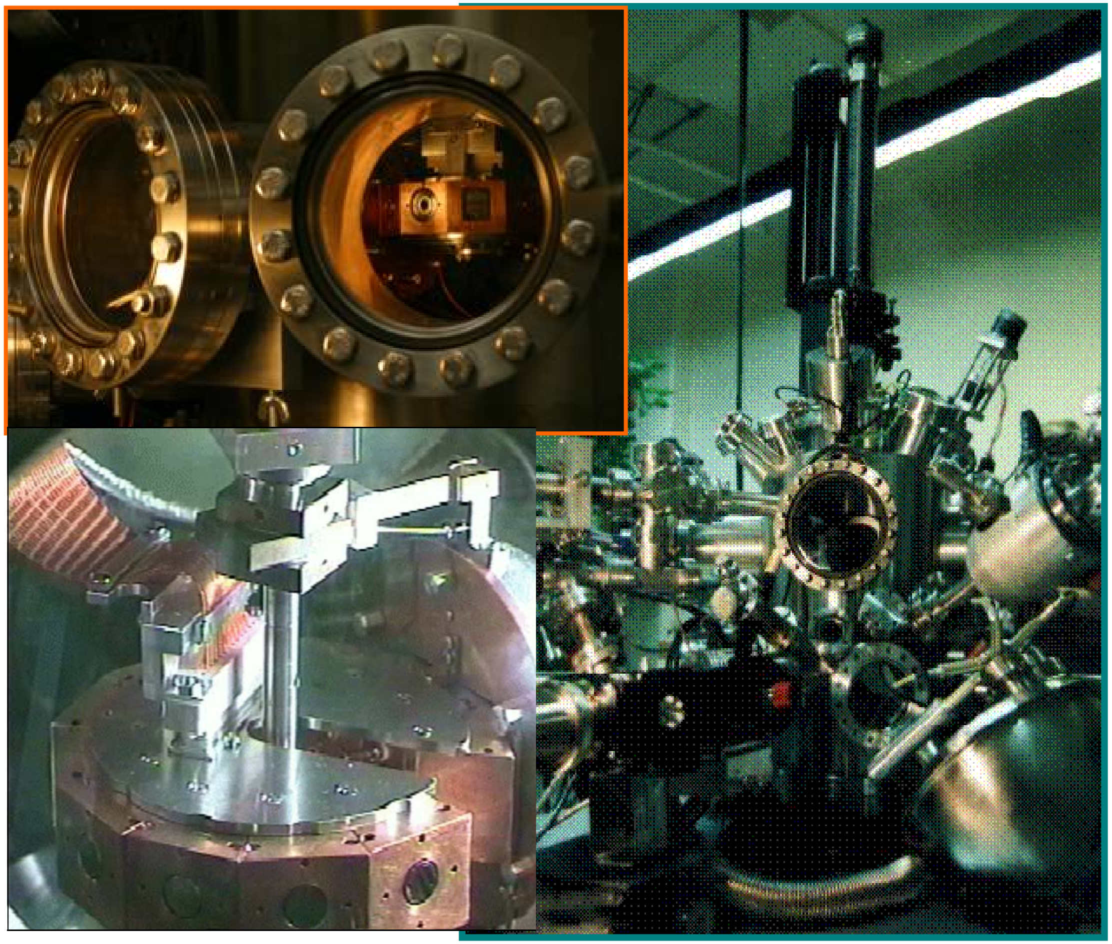
Materials Physics Group Measurement Capabilities

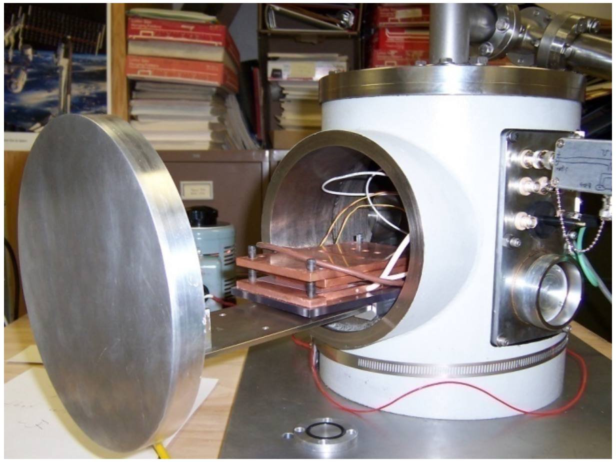
Electron Emission
Ion Yield

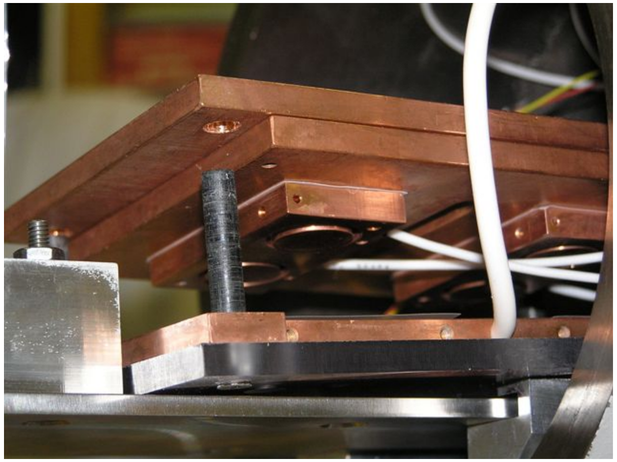
Photoyield
Luminescence

Conductivity
Electrostatic Discharge

Radiation Induced Cond.
Radiation Damage

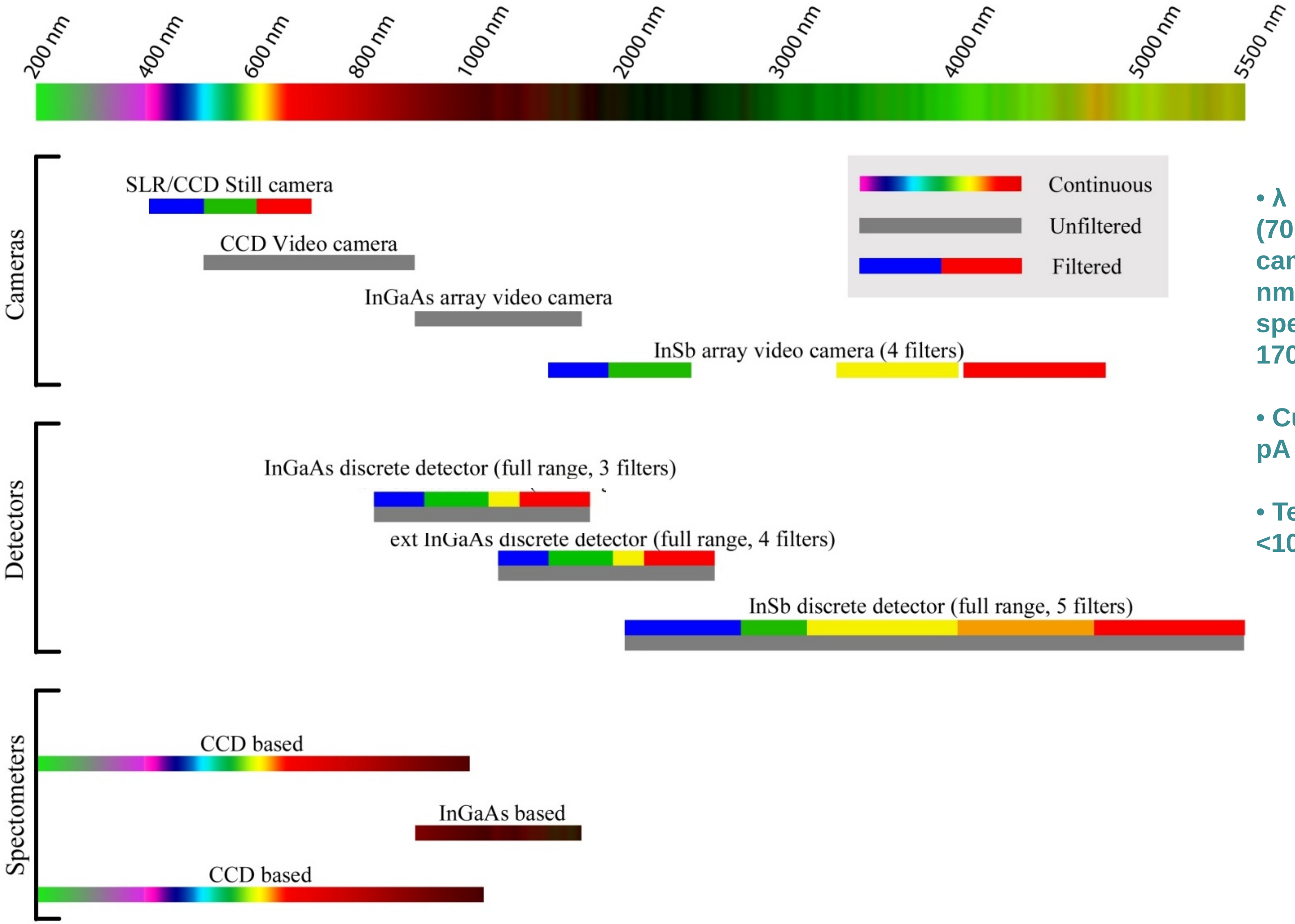






Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate

USU Phase V-A Arc/Glow Instrumentation Ranges

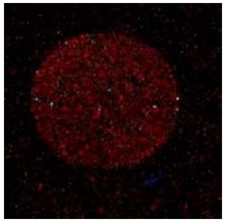


- λ range: detectors (700-5500 nm), cameras (400-5000 nm), and spectrometers (200-1700 nm)
- Current range: (0.1 pA to 1 mA)
- Temporal range: $<10^{-9}$ s to $>10^{4}$ s

Electron-Induced Luminescence

USU Tests

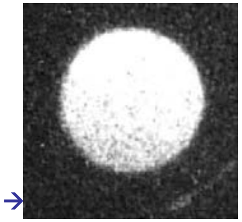
1 cm Dia test samples
30 s Exposure SLR Camera



Kapton XC

500 nA/cm^2
22 keV
150 K

← SLR **NIR Video 33 ms exp. →**



"Flare"

M55J

1 nA/cm^2
22 keV
100 K

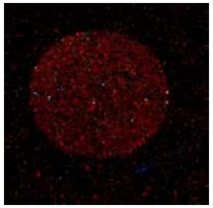
Sustained Glow

"Flare"

IEC Shell Face Epoxy Resin with Carbon Veil

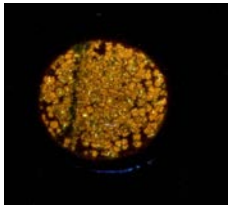
1 nA/cm^2
22 keV
100 K

Sustained Glow



Sustained Glow

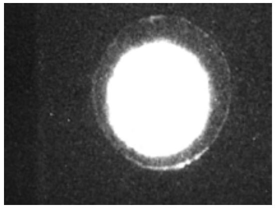
1 nA/cm^2
22 keV
100 K
100 s exp.



Sustained Glow

Kapton E

500 nA/cm^2
22 keV
150 K



NIR Video

5 uA/cm^2
22 keV
150 K

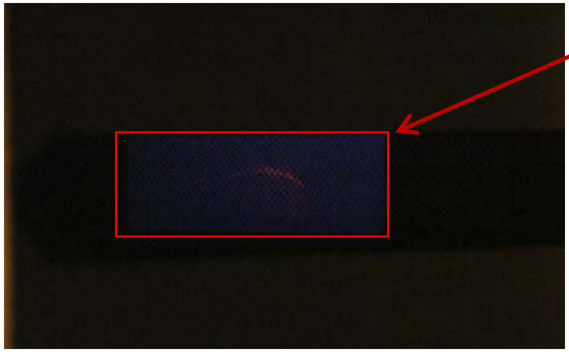
Click to edit Master title style

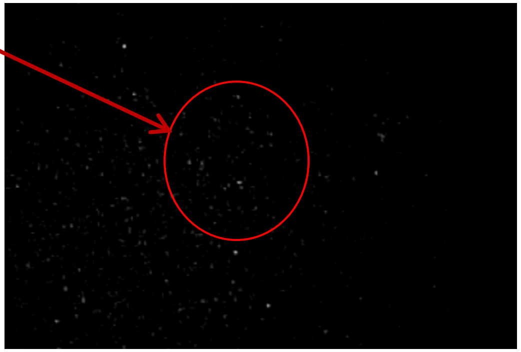
Emission Increases with Decreasing Temperature

Sample Area

Surface Glow

296 K



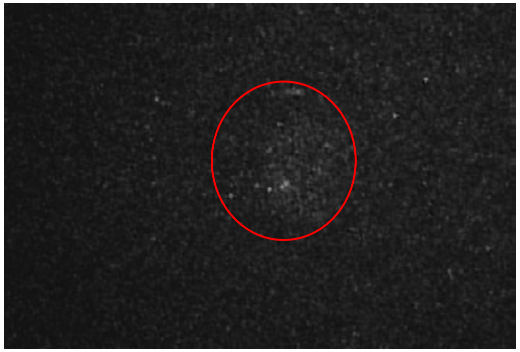


Surface Glow

294 K

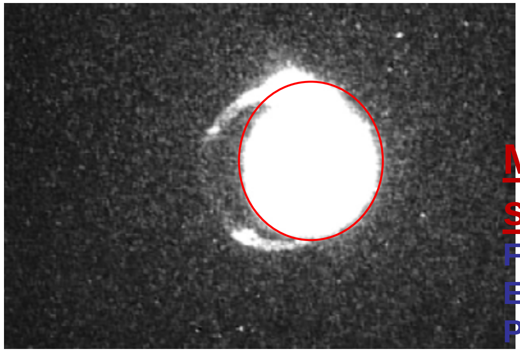
Surface Glow

90 K



Surface Glow

130 K



“Flare”

130 K

T300 Glow seen at MSFC

Flux density =1 nA/cm^2

Energy=22 keV

Power 22 uW/cm^2

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/cm^2

Energy=22 keV

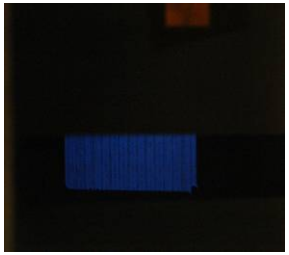
Power 110 uW/cm^2

Temp = 294 K and 130 K

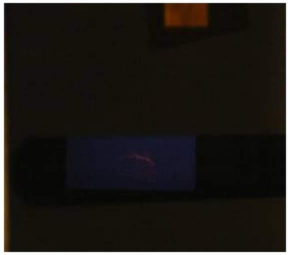
Electron-Induced Luminescence

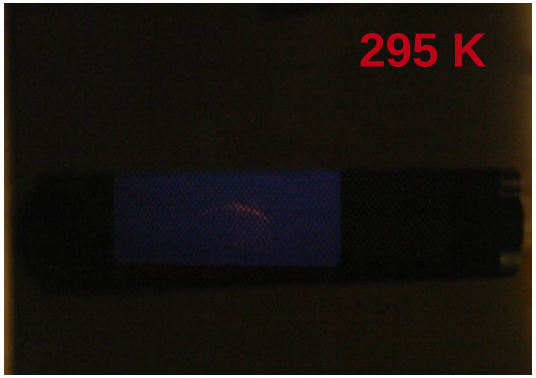
MSFC Tests

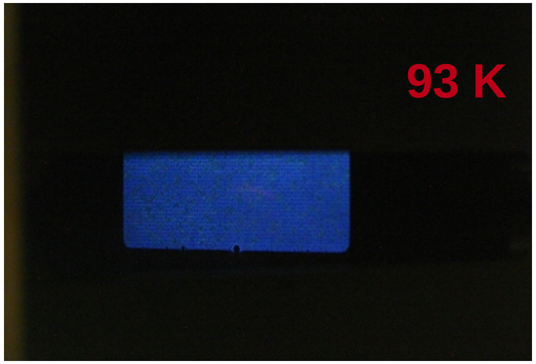
15x5 cm test samples
120 s Exp. SLR Camera

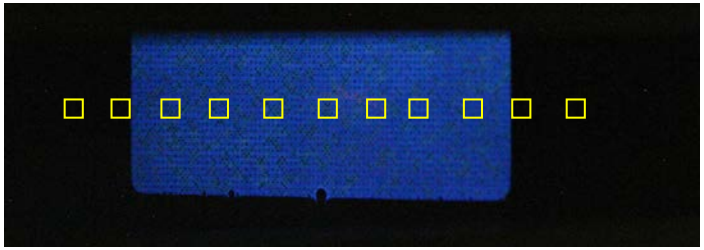


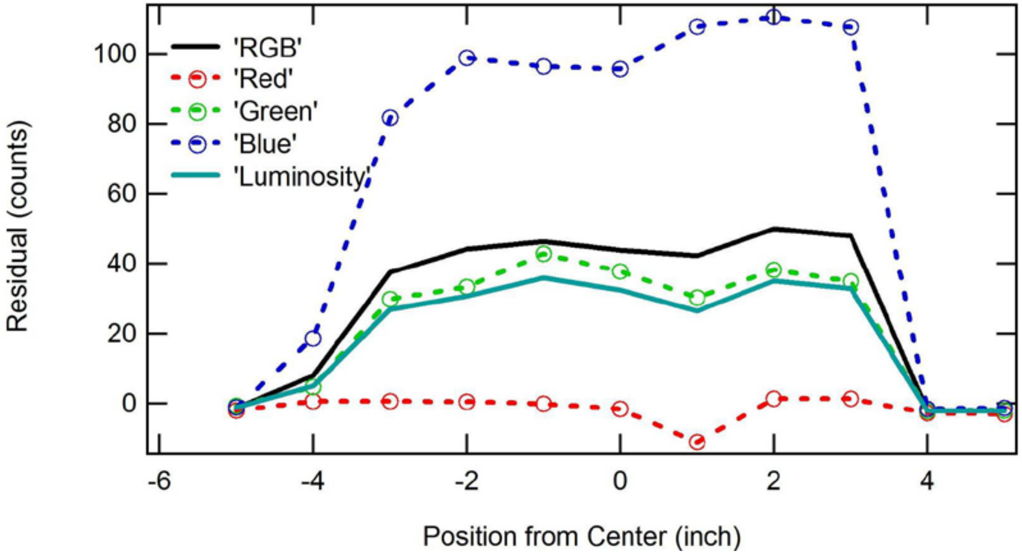
M55J	T300 DTA
1 nA/cm^2 22 keV 90 K	1 nA/cm^2 22 keV 90 K









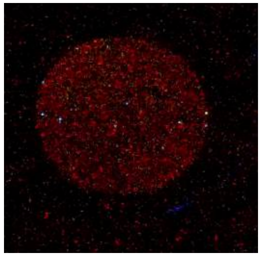


JWST Glow and Arcing Studies

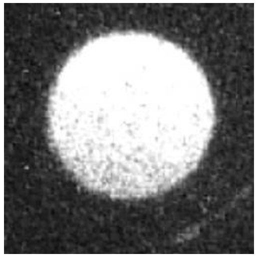
Primary Concern:

What are the risks related to spacecraft charging—including arcing and electron-induced luminescence—for insulating structural materials and mirrors or other optical surfaces when exposed to electron fluxes under "worst case storm" or prolonged typical L2 conditions?

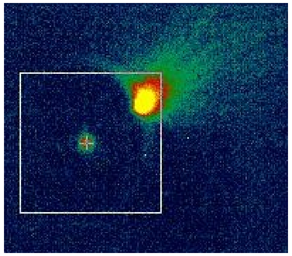
Black Kapton XC Blanket



Surface Glow



"Flare"



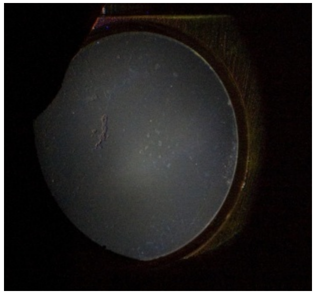
Arc

M55J Carbon/Epoxy Composite

Surface Glow

"Flare"

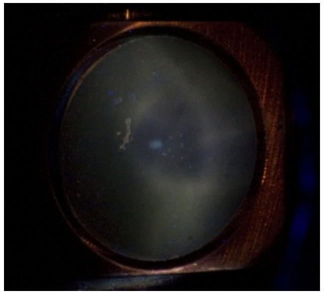
Arc and "Flare"



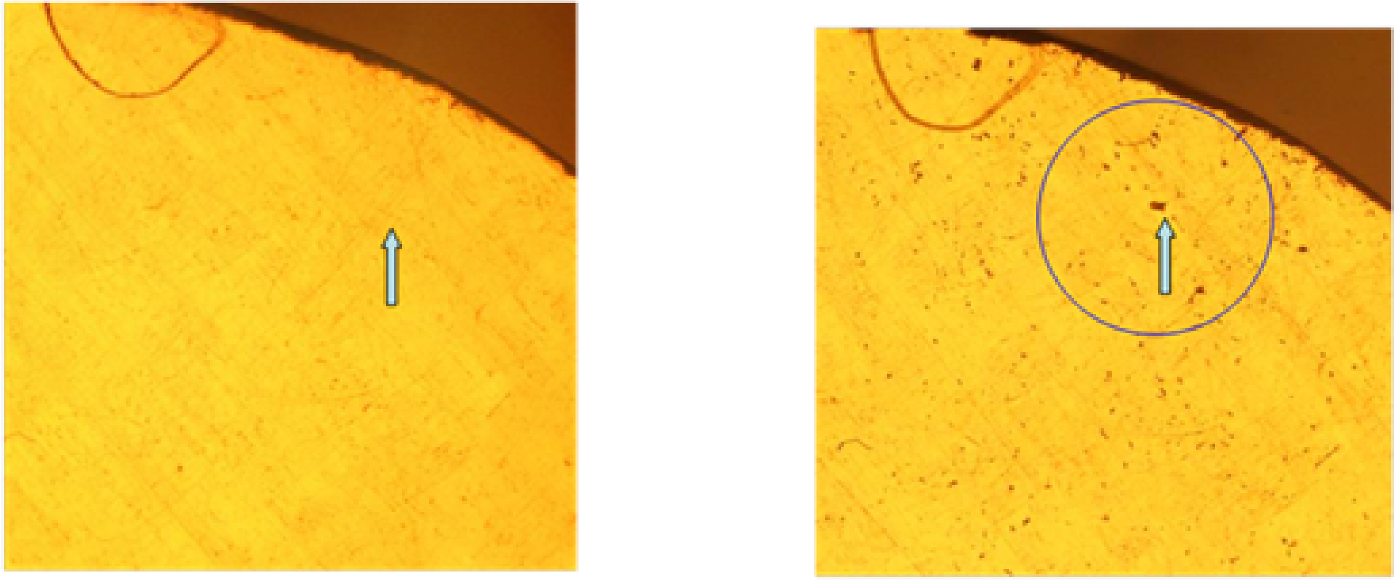
Disordered SiO_2 Optical Coatings on Mirrors

Play movie POMGlow.wmv

Surface Glow



Arc Damage

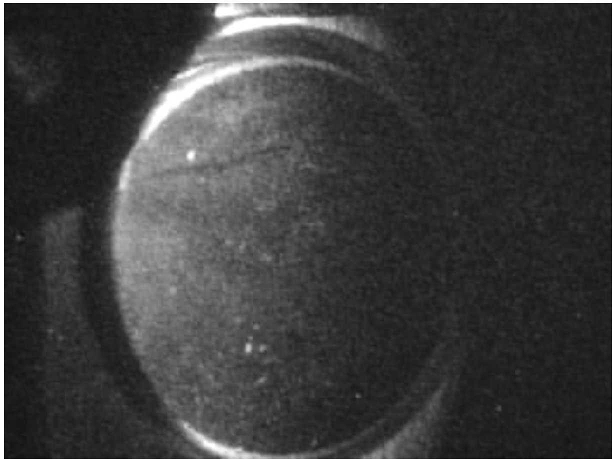


(a)

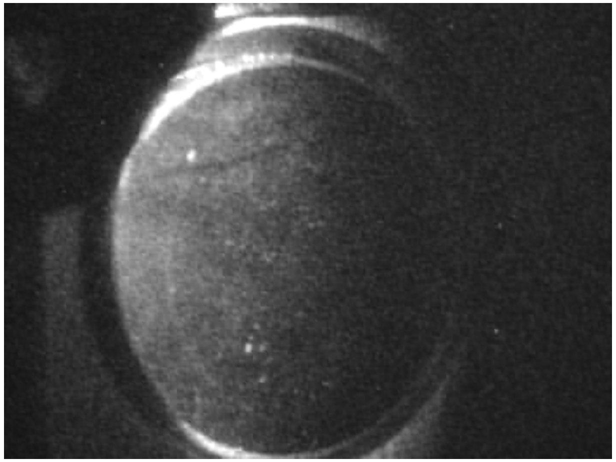
(b)

Figure 8. Comparison of optical microscope images of composite sample surface (a) before and (b) after electron bombardment (22 µW/cm2, 1 nA/cm2 at 22 keV) at 150 K. Sample is a composite material with an ungrounded 0.1 µm Au/Cr coating on an epoxy resin fiberglass and carbon fiber composite substrate, with the Au side exposed to beam. Numerous damage sites from arcing are evident on the exposed sample, including the ~250 µm diameter features identified with the arrows.

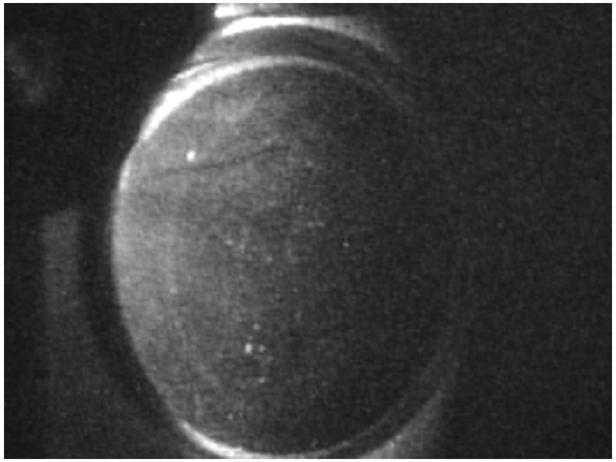
Example of POM Arc-Video



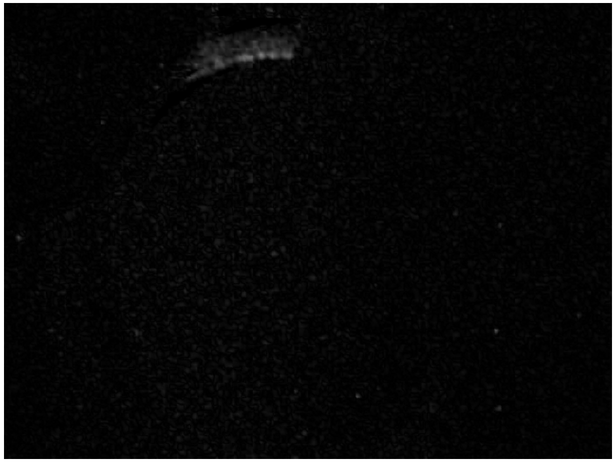
Frame before arc



Frame of arc



Frame after arc



Difference between frame before and frame of arc